

The Effects of the Fourth Dike on the Kim Đông Coastal System

Balancing Flood Protection, Ecosystem Resilience and Economic Development in Vietnam's Coastal Zone
space
MDP397

Report

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Preface

This report presents an integrated assessment of how completing a fourth sea dike (Bình Minh 4) in Kim Đông, Ninh Bình, may affect coastal dynamics, and what this means for mangrove ecosystems, local livelihoods and development goals of Kim Đông. Ultimately to propose interventions to minimise negative outcomes resulting from the completion of the fourth dike.

This report is intended for provincial policymakers in Ninh Bình, particularly the Department of Agriculture and Environment, and for academic communities working on nature-based solutions and coastal resilience in delta environments. It can provide as a base for discussing trade-offs, identifying future steps and a base for hydrodynamic modelling in the area. The recommendations can be used in the design phase of the dike, and after the construction of the dike.

We would like to extend our gratitude to our supervisors at Thuyloi University and Hanoi University of Civil Engineering (HUCE), Lê Hải Trung, Lê Hải, and Mai Cao Tri, for their supervision, granting access to facilities, and continuous sharing of local knowledge and context. Beyond our official supervisors, we especially thank Tung Dao for invaluable help in organising the field trip, setting up the numerical model, and providing important technical insights. We are grateful to Trần Thị Lợi for her guidance on the physical drivers of mangrove growth and for sharing information on local mangrove conditions in Kim Đông. Finally, we thank our TU Delft supervisors, Cong Mai Van and Ellen Minkman, for steady support and constructive feedback throughout the project. We also appreciate the cooperation of local authorities and residents who shared their time and perspectives.

Hanoi, November 2025

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AI Statement

While writing this research, several AI tools were used, including ChatGPT (model GPT-5) and Gemini. These tools supported the writing and analysis process by helping to structure the text, correct spelling and grammar, summarise scientific information, locate Vietnamese sources, and create structured tables. The tools were used solely as a means of support, not to write the entire report.

In addition, AI was used for programming, data processing, and modelling. The tools helped to optimise code, identify errors, clarify programming steps, and automate calculation methods. All generated code suggestions were thoroughly reviewed, adapted, and validated before being implemented.

Using AI made the writing process more efficient while maintaining integrity of the information. All AI-generated content was carefully reviewed and edited by at least two team members to ensure academic accuracy and integrity. All final decisions and formulations were made independently.

Approximately 20-30% of the AI-generated suggestions were either corrected or omitted because they contained unverifiable or inaccurate information. This ensured that only factually supported and contextually relevant content was included in the final report. When it was included in the report, it was, however, still rephrased and changed to fit the context and not copied directly.

To ensure transparency, a list of example prompts used throughout the writing process is included.

Textual support

- *'Could you summarise this paragraph of text into two sentences?'*. This prompt was used to condense sections from the appendix into concise summaries for the main text.
- *'Could you rewrite this paragraph into academic English whilst keeping it mostly the same?'*. This prompt was used to refine phrasing, correct grammar, and improve the academic tone of the text.
- *'Could you write a concluding text for this chapter to link to the next chapter?'*. This prompt was used to ensure smooth transitions between chapters and maintain consistency in writing style and focus.
- *'Could you provide the LaTeX-APA format for this source?'*. This prompt was used to correctly format references according to the APA citation style for inclusion in the bibliography.

Modelling support

- *'Check this code for logical or syntax errors?'*. This prompt was used to discover and solve errors
- *'From this array, write a piece of code that transforms all values that are over 5 in column 3 to -999'*. This prompt would be used to reduce coding time for simple tasks.
- *'What is the best way to accurately visualize the following code by using matplotlib'*. This prompt was used to compare different ways to visualize results.
- *'How can I extract these results to an excel file?'*. This prompt was used to easily transfer data to team members with less experience in coding.

Content-related support

- *'Could you explain how an aquaculture farm works in detail?'*. This prompt was used to discover how aquaculture works and to decide on search terms.
- *'What are the differences between the Law on Forestry 2017 and the Land Law 2024?'*. This prompt was used to discover detailed information about certain laws and identify differences.
- *'Explain the concept of wave shoaling to me, and provide me with the source where you retrieved the provided information from'*. This prompt has been used to refresh understanding of the concept of wave shoaling.

Abstract

The completion of a fourth sea dike (Binh Minh 4) in Kim Đông, Ninh Bình, in Vietnam will reshape local hydrodynamics and will result in land reclamation. Thus, the balance between mangrove forest health, flood protection, local livelihoods and development goals will be changed. This report addresses the impacts and fills knowledge gaps regarding the completion of this fourth dike on hydrodynamics in Kim Đông, and examines hydrodynamic, ecological, governance, and social factors in relation to the mangrove ecosystems in the region.

To achieve this, a governance analysis and system analysis are combined with a hydraulic analysis and a conceptual hydrodynamic model in Delft3D. This approach is supported by literature and institutional reviews, expert interviews, a community survey, and hydraulic data, including satellite-derived wave and wind records, as well as field measurements. Together, these elements shape the model set-up, boundary conditions and interpretation. The modelling framework compares a baseline situation without a dike with two with-dike scenarios, simulating both storm and regular weather conditions. Physical changes in the model are linked to drivers of ecological change, allowing an assessment of their impact on mangrove forests and socio-economic conditions in the area.

Findings from the conceptual Delft3D model indicate that the completion of a fourth dike is likely to reduce tidal connectivity and sediment supply to the enclosed area, leading to longer inundation times and lower water levels. These change in conditions drive mangrove squeeze, reducing habitat, shelter and carbon storage potential. At the same time, land reclamation creates development opportunities for aquaculture. Interventions to mitigate the effects of the fourth dike are presented using a COCD box, and evaluated via a multi-criteria analysis. Suitable interventions are further elaborated on their trade-offs and implementation process.

Decision-making in Vietnam, and in Kim Đông especially, is highly hierarchical, which limits involvement of local authorities and residents even though they are most affected. Conflicting priorities among sustainability, economic growth and climate adaptation further complicate this involvement in decision making. Additionally, limited data availability and experience with nature-based solutions also constrain adaptive management and long-term monitoring. With this in mind, four potential interventions are assessed: adaptive gate management, mangrove co-management with incentives, sustainable aquaculture certification, and a digital monitoring platform. No single measure resolves all challenges. However, co-management with incentives and sustainable aquaculture emerge as promising options that couple ecological restoration with socio-economic benefits, supported by adaptive gate operations and a digital platform to improve coordination and transparency.

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1 Introduction

Mangrove forests are key to coastal protection and biodiversity, and can be a source for economic benefit, forming the living connection between land and sea across tropical and subtropical shores. Yet, mangrove coverage in Vietnam has decreased sharply, stressing the need for targeted conservation and restoration (Lê et al., 2025). This study centres on the Kim Đông commune in the province of Ninh Binh, where the government, Thuyloi University (TLU) and Hanoi University of Civil Engineering (HUCE) have been testing integrated approaches to mangrove conservation and sustainable coastal management (Lê, 2025). Figures 1.1 and 1.2 show the location of the Kim Đông commune, which serves as the focus area of this report.

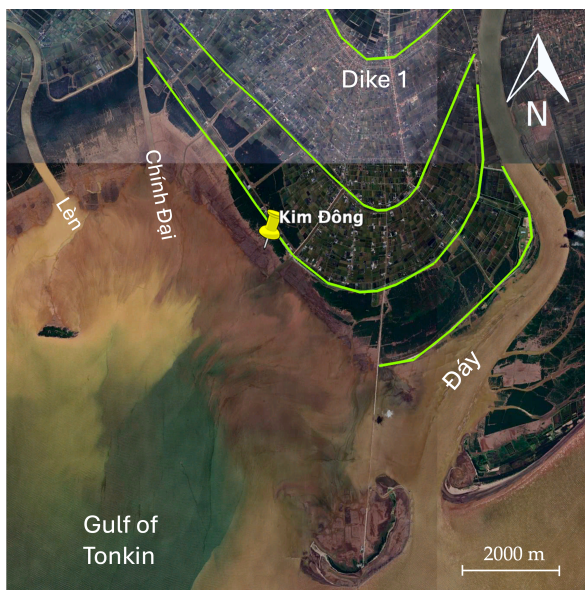


Figure 1.1: Kim Đông Commune Location (Google LLC, 2024)

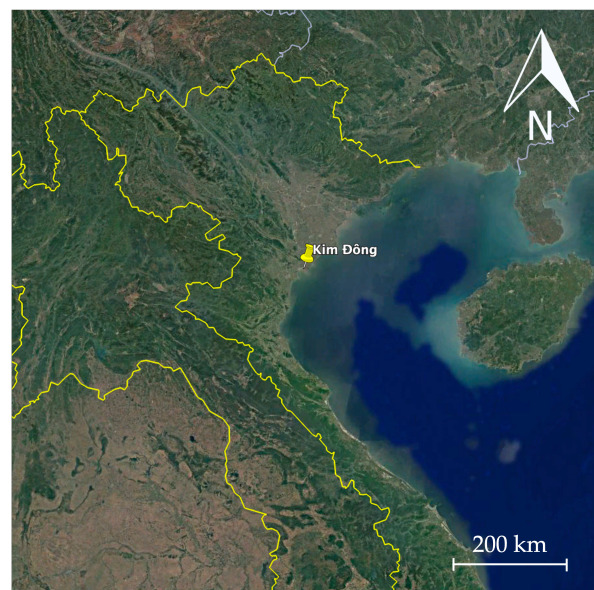


Figure 1.2: Kim Đông Commune Location Zoomed-out View (Google LLC, 2024)

Over the years, several dike rings have been constructed to enclose the area, secure new land, protect the area from floods and expand the commune seaward. In 2018, construction began on the first segment of Kim Đông's fourth sea dike, but the rest of the shoreline was never embanked. The eventual closure of this dike is expected to change tidal exchange, currents, salinity, and sediment transport, impacting both the mangrove ecosystems and local aquaculture activities. These changes create both risks and opportunities for the commune, which this study aims to explore in detail.

This project focuses on mangroves, which provide multiple ecosystem services, including coastal defence against extreme storm surges, wave attenuation, and erosion control. They also support local livelihoods through fisheries, timber and honey production, while offering critical habitats for shrimp, oysters, crabs, and fish (Anu et al., 2024) (Vietnam News, 2024). Furthermore, mangroves act as highly effective "blue carbon" ecosystems, storing carbon at relatively high rates, thus playing an essential role in climate change mitigation (Gijón Mancheño et al., 2025; Zhang et al., 2025), (Dr. Tung Dao, Appendix C.2.4).

Although the loss of mangroves is a national concern, Vietnam has lost over 60% of its mangrove coverage since 1943 (Lê et al., 2025), this study focuses on the role and status of mangroves in Kim Đông. The possibility of the continuing construction of the fourth dike which, in combination with a lack of operational planning and spatial management, may threaten the integrity of the mangrove belt and

undermine aquaculture and fisheries. By clearly examining the immediate local impacts of constructing the fourth dike ring and using that knowledge to guide planning, the province can protect mangrove functions while still pursuing its development goals.

1.1. Problem Analysis

Mangrove ecosystems in Kim Đông are influenced by a complex interplay of hydraulic dynamics, sediment transport, human activities, and governance structures. These factors determine the sustainability and resilience of mangroves, which in turn affect coastal protection, aquaculture, and biodiversity. While hydraulic processes significantly shape the environment, human activities such as dike construction, land reclamation, and aquaculture also have profound effects. Looking at the near future, the second section of the fourth dike could be constructed, following the path of the construction of the other dikes in Kim Đông. The key unknown is how the hydraulic processes, human activities and policies will interact if this happens. This could potentially disrupt or enhance the mangrove ecosystems in Kim Đông and the broader physical and socio-economic balance.

The hydraulic processes in Kim Đông are strongly influenced by the construction of the dikes, including Dike 4, of which the first section was constructed in 2018. The eventual closure of this dike is expected to significantly alter tidal exchange, currents, and sediment transport patterns in the region (Lê, 2025). The change in these hydraulic processes could limit the inflow of vital sediments needed for mangrove health.

These hydraulic changes also have implications for the aquaculture systems in the area, which rely on the natural tidal movement supplying fresh seawater, ensuring water quality and nutrient cycling. Aquaculture has become increasingly important for the local economy, but it also contributes to pressure on mangrove habitats by occupying coastal land and introducing pollutants into the water system, creating tension between economic development and ecosystem preservation.

In addition to this, the governance structure of Kim Đông is complex, with policies surrounding dike construction, aquaculture expansion, and mangrove conservation often conflicting. At the local level, fragmented policies and unclear responsibilities lead to slow decision-making and coordination (Interview Dr. Tung, 2025, Appendix C). Without integrated governance that considers the connection of hydrodynamics, ecology, and local livelihoods, efforts to protect and restore mangroves may be ineffective.

In short, there is insufficient clarity on how completing and operating Dike 4 will affect hydrodynamics, mangroves and aquaculture. This is mainly because of limited data and knowledge about the area.

1.2. Project Objective

The main objective of this project is:

To address and fill knowledge gaps regarding the impact of the completion of Dike Four (Binh Minh 4). This analysis will examine hydrodynamic, ecological, governance, and social factors in relation to the mangrove ecosystems in the region. Based on these insights, the goal is to propose recommendations for the province that will mitigate the negative outcomes resulting from the completion of the fourth dike.

In order to achieve this objective, the project adopts a multidisciplinary approach that combines literature study, field observations, stakeholder analysis, governance review, hydrodynamic modelling and technical evaluation of hydraulic conditions.

To address the objective, the main research question is formulated as follows: *'How can the social, ecological and hydraulic effects of the completion of the fourth dike be addressed to support both sustainable management of ecosystems and the development of the area?'*

1.3. Project Scope

The project area is enclosed by four physical boundaries, as can be seen in Figure 1.1. The eastern and western boundaries are defined by the Đáy River and the Chính Đại River, respectively, while the southern boundary is formed by the Gulf of Tonkin. To the north, the system is enclosed by the first dike. Within these boundaries, all ecological, physical, and human processes relevant to mangrove development take place.

By contrast, the socio-economic boundary is defined to cover the decision-making arena that shapes the coastal system. It includes authorities that have an influence on Kim Đông, the local community, contractors that work in Kim Đông and organisations that have (had) an influence on Kim Đông. Framed this way, the boundary captures the critical interfaces where operational rules, permits and investments can be adjusted, and where stakeholder action most directly affects hydrodynamics, mangrove condition and livelihoods.

1.4. Research Questions

Besides the main research question formulated in section 1.2, supporting sub-research questions are formulated. This project seeks to answer the following sub-research questions:

1. *What is the spatial, ecological and social context of Kim Đông and what are the main development goals?*
2. *How do mangrove ecosystems function on this coast, and what site-specific conditions favour establishment and persistence?*
3. *What governance structure and stakeholder landscape shape decisions in the project area, and who decides on what?*
4. *What are the expected effects of completing and operating the fourth dike on hydrodynamic conditions and human activities, and what do these effects imply for mangrove performance?*
5. *Which interventions can minimise negative impacts of the completion of the fourth dike?*

1.5. Outline

This report examines sustainable mangrove development in Kim Đông in relation to the completion of Dike 4 and is structured into eight chapters. Chapter 1 introduces the project. It presents the background and context, main objective, scope, and research questions. Chapter 2 provides the methodology, describing the methods used for the research and to ultimately answer the research questions. Chapter 3 offers a system analysis of Kim Đông coastal zone. It explains the historical evolution of the area, mangrove ecology, stakeholders, and institutions. The chapter concludes with a system diagram used later for assessment. Chapter 4 focuses on hydraulic analysis, including river inflows, bathymetry, tides, waves and salinity. Chapter 5 describes the conceptual numerical model in Delft3D and its results. Chapter 6 integrates the results from the conceptual model and system analysis. Also, it explores possible interventions, including implementation and trade-offs. Chapter 7 presents the main conclusions, and Chapter 8 closes with a discussion of key insights, limitations, and recommendations for further research. In the appendices, detailed background information can be found.

2 | Methodology

In this chapter, the research methodology is outlined, ultimately showing how the research questions will be addressed. The aim of this study is to identify and close knowledge gaps regarding the impact of the expected completion of Dike Four in the Kim Đông commune. This is achieved through a combination of different interdisciplinary methods, both qualitative and quantitative, which are then synthesised to develop recommendations that mitigate the negative effects of the dike and support sustainable preservation and restoration of mangroves. The overall flowchart of the research process is shown in Figure 2.1.

The methodological design consists of four main components:

1. Data Collection
2. Data Analysis
3. Synthesis
4. Discussion and Conclusion

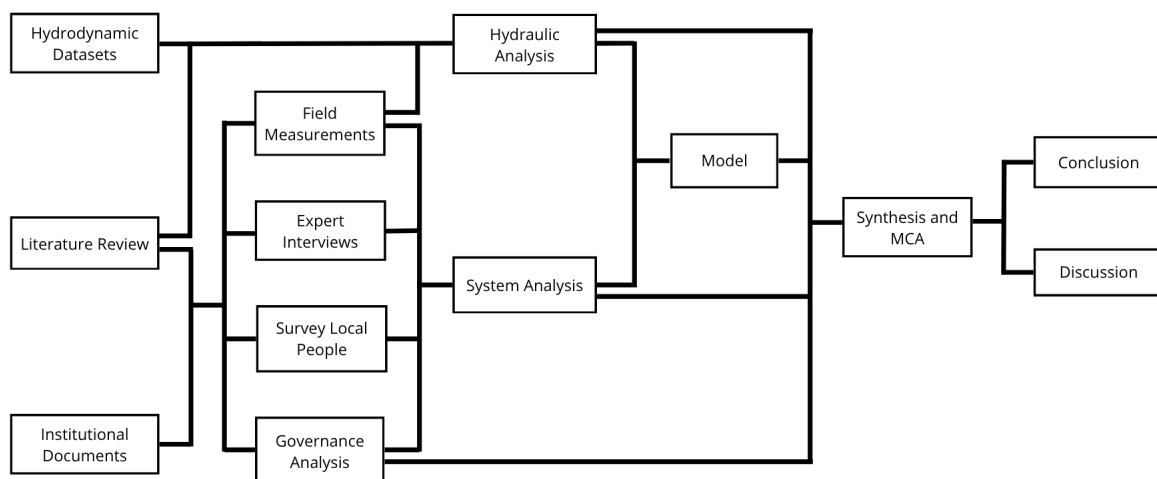


Figure 2.1: Flowchart Methodology

2.1. Data Collection

The data collection phase combines data from literature and institutional documents with data from expert interviews, community surveys, satellite data, and field measurements. This combination ensures comprehensive coverage of both qualitative and quantitative aspects of the study, providing a solid foundation for subsequent analyses.

2.1.1. Literature Review and Institutional Documents

The research starts with a literature review. The goal of the literature and institutional review is to build a strong knowledge base and identify knowledge gaps in the system. The literature is both national (Vietnamese) as international. Vietnamese literature was either translated by Vietnamese people from Thuyloi University helping us or AI. The main search engines used are Google Scholar, Scopus and ResearchGate. Central themes include:

- Kim Đông commune & coastal system
- Hydrodynamics & sedimentation
- Mangrove ecology & restoration
- Aquaculture & ecosystem impact
- Governance & mangrove policy (related to mangroves)

Because the Kim Đông coastal area was officially named Kim Sơn coastal district before 1 July 2025, search terms include both names to ensure historical completeness. To collect knowledge relevant at multiple spatial scales, broader search terms related to Vietnam's coastal regions were also used.

Example search terms are:

- Kim Đông coastal system
- Kim Sơn mangroves
- Ninh Bình mangroves
- Vietnam mangrove restoration
- Red River Delta hydrodynamics
- Tidal dynamics Vietnam
- Sediment transport mangroves
- Sustainable aquaculture Vietnam
- Shrimp farming environmental impact
- Vietnam mangrove governance
- Co-management coastal resources Vietnam

While all information about Kim Đông commune is considered relevant to the project, particular emphasis is placed on literature that directly addresses the themes above. Priority is also given to literature specific for Vietnam or the Red River Delta and to literature publicised recently.

The institutional documents review legislative documents to map the governance context. The main focus of these institutional analysis are

- Environmental laws
- Public investment laws
- Informal rules and regulations
- Donations for mangrove projects

In total, there have been 120 documents and articles included, which shows the diversity and quantity of information used.

2.1.2. Hydrodynamic and Environmental Datasets

Hydrodynamic and environmental datasets are collected from satellite data and field measurements. This provides the quantitative inputs required for the hydraulic analysis and numerical modelling. The datasets involve two primary sources:

1. Satellite Data

Wave and wind conditions are extracted from Copernicus (the earth observation component of the European Union's Space programme). This provides continuous data in space and time, which are particularly useful for offshore areas where in-situ measurements are limited (Appendix B.5.1).

2. Field Measurements

Two types of field measurements were used. In April, the research team from Thuyloi University, as part of a Vietnamese government project in collaboration with Hanoi University of Civil Engineering, conducted a series of measurements, the results of which were made available for this study. These raw data are used directly to inform the bathymetric and hydrodynamic models.

Additionally, the MDP group carried out its own field campaign. Due to unforeseen circumstances, most of the planned measurements could not be performed directly. However, with the assistance of the supervising team, the most essential measurements to complement existing data and validate model assumptions were successfully completed. An overview of the existing and supplementary in-situ data is presented in Table 2.1. The table outlines the data that were already available, the measurements initially planned for the field trip, and the ones successfully carried out. Further details on the field trip and the measurements conducted by the MDP group and supervisors can be found in Appendix D.

Table 2.1: Field Measurement Data

Data	Previously Available	Planned	Obtained
Bathymetry Validation Points	X	✓	✓
Cross-shore Profiles	✓	✓	✓
Offshore Current Velocity	X	✓	X
Propagule Collection	X	✓	✓
Salinity	X	✓	✓
Suspended Sediment Concentration	✓	✓	✓
Water Level	✓	X	X

The goal of collecting these datasets is to build a comprehensive quantitative basis for the hydraulic analysis and to provide the necessary input and validation data for subsequent hydrodynamic modelling.

Bathymetry validation is performed using the RTK GNSS module to survey key checkpoints in the area. Due to adverse weather conditions, the MDP team could not complete all planned measurements but received training for future deployments. Suspended sediment concentration measurements were carried out by the MDP group and supervisors using a simple method, where a 1.5-litre bottle was submerged, filled with water, and retrieved using a rope weighted at the bottom. The samples were filtered, dried, and weighed in the Hydraulics Laboratory at Thuyloi University to calculate the SSC.

More detailed information on these methods is found in Appendix D.4.

2.1.3. Expert Interviews and Survey

Stakeholder and local insights are collected through expert interviews and a community survey, complementing the findings from the literature review. These methods provide valuable qualitative and quantitative data, contributing to a deeper understanding of the governance and development context in Kim Đông. The two methods applied are:

1. Semi-structured Interviews

Semi-structured interviews were conducted with key informants to gather in-depth, qualitative insights into system dynamics, governance, and specific knowledge gaps. Semi-structured means that there are pre-prepared questions (Appendix C), but also room for open conversation. The goal was to conduct interviews with individuals from the commune and other relevant sectors, ensuring a broad perspective. Five people were interviewed, with one interviewee being interviewed twice to ask follow-up questions after the field trip. The interviewees are mangrove experts, sociologists, coastal engineers or individuals with specific knowledge about Kim Đông. The interviews can be found in Appendix C.

The topics covered in the interviews were the ecosystem, mangroves, land use trade-offs, governance, policy, data and monitoring, coastal protection, Dike 4, stakeholders. Additional topics that came up during the interviews were development goals of Kim Đông, hydraulic processes, additional stakeholders, funding and legal frameworks.

2. Community Survey

A survey was administered in Vietnamese to local residents of the Kim Đông Commune, with the aim of gathering quantitative data on community perspectives regarding mangrove development. The survey was designed with simple closed questions in Vietnamese to ensure accessibility for the local community, who generally do not speak English. This allowed the collection of data that can be used to compare results. Eighteen local residents have filled in the survey. The main takeaways from the survey results can be found in Appendix E.

The combined insights from the expert interviews and the community survey provide input for the governance analysis, supporting a detailed understanding of institutional relationships, stakeholder dynamics, and local perspectives. Additionally, the interviews offer valuable information about Kim Đông's development goals, the construction of the dikes, and the hydraulic mechanisms in the area. Further details on the execution of the survey and an interview in Kim Đông can be found in Appendix D.

2.2. Data Analysis Methods

The collected data are analysed through several complementary methods that together explore the system's physical, ecological, and governance components. The integration of these analyses provides the basis for the subsequent synthesis.

2.2.1. Governance Analysis

The governance analysis interprets and integrates insights from the institutional documents, literature review, expert interviews, and community survey to develop an understanding of the governance system shaping mangrove restoration in Kim Đông. This iterative process was reviewed and adjusted several times during the development of the research. The primary aim is to identify key actors, their roles, and the dynamics that shape governance in Kim Đông, providing input and a framework for the system analysis and the system diagram. Several analytical methods are applied:

1. Policy documents and interview transcripts are synthesised to map the formal institutional structure, while also identifying informal rules, practices, and norms that influence decision-making and policy implementation.
2. The power-interest grid is used to assess the relative influence and interest of key actors in the governance system, helping to identify their roles and potential impact on decision-making processes.
3. The findings from the stakeholder analysis are summarised in a visual format, including formal charts that illustrate actor relationships, decision-making pathways, and feedback loops within the governance framework.

The goal of this analysis is to construct a comprehensive picture of the governance environment, capturing both formal institutions and informal dynamics. This improved understanding supports the identification of institutional strengths, gaps, and opportunities for more effective and sustainable mangrove management.

2.2.2. System Analysis

The system analysis synthesises diverse data sources, including the literature review, expert interviews, community surveys, field measurements, and governance analysis, to provide an integrated understanding of the Kim Đông coastal system. This analysis involves integrating both qualitative and quantitative data to develop a comprehensive understanding of the Kim Đông coastal system and how its ecological, hydrodynamic, governance, and socio-economic factors interact. The process of conducting the system analysis includes the following steps:

- **Identification of Key Components:** The first step is to identify the critical ecological, hydrological, and social components of the Kim Đông coastal system. These include mangrove ecosystems, water flow dynamics, local economic activities (e.g., aquaculture), and governance structures.
- **Mapping Interactions and Feedback Mechanisms:** Once the key components are identified, the analysis focuses on mapping how these components interact with each other. Feedback loops, where changes in one component influence others, are particularly important for understanding the system's behaviour over time.
- **Historical Land-Use Comparison:** The historical land-use trends are compared with the current state of mangrove coverage. This helps to identify changes over time and to assess how human activities, such as dike construction and aquaculture, have shaped the landscape.
- **Impact of Human Activities:** The analysis further explores how human activities, particularly the construction of the dikes and aquaculture practices, influence natural processes such as sediment deposition, water flow, and mangrove growth.
- **Setting Development Goals:** Based on the socio-economic and governance context, the development goals for the Kim Đông area are identified. This helps in understanding the long-term objectives of stakeholders and the role of the coastal system in supporting these goals.
- **System Diagram Creation:** Finally, a system diagram is created to visually represent the entire system. This diagram illustrates the relationships between ecological, hydrological, governance,

and socio-economic components, and serves as a tool to track the impacts of different interventions, such as the construction of the fourth dike.

By synthesising these elements, the system analysis provides a comprehensive framework for understanding the complex interactions within the Kim Đông coastal system. This process enables a clearer identification of how various factors, both natural and human-made, affect mangrove ecosystems and the broader coastal environment.

2.2.3. Hydraulic Analysis

The hydraulic analysis focuses on quantifying the key hydraulic variables that govern the coastal dynamics in Kim Đông. This step is essential for understanding how different hydrodynamic factors such as water flow, sediment transport, salinity fluctuations, and tidal dynamics influence the coastal environment, particularly the mangrove systems. These variables provide the necessary input for the conceptual numerical model and contribute to the synthesis process, helping to evaluate their broader effects on mangrove health and the coastal system. The main components of the analysis are summarised in Table 2.2, which lists the variables, sources, and their purpose in the analysis.

Table 2.2: Hydraulic Analysis Methodology

Variable	Source	Purpose
River Discharge & Sediment Supply	Literature	To use for synthesis to assess seasonal input into the coastal system
Bathymetry	Field Measurements	To create bathymetric surface for model input
Salinity	Literature, Field Measurements	To use for synthesis to assess the impact on mangrove health
Suspended Sediment Concentration	Field Measurements	To use for synthesis to assess the impact on mangrove health
Water Density	Literature	To serve as input variable for the model
Water Level Information	Field Measurements	To define tidal boundary conditions for the model
Wave Conditions	Satellite Data	To provide wave boundary conditions for model
Wind Conditions	Satellite Data	To serve as input variable for the model

The bathymetric data are processed using interpolation and extrapolation techniques to create a continuous bathymetric surface. The SSC measurements are processed using a 3-point rolling mean to smooth short-term fluctuations, enabling a more reliable interpretation of sediment dynamics. In addition, wave data are analysed using Python-based scripts in combination with Extreme Value Analysis (EVA) to assess wave conditions and calculate the extremes necessary for model boundary conditions.

Together, these components provide the necessary input and context required for the conceptual numerical model and synthesis, ensuring that the research captures the main processes affecting flow, wave conditions, sediment transport, and interactions with proposed structures.

2.2.4. Hydrodynamic Modelling

The conceptual numerical hydrodynamic model developed for this study uses Delft3D to simulate the coastal dynamics in the Kim Đông area. This conceptual model incorporates both the current hydrodynamic conditions and the expected impact of constructing the second section of the fourth dike, allowing for an assessment of how this infrastructure will affect coastal dynamics. The modelling process consists of three main steps:

1. **Model Setup:** Primary input variables (bathymetry, water levels, wave conditions, water density) are derived from hydraulic analysis. The model domain is set up to include the existing conditions and the anticipated changes from the construction of the fourth dike.
2. **Simulation:** The model simulates hydrodynamic conditions, including water levels, flow velocity vectors, and significant wave heights, after which the effects of the fourth dike under various sea state scenarios can be analysed. This allows for an assessment of the changes in water dynamics due to the dike's construction.
3. **Calibration and Validation:** Model outputs are compared with available field measurements

to ensure the model accurately reflects local hydrodynamics, ensuring the simulations provide realistic results for both the current situation and the scenario with the new dike section.

The goal of this hydrodynamic modelling is to generate conceptual quantitative outputs that describe the current conditions and allow for an assessment in the synthesis of how the construction of the second section of the fourth dike will influence the hydraulic conditions important for mangrove development.

2.3. Synthesis

In the synthesis, the various analyses conducted throughout the study (system analysis, governance analysis, hydraulic analysis, and numerical modelling) are integrated to assess the impact of the proposed completion of Dike 4 on the Kim Đông coastal system. Eventually, a Multi-Criteria Analysis is conducted to identify which interventions could best mitigate the negative effects of Dike 4. The goal of the synthesis is to combine these diverse findings in a multidisciplinary way, providing a comprehensive understanding of the potential effects of the dike on mangrove ecosystems, hydrodynamic conditions, and local livelihoods.

The synthesis methodology consists of the following steps:

1. **Integration of Analyses:** Combining insights from hydraulic, governance, and system analyses and the conceptual numerical model to create a multidimensional view of the situation, ensuring a comprehensive understanding of all influencing factors.
2. **Impact Assessment:** Using the integrated information to evaluate how the dike will affect mangrove ecosystems, water flow, salinity, and flood risks. This includes understanding changes in sedimentation, tidal exchange, water level and mangrove migration.
3. **Socio-economic Implications:** Examining how the changes in hydrodynamics will affect local communities, aquaculture, and overall economic sustainability. Identifying potential winners and losers of the proposed dike, particularly in terms of land use for mangrove restoration or aquaculture.
4. **Evaluating Mitigation Strategies:** Identifying potential interventions to minimise negative effects. These interventions are analysed through a multi-criteria analysis, considering ecological, economic, and social factors.
5. **Recommendations for Sustainable Management:** Proposing practical steps to ensure long-term sustainability and resilience of the coastal system in Kim Đông.

This synthesis serves as the starting point for developing recommendations for managing the completion of the fourth dike while minimising its negative impacts on both the environment and local communities.

2.4. Conclusion and Discussion

The final analytical phase is dedicated to interpreting the combined findings, drawing general conclusions, and reflecting on the validity of the study. This is achieved through three concluding steps:

1. **Answering the Research Questions:** The integrated findings from all preceding analyses are interpreted to formulate direct answers to the research questions, identifying the opportunities for mangrove restoration.
2. **Formulation of Recommendations:** Based on the conclusions, integrated recommendations are developed to protect mangrove forests while pursuing the development goals of the province.
3. **Critical Reflection:** The research process is reviewed to identify the primary limitations and uncertainties (e.g., in data quality or model assumptions) and to assess their potential influence on the results.

In summary, this chapter outlines the mixed-method and interdisciplinary approach that guides this research, enabling a detailed understanding of the Kim Đông coastal system and the formulation of targeted recommendations. The next chapter applies this approach through the first analytical step, the system analysis.

3 | Kim Đông Coastal System

This chapter provides an integrated overview of the physical characteristics and development of the Kim Đông area over time. It introduces the geographical context, traces the evolution of the coastal system, and outlines the human activities that have shaped its present configuration. Together, these sections form the foundation for understanding how natural and human processes interact in Kim Đông. Because of the importance of mangroves in the area, the ecological functions of them are described, along with their links to environmental and societal factors. After identifying the system components and their interactions, a governance and stakeholder analysis helps to clarify the institutions and interests involved. By combining all these elements, a system diagram is developed to visualise the full system and the relationships between its components and stakeholders. This diagram is later used to assess the potential effects of constructing a fourth dike on the system.

3.1. Kim Đông Commune

The project area is located in Kim Đông commune, a coastal part of the Ninh Bình Province, situated south of Hanoi. This location lies within the Red River Delta system. Kim Đông is bordered to the east by the River Đáy, to the west by the Chính Đại river and the Len river, and the south is connected to the Gulf of Tonkin, providing direct access to the open sea (as seen in Figure 3.1). The bay is sheltered from the west by an accumulated landmass, while a small island lies offshore in front of the Kim Đông coastline.

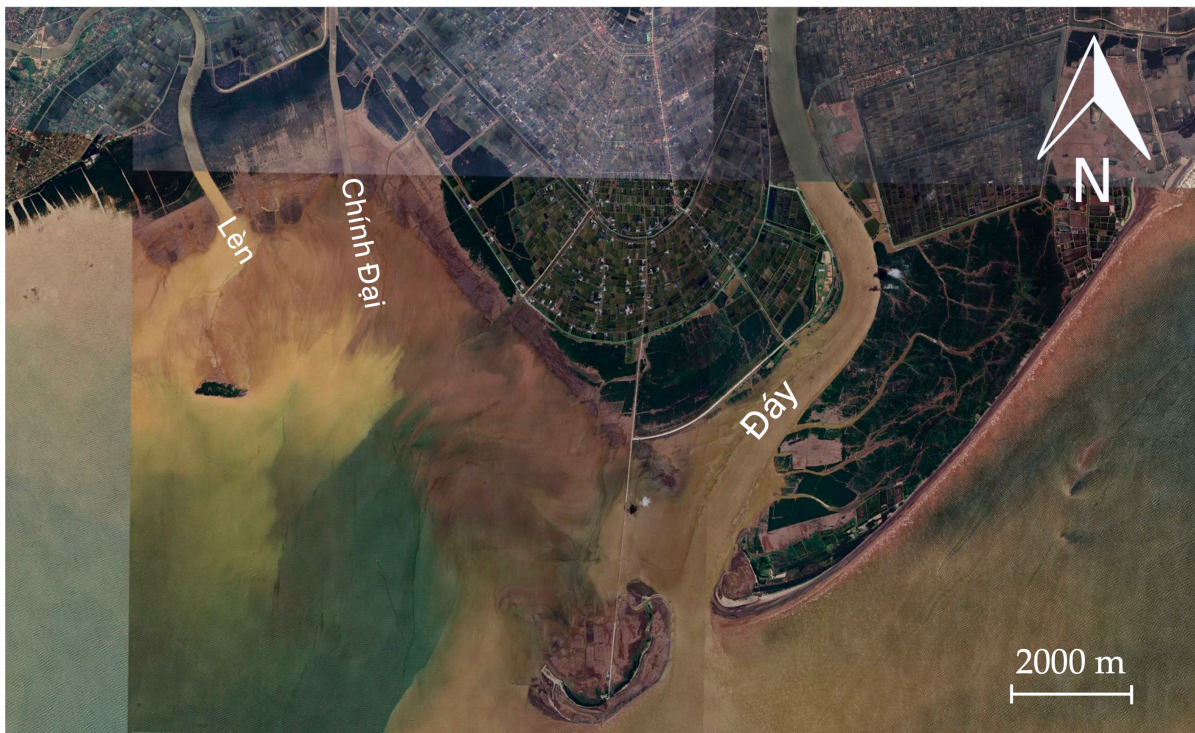


Figure 3.1: Project Area in Kim Đông (Google LLC, 2024)

On July 1st, 2025, Vietnam implemented its largest administrative reform since national reunification. The reform had the purpose of improving governance efficiency by consolidating provinces and abolishing district-level administrations (T. H. Nguyen & Le, 2025). As part of this reform, Ninh Bình Province was expanded, and the former Kim Sơn District, which previously encompassed the project area,

was dissolved. Kim Trung Commune, Kim Đông Commune, and the coastal zone (previously part of Kim Sơn District) were reorganised and merged into a newly defined Kim Đông Commune. This enlarged commune now includes both inland and coastal areas, including the project area (Nguyễn, 2025). Because many earlier studies and policy documents were written before this reform, they refer to the Kim Sơn District rather than the Kim Đông Commune. These sources remain relevant, however, as they describe the same geographical area now incorporated into the expanded commune. For reference, Google Maps has already updated the provincial boundaries to reflect the reform, but district and commune-level changes have not yet been implemented on the platform. This research will focus consistently on the Kim Đông commune, as it has been since July 1st.

3.1.1. Demographics

As a coastal area frequently exposed to natural disasters, the economy and livelihoods in the area have historically been vulnerable (Lam, 2024). In 2019, the commune consisted of roughly 7000 inhabitants (General Statistics Office of Vietnam, 2020), and the educational level in 2021 was relatively low compared to the rest of Vietnam (United Nations Development Programme, 2021). However, it is uncertain whether these numbers are still correct because of the reform in July 2025.

Most of the people in Kim Đông are Christians. This comes from the French colonial period around 1857. Religion is part of local culture. Churches can be useful for mobilising communities. Religion is not political in Kim Đông, but it helps strengthen community ties (Interview Dr. Tung Dao, 2025; Appendix C.2.6).

3.1.2. Current Land Cover Distribution

Figure 3.2 illustrates the spatial arrangement of mangrove vegetation, mudflats, and hydraulic infrastructure within the Kim Đông coastal zone. The region's sediment supply from the Đáy, Chính Đại, and Lèn rivers, alongside the tidal movements, has created favourable conditions for mangrove growth.

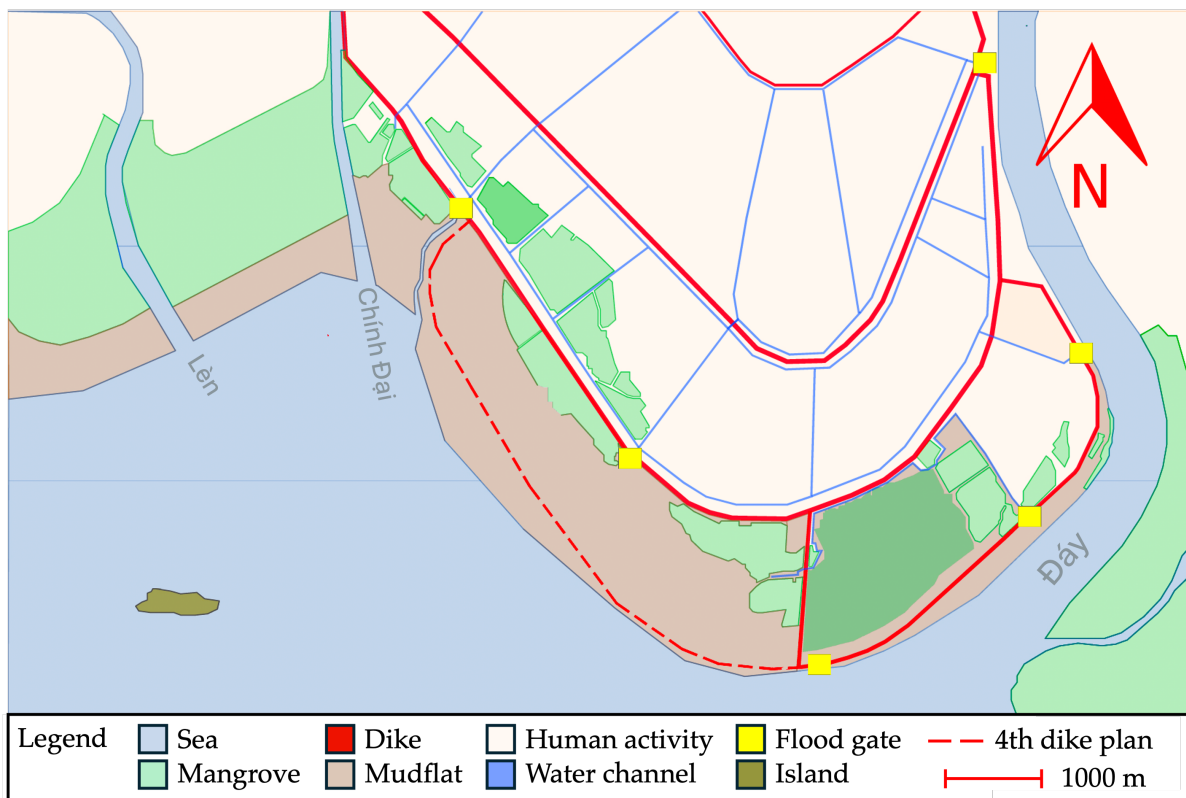


Figure 3.2: Schematic Map of the Project Area (2024 Situation)

In Figures 3.3 and 3.4 and 3.5 some photos of the area are shown from the ground. Two sluice gates

are included, and a mudflat with mangroves growing just outside dike ring three.



Figure 3.3: Gate in Dike 4
(Authors, 2025)



Figure 3.4: Mudflat with Mangroves
outside of Dike Ring 3 (Authors, 2025)



Figure 3.5: Gate 10 in Dike Ring 3
(Authors, 2025)

The land area of Kim Đông is divided into different sectors by an extensive dike system. The different dike rings (in red) protect low-lying areas used for human activity, providing protection against tidal flooding, Section 3.2.2 further explains the evolution of the area and the dike system. Since the aim of this research is to identify and mitigate the effects of finishing the fourth dike, this is also shown in the figure with the red dotted line. The red dotted line was constructed in this way due to information from an interview with Dr. Tri (2025, Appendix C. He stated that the land on the left side of the Chính Đại river belongs to another province. The area between the Chính Đại river and gate 10 has a lot of mangroves. Due to regulations about constructions that cannot lead to mangrove degradation, it will not be likely that the fourth dike will be constructed on the left side of gate 10.

Within the dike system, the land consists mainly of aquaculture ponds, mangrove forests and small farms scattered across the area. A mudflat is a muddy, tidal coastal plain where fine sediments accumulate. They are essential for mangrove growth and coastal stability. The mangrove belts (in green) are located mainly along the seaward edge of the mudflats, forming a natural buffer between the dike system and open sea (C. T. K. Nguyen, 2011; Q. H. Nguyen et al., 2019). Sluice gates (yellow squares) integrated into the dikes are intentionally operated to admit a controlled amount of water from the sea into man-made channels that connect the irrigation discharge to the sea. This is primarily to meet the needs of aquaculture. Aquaculture performance is therefore highly dependent on reliable gate functioning and timely operations (Interview Dr. Tung Dao, 2025; Appendix C.2.4). The water level in these channels is purely dependent on the level of the tide and the control of the sluice gates integrated into the dike and does not serve as a discharge mechanism of the two flanking rivers.

3.1.3. Human Activity

Kim Đông remains a mixed rural commune. Due to the flat terrain near the sea, most people depend on aquaculture, small-scale fishing often dependent on mangrove forests, livestock farming (MARD, 2020), and small-scale trade for their livelihoods, which makes these activities economically dominant (Lam, 2024).

Aquaculture is the practice of breeding, raising and harvesting aquatic organisms such as fish, shellfish, crustaceans and aquatic plants in controlled environments. In Kim Đông, this involves farming of marine organisms in a saltwater environment (Mai, Huong, Dat, & Truong, 2023). Aquaculture exists in two forms in Kim Đông. Intensive aquaculture and mixed mangrove-aquaculture. The intensive aquaculture is more dominant (Interview Dr. Tung Dao, 2025; Appendix C.2.6). In Figures 3.6 and 3.7, the difference between the two is shown.

For aquaculture, farmers dig within a piece of land and construct shallow ponds. These ponds are surrounded by natural or concrete walls to keep the water within the pond. At the edge, there is usually



Figure 3.6: Intensive Aquaculture (Aquaculture Magazine Editorial Team, 2024)



Figure 3.7: Mixed Mangrove-aquaculture (GIS Coastal Indonesia, 2023)

a gate, with which water from the sea can be let in and out. The bottom of the pond is set with clay, plastic foil (HDPE) or compact sand to prevent leaks from happening (Mai et al., 2023). Channels in which water from the sea flows, controlled by gates, can reach the aquaculture farms through smaller channels inland (Interview Dr. Tung Dao, 2025; Appendix C.2.6).

In- and outflow of intensive ponds can be artificially regulated, as can feeding of the animals. Additionally, chemicals are often used to keep the conditions within the pond as optimal as possible. This pollutes the water and soil. The economic benefits are quick and high in the short term, but this form of aquaculture does harm the ecological system (Mai et al., 2023).

Mixed mangrove-aquaculture however, uses the mangrove trees and natural tidal flows. A regulated ratio of 60% mangrove cover and 40% pond area is required by forestry or provincial regulations (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2). The mangrove root systems filter the water, improving water quality naturally and avoiding the need for additional chemicals. Therefore, the animals live in a more natural environment, and the quality of the animals is better, leading to better economic benefits (Interview Dr. Tung Dao, 2025; Appendix C.2.6). However, in mixed mangrove-aquaculture, the production rates are lower, since the density of animals is lower than with intensive aquaculture (Mai et al., 2023). This method is more stable though, lower-risk and often qualifies for eco-certifications (e.g., ASC-certified organic shrimp) (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2).



Figure 3.8: Hands of a Mixed Mangrove-aquaculture Farmer (Trần, 2025)



Figure 3.9: Mixed Mangrove-aquaculture Farmers (Dao, 2025)

Aquaculture companies in Kim Đông are mostly family-owned, with few or no large companies involved (Interview Dr. Tung, 2025; Appendix C.2.4). Figures 3.8 and 3.9 show mixed mangrove-aquaculture farmers from Kim Đông and their hands. Around 45 high-tech aquaculture facilities and nearly 800 small households operate in the aquaculture sector in Kim Đông. The commune has approximately 431 hectares of aquaculture, producing species such as white-leg shrimp, tiger prawn, clams and oysters (Lam, 2024). In 2023, the commune generated a total output of over 3 600 tonnes of aquatic products.

Understanding this spatial configuration and the human activity is crucial for understanding the effects on the system. These will be simulated using hydrodynamic modelling. Also, this coastal configuration forms the physical framework within which environmental and social processes interact, shaping the conditions for mangrove development.

3.2. Evolution of Kim Đông

Understanding the historical evolution of the Kim Đông area is important for interpreting current hydraulic and ecological conditions. Patterns of land reclamation, dike construction, and mangrove expansion have continuously reshaped the coastal morphology and tidal dynamics. The interactions between environmental and social processes are influenced by these transformations.

3.2.1. Societal Evolution

The commune was considered relatively poor about ten years ago. Through the implementation of the New Rural Development (NTM) Program in 2014, the commune has made major progress in poverty reduction, infrastructure and health. By 2023, the average income in Kim Đông has risen to 69.5 million VND/person/year, while the multidimensional poverty rate has fallen to only 0.34% (Lam, 2024). Additionally, the local government plays an important role through national campaigns such as 'All people unite to build new rural areas' and 'Determined to build a civilised and wealthy homeland!', shown in Figure 3.10. This integrates social mobilisation and state support (Lam, 2024). It is important to keep the local community involved and informed to establish success of the development goals of the commune in the long term. A persistent problem, however, is the migration of younger generations



Figure 3.10: Example National Campaign integrating Social Mobilization and State Support (Authors, 2025)

from Kim Đông (Interview Ms. Thao, 2025; Appendix C.2.3). Young people tend to leave the area due to the relatively low incomes, leaving Kim Đông with an ageing population still highly dependent on natural resources. To ensure a sustainable future, strengthening community participation is essential to actively involve young local residents. At the same time, ensuring the continuation of livelihood diversification and transition to a more resilient local economy will help the commune to adapt to demographic changes, ensuring that the progress achieved by the New Rural Development (NTM) program can be maintained in the long term.

As of today, Kim Đông is still transitioning from traditional rural livelihoods toward a more modern and resilient community. Understanding this socio-economic context is essential for assessing both pressures on mangroves and the feasibility of community-based management.

3.2.2. Land Reclamation and Dike Construction

Besides the societal evolution, the area has also physically changed a lot over the years. The Kim Đông area benefits from its position at the mouths of the Đáy, Chính Đại, and Lèn rivers, where sediment accumulates continuously. This natural sedimentation process contributes to the expansion of land in the area. The rate of land expansion is reported to be around 28 metres per year (C. T. K. Nguyen, 2011). This ongoing process results in the formation of mudflats. In the past, once the mudflats reached a sufficient size and elevation, the Ministry of Agriculture and Environment decided to construct new sea dikes further seaward to enclose and protect the land, making it suitable for agricultural and aquaculture use (Interview Mr. Mai Cao Tri, 2025; Appendix C.2.7).

This ongoing process of coastal accretion has led to the rapid expansion of land area, for which a total of 3 complete dikes and a fourth partial dike have been realised. These milestones, together with the then-current mangrove area and total dike length are shown in Table 3.1. The table also shows the increase in percentage for each milestone. A spatial time series of the constructed road and dike infrastructure and mangrove area is provided in Figure 3.11, with a more detailed time series in Appendix A.1. There have also been significant land use and building developments in recent years, as the commune is transitioning from a rural to a more residential community. However, these changes are difficult to quantify and are therefore not visualised in the spatial analysis. This spatial time series shows that the effect of new dikes restricts the tidal exchange, hereby reducing the circulation of fresh sediment and water, resulting in a gradual decline of the mangroves enclosed by the dike system (Q. H. Nguyen et al., 2019). Notably, no new mangrove growth has occurred behind completed dikes, highlighting their vulnerability and dependence on favourable environmental conditions. Field observations further indicate denser mangroves seaward of dike 3 than visible in recent satellite scenes, which suggests ongoing expansion that may lag in mapping (Google LLC, 2024). Lastly, each dike has been constructed approximately 20 years after the previous one. However, the observed area of land reclaimed with each new dike segment has decreased, which may indicate that the amount of sedimentation in the area is decreasing, although further data would be required to confirm this trend.

Table 3.1: Dike Construction Milestones and Contemporaneous Mangrove Area and Total Dike/Road Length in Kim Đông

Dike	Year	Mangrove Area (ha)	Increase Mangrove (%)	Dike Area (km)	Increase Dike (%)
1	1975	470	n/a	10	n/a
2	1993	590	+26%	25	+150%
3	2010	470	-26%	61	+144%
4	2018*	580	+23%	79	+30%

* Dike 4 is not fully enclosed in 2018.

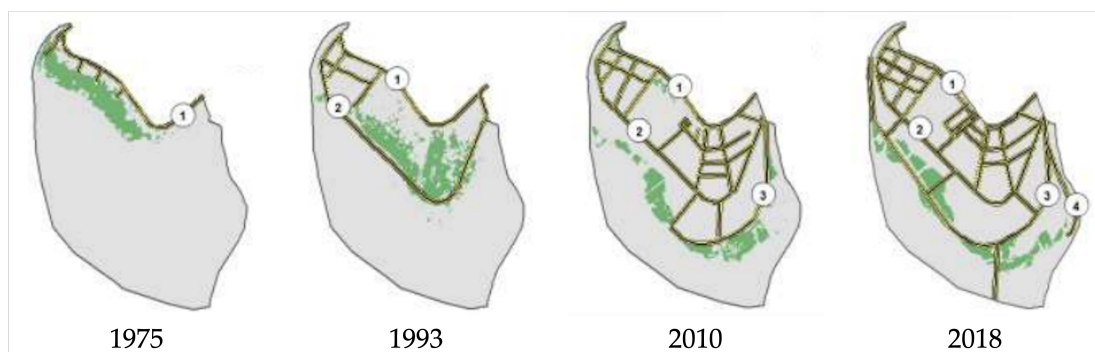


Figure 3.11: Spatial Time Series of Mangrove and Dike Development in Kim Đông (Q. H. Nguyen et al., 2019)

Mangrove planting programmes on newly formed mudflats outside the dike system have caused the mangrove belt to progressively expand seawards (Q. H. Nguyen et al., 2019; Tri, 2025). While these efforts, together with land reclamation, have supported regional economic activities such as mixed mangrove aquaculture, they have also contributed to increasing fragmentation of the mangrove forest, reducing its ecological resilience and weakening natural coastal protection functions.

Before the completion of the first section of Dike 4, the area between Dike 3 and Dike 4 looked quite different from today. In 2016, this area mainly consisted of mangrove forest with only two aquaculture ponds (Figure 3.12). The section outside Dike 3, along the Day River, had already been used for aquaculture for a long time. By 2024, the mangrove forest between the dikes has become denser and expanded further seaward (Figure 3.13). The two original aquaculture ponds have been subdivided into several smaller ponds, although they may still belong to the same farmer(s). This shows that there is definitely potential for mangroves to thrive, even when another dike ring is built.

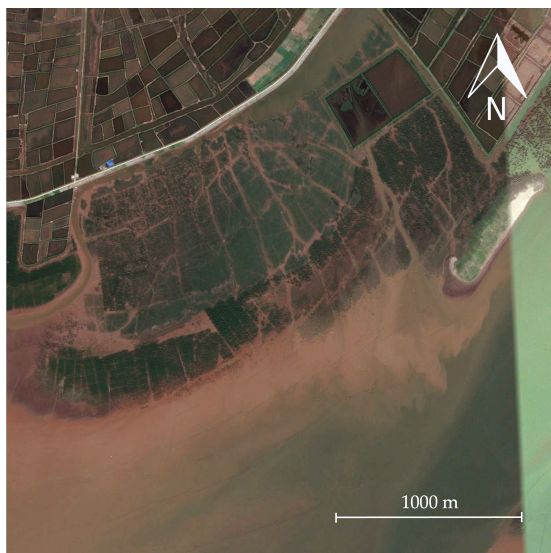


Figure 3.12: Area outside Dike 3 in 2016

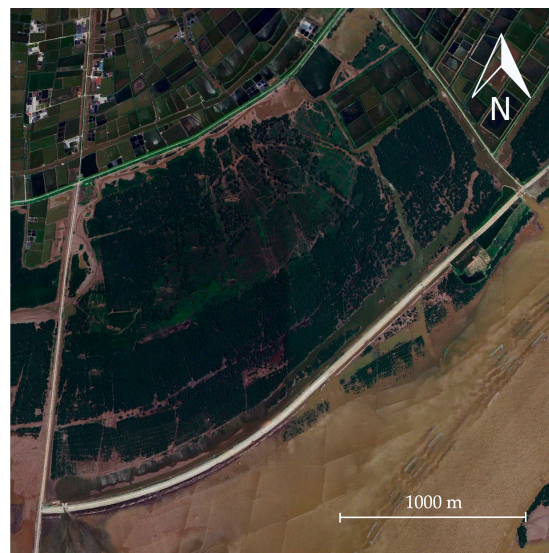


Figure 3.13: Area between Dike 3 and Dike 4 in 2024

The reason the mangroves have thrived instead of degraded could be due to several reasons. First, mangrove ecosystems can take several years to respond to hydrological changes. Also, it is unsure how the hydraulics have changed in the specific area. Lastly, local and provincial management regarding land allocation could have changed or mangrove restoration and planting projects could have occurred.

3.2.3. Development Goals and Risks

As explained in Section 3.2.1, the government aims to reform Kim Đông and build a strong economy in the coming years, like they have already started in the past years through the implementation of the NTM Program in 2014, which is still active. Therefore, community participation, livelihood diversification and a transitioning economy are needed.

In recent years, the government has promoted diversification through the development of the Kim Đông Industrial Park and tourism zones inside mangrove forests (VietnamPlus, 2023), attracting investment in food processing, aquaculture technology and transport combined with tourism (TTT Foreign Investment Consulting, 2024). Significant investments have been made in infrastructure and public services over the years. These developments support both production and disaster prevention, such as the dike rings. The fourth sea dike was constructed in 2018 and remains partially completed. This was primarily due to funding constraints, according to Mr. Mai Cao Tri (2025; Appendix C.2.7). For the first section of Dike 4, VINWATER, a Vietnam–Netherlands collaboration, prepared the design. This section includes a gated structure with an opening width of 4 m and a sill height of 4.9 m; three gates are currently present along Dike 4. The construction of the dikes has restricted tidal exchange, reducing sediment deposition and impacting mangrove health. This could lead to a decline of mangroves over time.

It is expected that the process of building new dike rings will continue and thus that the fourth dike ring will also be constructed in the near future (Interview Mr. Mai Cao Tri, 2025, Appendix C.2.7). Decision making and funding for the works are led by the Ministry of Agriculture and Environment (MAE), with design and construction awarded through tenders. The fourth dike is expected to close next to Gate 10 (the most western gate enclosed in Dike 3, as shown with the dotted line in Figure 3.2), to comply with restrictions on mangrove removal (Interview Mr. Mai Cao Tri, 2025, Appendix C.2.7).

3.3. Mangrove Ecosystems

Mangrove ecosystems play a vital role in the Kim Đông commune and therefore form the main focus of this research. This section outlines the key functions of mangroves and explains how they interact with both environmental and social components. Understanding these interactions helps to identify the main elements of the Kim Đông coastal system and how they influence one another. The relationships between these components are later visualised in the system diagram.



Figure 3.14: Example of a Mangrove Tree (ReefCause Team, 2021)

3.3.1. Functions of Mangrove Ecosystems

Mangroves are (sub)tropical forests that reside in the tidal region along sheltered shorelines. An example of a mangrove ecosystem can be seen in Figure 3.14. As can be seen in Table 3.2, mangroves are not only important for coastal protection but also do contribute to the environment and can be used for economic benefits for the residents of Kim Đông.

Table 3.2: Key Functions of Mangroves

Function	How
Protection against floods and storms	Root network dissipates wave energy.
Reduce erosion	Root structures stabilise sediments and prevent soil loss.
Increase sediment accumulation	Mangrove roots trap suspended particles.
Carbon storage	Photosynthesis captures CO ₂ and stores it in biomass.
Blue carbon storage	Burial of organic material in oxygen-poor sediments.
Biodiversity and nursery grounds	Provide habitat and shelter for numerous species.
Nutrient and carbon transfer	Export of organic matter and nutrients to seagrass beds and coral reefs (adjacent ecosystems).
Ecosystem resilience	Healthy mangroves improve recovery after extreme weather events.
Pollution mitigation for aquaculture	Roots and sediments filter and absorb nutrients and pollutants.
Support to aquaculture	Brackish-water regulation, nutrient recycling & shrimp farms protection.
Land reclamation support	Stabilising mudflats and supporting controlled land formation.

3.3.2. Environmental Interactions with Mangrove Ecosystems

The environmental interactions with mangrove ecosystems involve climate, hydrology and sediment processes. These factors influence the health and resilience of mangroves. Due to the constant evolution of Kim Đông, as described in Section 3.2, mapping these interactions is even more important.

The area's tropical monsoon climate, coastal location and sediment-rich mudflats provide suitable conditions for mangrove development. The key hydraulic variables that influence mangrove development are listed and shortly explained later in this section. A more detailed explanation of each environmental and hydraulic process is provided in Appendix A.

Environmental Factors

First of all, the climate of Vietnam has a significant influence on the mangrove development in Kim Đông. Vietnam lies within the tropical monsoon climate zone with a hot, wet season from April to October and a cooler, dry season from November to March. During the monsoon season, extreme storms and typhoons influence tidal dynamics, river discharge and salinity levels, which directly affect mangrove ecosystems. The consistent warm temperature allows mangroves to thrive year-round since they cannot survive in freezing conditions (Alongi, 2008).

The location of Kim Đông is at the mouths of three rivers, where the constant flow of sediments allows mudflats to form. The shores are relatively protected from the open sea by an offshore island and a headland. Mangroves also thrive in brackish environments where salt and fresh water mix, bringing essential nutrients. These mudflats, with low impact from the open sea, are perfect for mangrove growth (Alongi, 2022; Gijssman et al., 2024). Another reason mangroves occupy this coastal transition is because further inland, they are outcompeted by true freshwater species (Marchand, 2008).

It is important to note that seasonal saltwater intrusion and fluctuating salinity levels can stress these ecosystems and reduce their growth and resilience (Alongi, 2022).

Hydraulic Processes

Firstly, sediment transport is crucial for mangrove health and survival, as the continuous supply of fine sediments helps maintain the elevation of the mudflat, soil fertility, and stability. As stated before, the location of Kim Đông in the river delta creates ideal conditions for mangrove growth (Q. H. Nguyen et al., 2019) and (Ruiz-Fernández et al., 2017). However, areas of mangroves behind sea dikes face degradation due to reduced sediment input and poor water exchange, leading to a decrease (Interview Ms. Trần Thị Lợi, 2025; Appendix C).

Mangroves act as natural coastal barriers that absorb wave energy, reducing coastal erosion and protecting the shoreline. In Kim Đông, there are four mangrove species with three different root systems. A schematic representation of these root systems is displayed in Figures 3.15, 3.16 and 3.17.

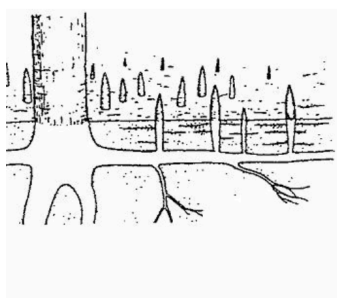


Figure 3.15: Pneumatophores
(Marchand, 2008)

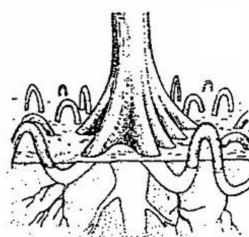


Figure 3.16: Knee Roots
(Marchand, 2008)

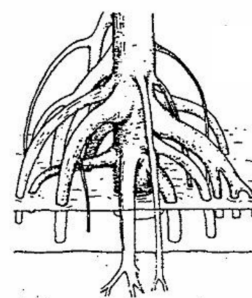


Figure 3.17: Prop Roots
(Marchand, 2008)

Mangroves enhance sediment stability by wave attenuation and slowing flow velocity. Their dense root systems create resistance to flow and waves, slowing down water and allowing fine sediments to accumulate and form stable mudflats, while protecting the coast from erosion (Horstman et al., 2014; Quartel, Kroon, Augustinus, Van Santen, & Tri, 2007). This is further explained in Appendix A.3.2.

Lastly, tidal dynamics are crucial for mangrove health, as they regulate oxygen availability, salinity, and sediment transport. Kim Đông experiences a diurnal tidal cycle (Trinh, Pattiaratchi, & Bui, 2020). Due to this, regular flooding and exposure allow mangroves to breathe and receive nutrients (Alongi, 2022). However, disrupted tidal flow can cause oxygen loss, increased salinity and stress that weakens mangrove resilience, especially for immature mangroves (Alongi, 2022; Q. H. Nguyen et al., 2019).

Hydraulic Variables connected to Mangrove Development

The hydraulic processes that shape environmental conditions in mangrove ecosystems are closely linked to several key hydraulic variables, shown in the list below.

- **Suspended Sediment Concentration (SSC):** The amount of suspended sediment in the water column directly impacts sediment deposition and root stability in mangroves.
- **Bathymetry:** The underwater topography influences water flow, sediment deposition, and areas suitable for mangrove establishment.
- **Salinity:** Fluctuations in salinity levels, driven by tidal movement and freshwater influx, are critical for mangrove health, as mangroves are adapted to brackish conditions.
- **Water Density:** Changes in water density, influenced by temperature, salinity, and suspended sediments, affect flow dynamics and sediment transport.
- **Wave Conditions (Height and Period):** Wave height and period determine the extent of wave energy reaching the mangrove shoreline, affecting sediment transport and mangrove root protection.
- **Current Velocity:** The speed of water movement influences sediment transport and deposition, which in turn impacts the stability of mangrove habitats.
- **Water Level:** Changes in water level due to tides or seasonal variations determine the frequency of mangrove inundation, which is vital for nutrient exchange and gas exchange in mangrove roots.

The identified variables are used to shape the system diagram and serve as essential input for the hydraulic analysis and subsequent modelling in Delft3D.

3.3.3. Societal Interactions with Mangrove Ecosystems

The societal interactions with mangrove ecosystems consist of man-made constructions, economic activities and involvement of the local community. These factors have an influence on how healthy and resilient mangroves are in Kim Đông. Because of the constant evolution of the area, also mapping these interactions is important. The key societal variables that influence mangrove development are listed and shortly explained. A more detailed explanation of each societal process is provided in Appendix A.

Man-made Constructions

In Kim Đông, the construction of multiple dike rings for coastal protection and land reclamation has caused mangrove squeeze. This is a process where mangroves lose space to migrate landward as dikes block tidal exchange and reduce available mudflat space, schematically shown in Figures 3.18 and 3.19. Due to mangrove squeeze, mangroves erode from both the landward and seaward sides.

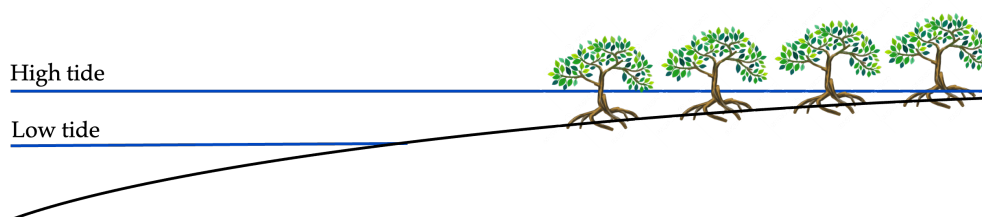


Figure 3.18: Original Situation for Mangrove Forests showing a Convex-up Mudflat Profile

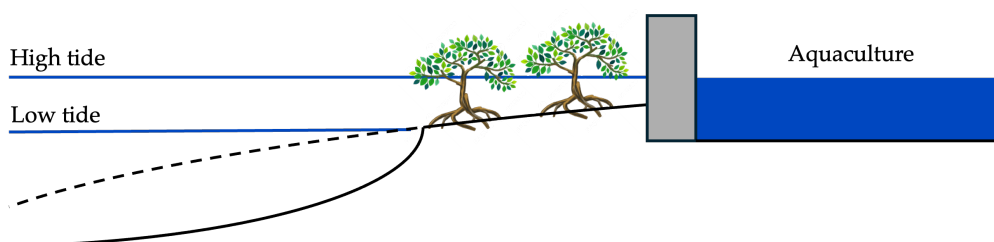


Figure 3.19: Mudflat Changes into a Concave-up Profile due to the Presence of a Hydraulic Structure

This phenomenon alters the natural convex-up mudflat profile into a concave one, increasing wave energy and erosion. Furthermore, there is a critical minimum width below which mangroves become unstable and cannot maintain their regenerative capacity (roughly 80-140 meters (Phan, van Thiel - de Vries, & Stive, 2014; Truong, Ye, & Stive, 2017)), leading to further degradation and coastal instability. Appendix A.4.1 explains the effect of mangrove squeeze more in-depth.

Economic Activities

Economic activities in Kim Đông strongly influence mangrove development, as they compete for the same land but also depend on each other. A very important economic activity that has an influence on the mangrove ecosystem is aquaculture (MARD, 2020). Aquaculture benefits from mangroves through natural water filtration, coastal protection and improved pond stability. Yet, the expansion of aquaculture often leads to mangrove loss due to altered land use, pollution and altered hydrology (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2).

However, integrating mangroves and aquaculture into mixed mangrove aquaculture systems could balance ecological and economic interests, supporting sustainable livelihoods. Additionally, the growing tourism sector presents opportunities to promote mangrove conservation while enhancing local income.

Involvement of the Local Community

Lastly, the involvement of the local community is crucial for the long-term success of sustainable mangrove management and restoration. Previous mangrove restoration projects in Vietnam often failed because local people lacked incentives to maintain mangroves once external supervision ended (Hai, Dell, Phuong, & Harper, 2020), while initiatives that share responsibilities and benefits between authorities and communities have been proven to be more effective. Engaging residents of Kim Đông in planning, monitoring and sharing benefits fosters ownership and accountability (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2). This aligns ecological goals with social needs. Therefore, community-based management should not be considered a side activity but rather a key aspect.

Societal Variables connected to Mangrove Development

Mangrove development is closely linked to several societal variables, shown in the list below.

- **Width of Mangrove Belt:** A width above the critical minimum width ensures mangroves remain stable and can maintain their regenerative capacity. This is influenced by infrastructure construction.
- **Land Allocation:** The allocation of land decides which activities will take place. Depending on those activities, the effect on mangroves can be good or bad.
- **Water Quality:** Mangroves naturally improve water quality. However, intensive aquaculture farms using chemicals to breed large numbers of animals can negatively affect mangroves.
- **Economic Benefit:** The economic benefit that can be gained in the area influences the mangrove forest, since this is a very important driver for many stakeholders. The amount of economic benefit decides which activities will take place (mixed mangrove-aquaculture, intensive aquaculture, tourism). Depending on those activities, the effect on mangroves can be good or bad.
- **Data and Knowledge:** Data and knowledge can make sure there is more awareness about mangroves and how the system works for both the local community as governing bodies and external parties. This can lead to better management and monitoring in the area. Additionally, this can attract projects in collaboration with foreign partners.

The identified variables are used to shape the system diagram. Information on these variables is backed up by a combination of interviews (Appendix C), a survey (Appendix E) and literature. Further information on how the societal and environmental components interact will be explained in the next section, which will show how policy can shape sustainable mangrove management using these factors.

3.4. Governance Analysis

This section presents a governance analysis, constructed in an iterative way, using input from literature, interviews, and the survey. First, the history of Vietnam is briefly explained, followed by an institutional analysis of Kim Đông. Next, a stakeholder analysis of Kim Đông is provided, explaining conflicting interests, values and needs. This governance analysis is the final piece needed for the system diagram.

It identifies the means of the system based on the institutional analysis and the criteria based on the values, needs and interests of stakeholders.

3.4.1. History of Vietnam

The history of Vietnam is needed to understand how governance structures have formed over the years and what the cause is for the governance structure as it is today. A detailed description of the history can be found in Appendix A. Vietnam's governance system has developed during multiple complex historical phases, which are illustrated in 3.20.

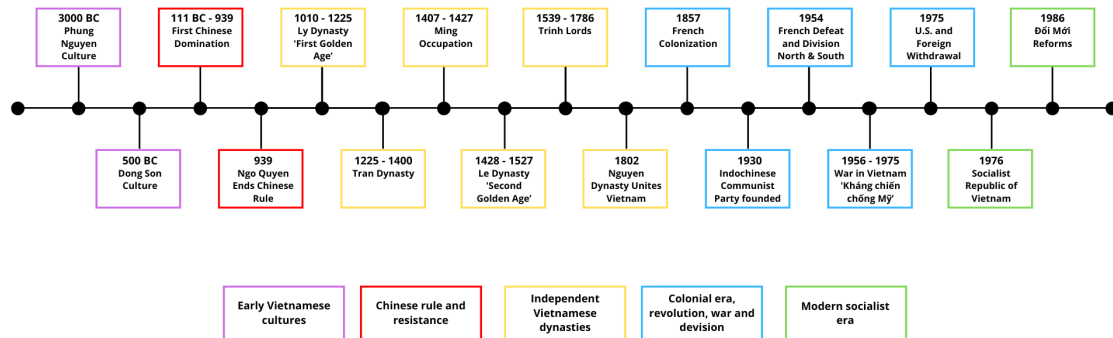


Figure 3.20: Timeline History Vietnam

Centuries of Chinese rule introduced the first formal governance structures, which were later transformed under French colonialism and socialist reunification. After independence and reunification in 1976, the Đổi Mới reforms of 1986 were the beginning of a shift toward a market-orientated economy with partial decentralisation of governance. As of today, Vietnam operates under a one-party system led by the Communist Party of Vietnam.

3.4.2. Formal Governance Structure

Vietnam's governance system is highly centralised under the Communist Party of Vietnam (CPV), which comes from the long history explained in subsection 3.4.1. The CPV dominates the legislative, executive and judicial roles.

Power is concentrated among the 'four pillars': The Secretary-General (legislative power), President (formal role), Prime Minister (executive power) and Chair of the National Assembly (judicial power). These four people are all members of the Politburo that sets national policy (Stiftung, Donner, Hartmann, & Steinkamp, 2024). More information on these four pillars can be found in Appendix A. Below the central level, authority is distributed to provinces and communes, which mostly implement the policies of the CPV through mirrored administrative structures (Stiftung et al., 2024). As a result of the 2025 reform, the country's administrative system was streamlined, reducing the number of provinces and eliminating districts altogether to increase efficiency (T. H. Nguyen & Le, 2025).

Although elections are held every five years, the CPV pre-selects candidates, making the political participation largely formal. More information on political participation in Vietnam can be found in Appendix A. These structures illustrate how decision-making works at the national level. This is important for Kim Đông, since the commune must follow the rules and policies set by the national government.

3.4.3. Institutional Environment

Mangrove management in Kim Đông is influenced by a complex web of formal laws, informal rules and regulations, and international influences. While formal rules define land use, forestry, environmental protection, and project management (Table 3.3), informal norms often determine how these rules are applied in practice (Table 3.4). International funding and agreements play a big role in Kim Đông, shaping restoration and conservation efforts and reflecting Vietnam's increasing involvement in global climate and sustainability initiatives (Table 3.5). The tables below summarise the key institutional mechanisms relevant to mangrove management in Kim Đông. A more detailed explanation of every institutional component can be found in Appendix A.

Table 3.3: Formal Rules (National and Local)

Law / Mechanism	Main Focus	Impact on Kim Đông
Land Law (2024)	Land ownership and allocation	Local people's committees allocate land. This can be either for mangrove protection, aquaculture, or something else.
Law on Forestry (2017)	Forest ownership and protection	Mangroves (also in Kim Đông) are classified as protected forests. This law prohibits illegal clearance.
Environmental Protection Law (2020) & Decree 08/2022	Environmental licensing and impact assessment	EIAs are required for projects affecting mangroves. In Kim Đông, this would apply to the dike rings and aquaculture expansion.
Law on Water Resources (2023)	Water use and discharge regulation	Protects water quality and maintains flow balance, if there is consistent monitoring.
UNESCO Red River Delta Biosphere Reserve (2004)	Habitat protection under soft law	Restricts harmful activities in core and buffer zones, such as Kim Đông. Aquaculture is allowed if it does not harm water quality or mangrove health. Good monitoring is needed.
Decision No. 1662/QĐ-TTg (2021-2030)	National coastal forest planting plan	Aims to restore 9 800 ha of mangroves nationwide. Kim Đông is part of the national restoration target.
Law on Fisheries (2017)	Sustainable fishing practices	Promotes conservation of marine and mangrove ecosystems. Supports mixed mangrove-aquaculture.
Kim Son Ecotourism Scheme (to 2030)	Regulates ecotourism in protection forests	Allows low-impact, licensed tourism, which aligns with Kim Đông's goal of developing ecotourism.
Law on Public Investment (2024)	Allocation of state investment	Influences whether communes receive funding for projects like mangrove restoration or dike construction and determines ownership.
Law on Construction (2014)	Infrastructure standards	Ensures compliance in coastal protection works like dikes.
Law on Investment (2020)	Private and international investment	Governs foreign participation in projects, including the Korean-funded mangrove restoration in Kim Đông.
State Budget Law	Allocation and management of funds	Defines budget flow between central and local governments. Mangrove initiatives in Kim Đông depend on provincial and external co-funding.
Decree No. 34/2014	Border area regulations	This decree defines which people, organisations, and transport are allowed to be active in Vietnam's border areas, including tourism activities in Kim Đông.
Law on national defence	Declares areas for national defence and safety	Projects or activities in these areas have to adhere to special rules. Kim Đông lies within a strategic coastal zone, subject to special safety and defence measures.

Table 3.4: Informal Rules

Law / Mechanism	Main Focus	Impact on Kim Đông
Corruption	Power and privilege influence implementation	Land allocation in Kim Đông may favour wealthier households or relatives of officials.
Informal land use practices	Illegal conversion of land	Farmers in Kim Đông sometimes extend ponds into zones where mangroves grow with limited oversight.
Unequal law enforcement	Biased monitoring	Local farmers in Kim Đông sometimes face stricter penalties, while larger operators avoid fines.
Transparency issues	Access to information and data	Research and local monitoring in Kim Đông are hindered by a lack of data and limited access.
Public investment management complexity	Overlapping responsibilities	Mangrove projects in Kim Đông can be delayed by bureaucratic procedures between different levels of government (commune & province)
Administrative risk aversion	Fear of personal responsibility	Officials hesitate to sign approvals due to personal liability under the anti-corruption drive, delaying public investment disbursement.

Table 3.5: International Influences

Law / Mechanism	Main Focus	Impact on Kim Đông
Korea Forest Service (2024-2026)	Mangrove restoration (250 ha)	Korea funds mangrove projects for CO ₂ offsets, creating dependency on external finance.
Red Cross (since 1994)	Disaster risk reduction	Provides technical support for flood risk mitigation in Kim Đông's coastal belt.
UNDP & GCF (since 2015)	Coastal resilience	Contributes expertise to mangrove-aquaculture pilot projects in Kim Đông. It restores mangroves for extreme storm buffers.
Japan (ODA projects)	Climate and forestry support	Funds large-scale environmental projects.
EU Deforestation Regulation (2023)	Deforestation-free supply chains	Reduces potential exploitation of mangrove timber in Kim Đông, encouraging protection instead.

3.4.4. Stakeholder Analysis

The stakeholder analysis is important to understand the values, needs and interests of different stakeholders in Kim Đông. These can later be transformed into the most important criteria of the system which will be placed in the system diagram. Also, by understanding how these stakeholders interact with each other, the way policy is shaped and implemented can be illustrated.

In Kim Đông there is a large web of stakeholders operating within Vietnam's hierarchical governance system. As shown in Figure 3.21, the most influential actors are the different government institutions. Particularly the CPV, Ministry of Agriculture and Environment (MAE) (Vietnam Law & legal forum, 2025) and the Ninh Binh Department of Agriculture and Environment (DAE). These government institutions hold most of the decision-making power over land use, funding, and environmental policy, while local authorities primarily execute higher-level directives.

The decision to construct and complete Dike 4 was taken at provincial level by the Department of Agriculture and Environment, following national directives from the Ministry of Agriculture and Environment (Interview Dr. Tri, 2025, Appendix C). The project received financial approval through the Ministry of Planning and Investment. Local authorities are mainly responsible for facilitating access and implementation of the project, rather than initiating or approving the project. This clearly shows how decisions are made in a top-down way, reflecting the hierarchical system.

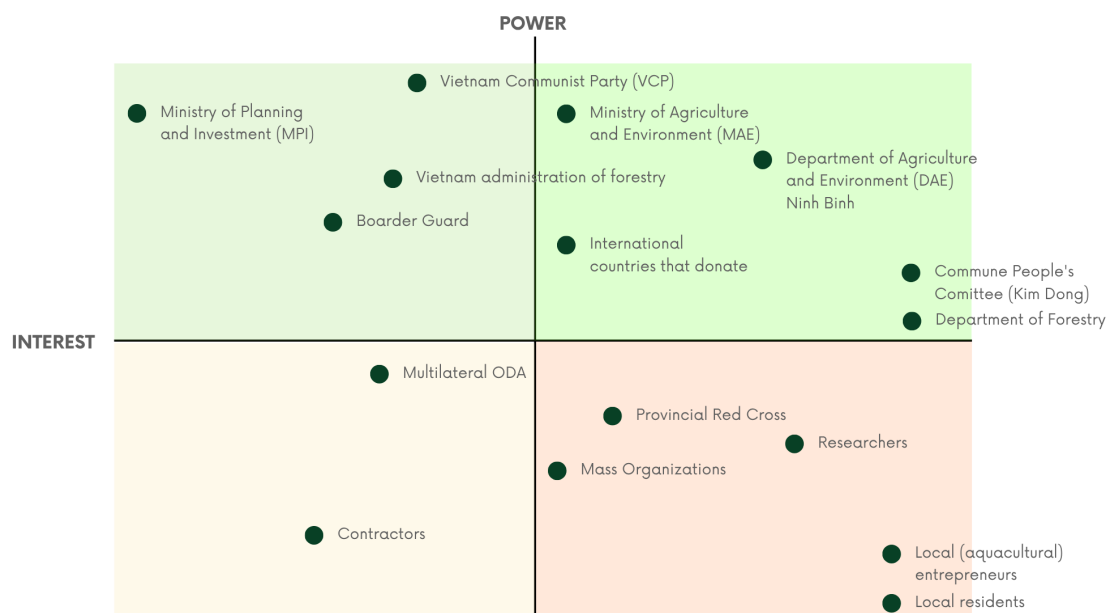


Figure 3.21: Power-Interest Grid Involved Stakeholders

At the commune level, the People's Committee of Kim Đông has limited autonomy because it relies on approval from the province or the national government (Vietnam National Assembly, 2015). Other stakeholders, such as the Department of Forestry (Vietnam National Forestry Association, n.d.), border guards and local residents, directly shape the system but have less influence over policy and decision-making processes.

The limited autonomy also explains the tension visible in the Power-Interest grid. While provincial and national institutions are the primary decision-makers and push for large-scale infrastructure to meet development goals, local communities have other priorities. They need short-term livelihood security through aquaculture and land access and are often dependent on healthy ecosystems like those of mangroves. These conflicting interests define the current management dilemma.

Moreover, the Border Guard, responsible for security near the coastal border zone, holds informal power over field research, foreigners and development activities in Kim Đông (Interview Dr. Tung Dao, 2025; Appendix C.2.6). This adds another layer of complexity to the governance structure and limits both local participation and research in the area.

External actors include international donors, NGOs and research institutions (Pham et al., 2022). They play a supporting role by funding and monitoring restoration initiatives (Vietnam News, 2023). In the context of Kim Đông, these external actors have financed mangrove restoration projects and coastal protection projects. However, these initiatives often remain project-based with limited long-term monitoring or coordination with other stakeholders. As a result, projects funded by foreign partners sometimes operate in parallel rather than integrated into the system and national or local planning.

Figure 3.22 illustrates the vertical relationships between stakeholders, showing how national, provincial, local and international actors interact and where opportunities for collaboration or conflict arise.

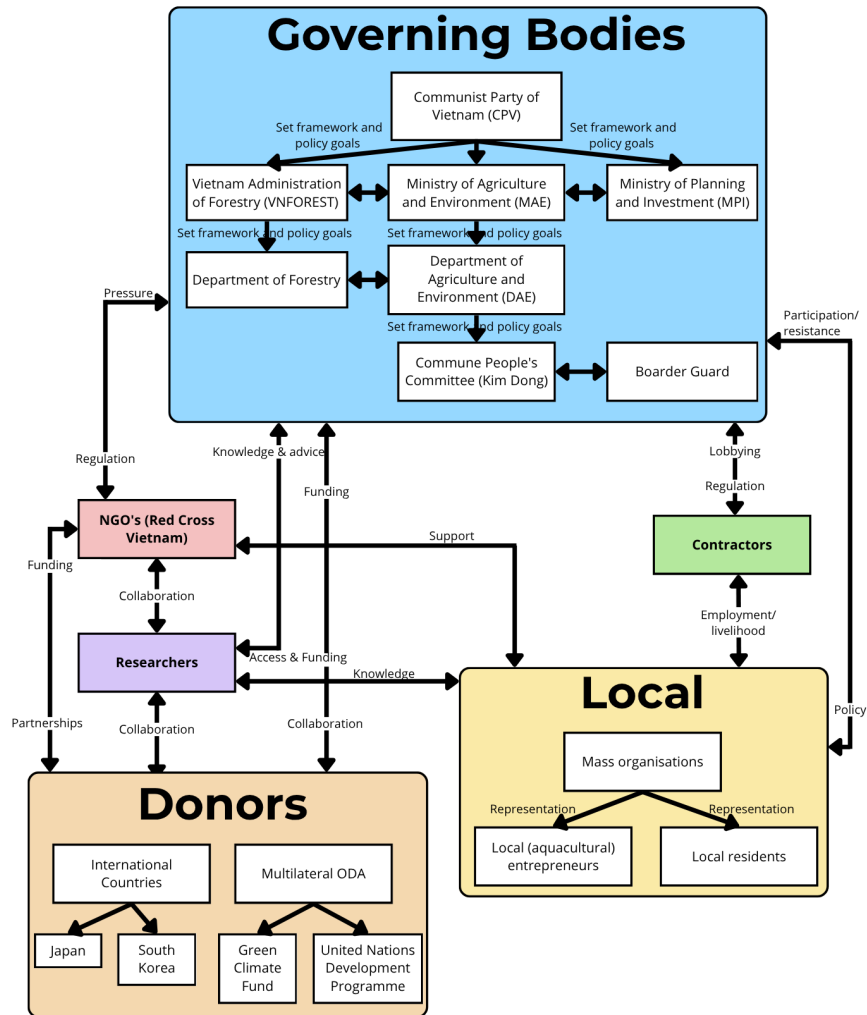


Figure 3.22: Formal Chart of Stakeholders Involved

3.5. System Diagram

In this section, all components of the system are combined into an overarching system diagram in Figure 3.23. It is important to understand the system as a whole, as it connects the social, hydraulic, ecological, and governance components and illustrates their interactions. The system diagram assesses the influence of different intervention on the system, and criteria, allowing for impact assessment and effect prediction. Insights from this chapter, including environmental and social interactions, institutional environment, and stakeholder analysis are used to create the diagram.

This diagram visually captures the complex interactions between the system components. The dotted line describes the system boundary. At the left side, the means of the systems are placed, mainly

explained in Section 3.4.3. At the top, external factors, such as weather, are placed. These are factors that are not influenced by anything within the system. The criteria, mainly based on the values, needs and interests of the important stakeholders within the system (Appendix A), are on the right. The components within the dotted rectangle are linked by arrows that indicate positive or negative influences on each other.

The diagram clearly shows the interaction between components. The purple squares represent policy and management-related components, blue represents economic components, green is for hydraulic and ecological components, and yellow represents social and research components.

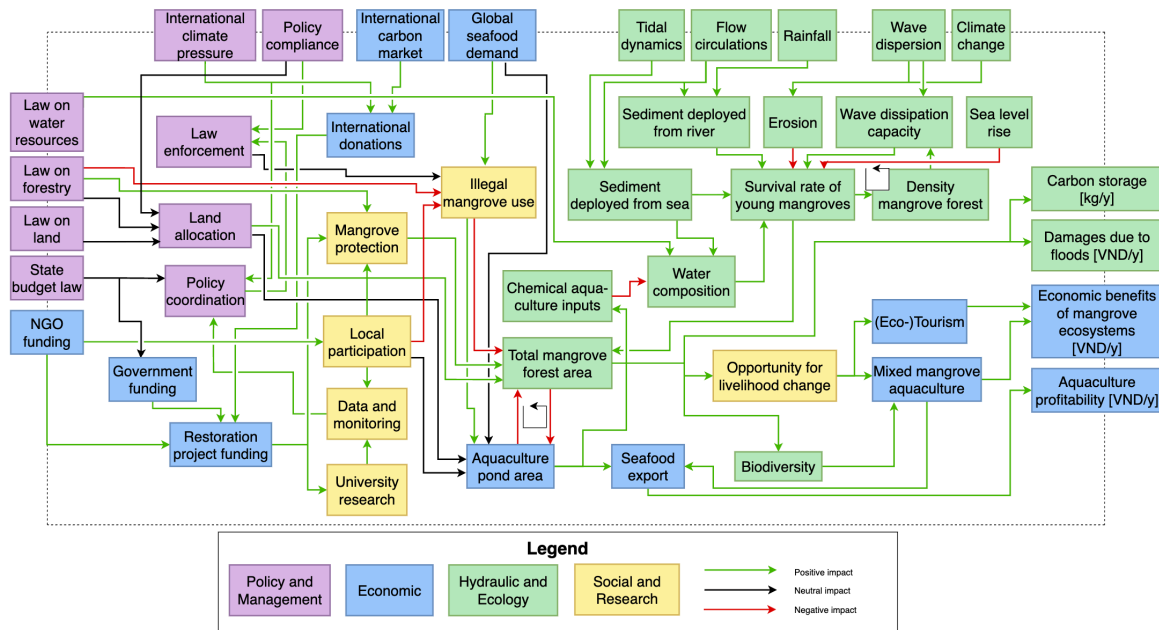


Figure 3.23: System Diagram of Kim Đông Coastal System

The system diagram includes two feedback loops. These show that some connections further strengthen the positive or negative impact. First, there is a hydraulic feedback loop: as the density of the mangrove forest increases, wave dissipation capacity also increases, positively impacting mangrove survival, which further increases the mangrove density. This is a positive feedback loop. Second, there is also a social-economic feedback loop between the aquaculture pond area and the total mangrove forest area about the trade-off of land acclimation. If the aquaculture pond area increases, the chemical inputs also increase, which worsens the water composition, reducing mangrove survival and forest area. This negative feedback loop for mangroves, however, benefits aquaculture. This also highlights the importance of distinguishing between intensive and mixed aquaculture, as mixed aquaculture uses fewer chemicals.

The main criteria in the diagram on the right are carbon storage, flood damage, economic benefits from mangroves, and aquaculture profitability. These are important for different stakeholders in the system. The local government prioritises land-use for economic gain. The commune manages land and proposes changes but doesn't allocate it, while the province can allocate or lease land for aquaculture, mangroves, or other uses, depending on the institutional environment, funding, and policy compliance. Whether this will be aquaculture farming, mangroves or something else is up to them. The aquaculture criterion is crucial for the local economy, while mangroves, on the other hand, offer environmental benefits, including carbon storage, flood protection, and economic opportunities (honey, eco-tourism, or mixed aquaculture).

The system diagram is later used to track what the results of fourth dike will be, and how this dike influences the criteria on the right.

4 | Hydraulic Analysis

Chapter 3 discussed quantifiable hydraulic parameters that have an influence of mangroves. This chapter discusses the Kim Đông river system, bathymetry, salinity, water density, tidal information and wave information that can be used as input for numerical modelling in Chapter 5, but also serves as an independent benchmark for mangrove performance.

It is good to note that quantifying these hydraulic parameters comes with its uncertainties, as data are taken from large-scale satellite datasets and field measurements. Where relevant, assumptions are stated clearly, and the impact on final research results is revisited in Chapter 8.

The Kim Đông area is situated in the Gulf of Tonkin, where sediment supply from the Red River System is substantial, the tidal cycle is a main driver for currents, and offshore wave energy is relatively moderate compared to that of the tides. Tide-dominated deltas often resemble tidal flats, marshes and swamps, which is consistent with observations from the northern Vietnamese coast (Bakker, 2017; V. V. Ha et al., 2021).

4.1. River System

Within the hydraulic domain, three rivers discharge into the area: the Đáy, Chính Đại, and Lèn rivers, shown in Figure 4.1. The focus is on estimating water discharge and sediment supply, as these processes shape coastal development. Due to limited data, values are derived from scientific literature. Among the three, only the Đáy River has documented hydrological and sediment parameters based on computational models, shown in Table 4.1 (Vinh, Ouillon, Thanh, & Chu, 2014). No data are available for the Chính Đại and Lèn rivers. Given their smaller size and limited connectivity to the main rivers, it is expected that their discharges are significantly smaller than that of the Đáy River. Due to the limited knowledge about these rivers, no estimate is made for the discharge of these rivers.

Table 4.1: Average Water Discharge (Q) and Suspended Sediment Supply (M) of the Đáy River from Numerical Simulations (Vinh et al., 2014).

Parameter	Dry Season (December - April)	Wet Season (June - October)	Yearly Total
$Q (\times 10^9 \text{ m}^3)$	4.8	19.5	27.6
$M (\times 10^6 \text{ t})$	0.4	7.0	8.0

Seasonal variations in river discharge influence the salinity, water density, and flow conditions in the coastal area of Kim Đông and are therefore an important factor in the overall hydraulic system.

4.2. Bathymetry

For the Kim Đông area, only ten short cross-shore bathymetric measurements are available near the existing third dike, of which six are still outside the completed segment of Dike 4. To better represent the bathymetry in front of Dike 3, a model domain is defined to capture the main hydraulic interactions (Figure 4.1). The domain includes the end section of the existing Dike 4 near point P2 (see Figure 4.1), allowing assessment of both the current situation, where the second segment is unfinished, and the future, fully completed configuration. The south-western boundary is drawn behind the offshore island to include the effects the island has on hydraulic parameters. The north-western boundary is limited before the land barrier, because this land barrier contains two rivers. Although these rivers may have an effect on the model domain, they are excluded from the analysis due to the absence of discharge data and unknown bathymetry which can not be estimated adequately.

To refine the bathymetric estimation, two additional depth points (P3 & P4) were derived from fishing maps (GPS Nautical Charts, 2025b). Between the measured points, the bathymetry of the domain has been determined by interpolation and extrapolation. The exact method can be found in Appendix B.1.

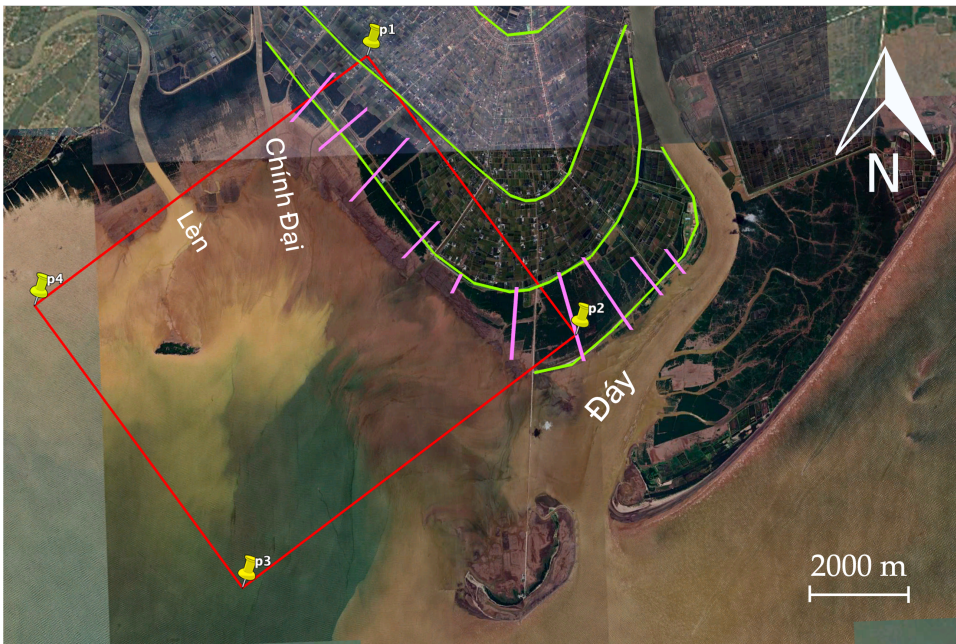


Figure 4.1: The Selected Domain for Bathymetry Estimation in Kim Đông (Google LLC, 2024)

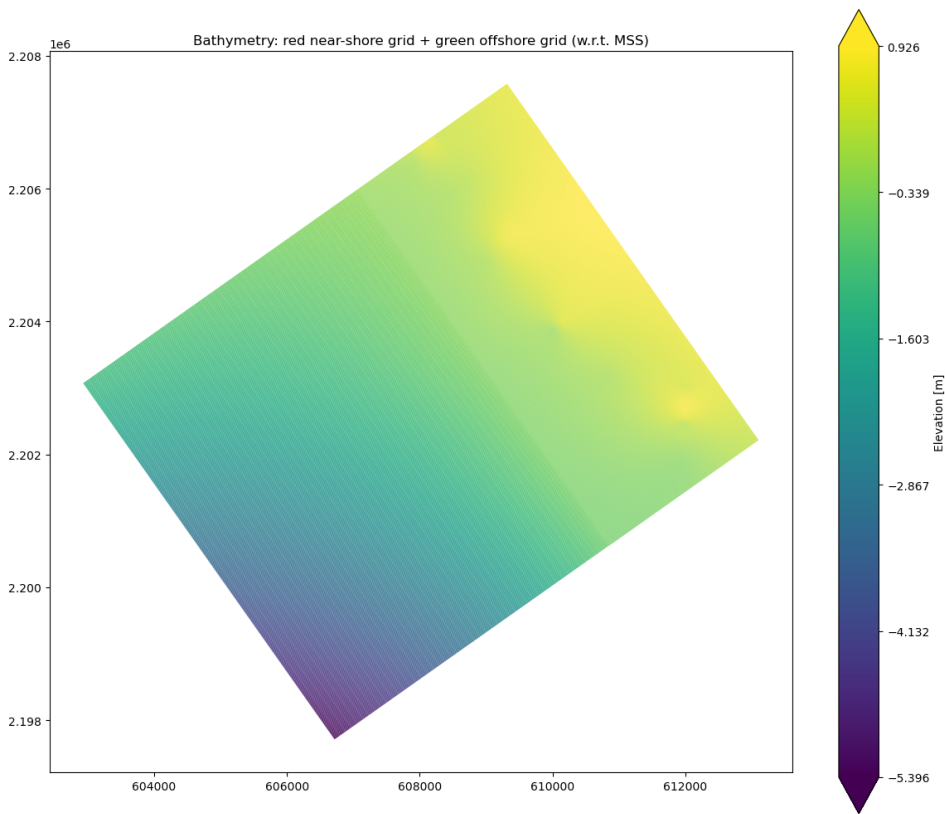


Figure 4.2: The Estimation of Bathymetry in Kim Đông (Google LLC, 2024)

The resulting bathymetric surface is shown in Figure 4.2. Because most of the domain relies on interpolated rather than measured data, the final bathymetry contains a considerable level of uncertainty. The constructed bathymetry should therefore be regarded as an approximation of the true seabed, and local variations in depth may not be accurately represented.

Lastly, the island, Dike 3, and the connecting channels are manually added to the conceptual bathymetry model, and a second scenario is made where Dike 4 is manually included as well.

These adjustments result in a revised bathymetric representation, as shown in Figures 4.3 and 4.4. The new red lines indicate the canals, the dark blue area to the left represents the island, the dark blue line marks Dike 4, and the other dark blue area corresponds to Dike 3.

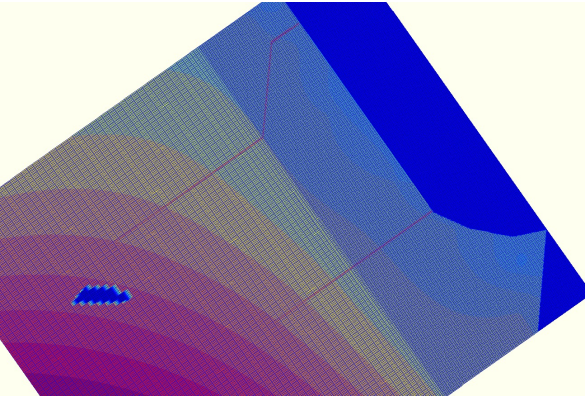


Figure 4.3: Resulting Bathymetry With Additions

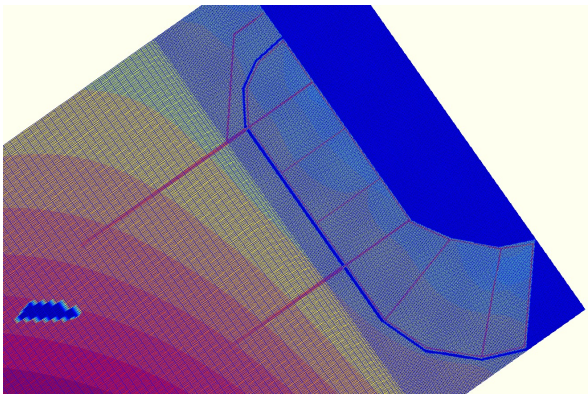


Figure 4.4: Resulting Bathymetry With Additions and Dike 4

4.3. Salinity

Salinity levels in the body of water in front of the Kim Đông are highly influenced by the discharges of the Đáy, Chính Đại and Lèn rivers, which vary seasonally. During the wet season, freshwater discharges are relatively high, lowering the salinity level in the seawater. In contrast, during the dry season, the reduced discharge results in higher salinity levels. These salinity changes are critical, since fluctuating salinity levels can stress the ecosystem and reduce mangrove growth. Furthermore, these seasonal variations in salinity affect the density of the seawater, which in turn causes different flow patterns during the two seasons (Wang et al., 2025).

Salinity estimations in the Gulf of Tonkin are based on scientific research in the Red River Delta in coastal zones with similar characteristics are displayed in Table 4.2 (Le, Pham, & Nguyen, 2015; Nguyen-Duy, Zavala-Garay, Rogowski, Lai, & Chen, 2021; Rogowski et al., 2019). In addition, field measurements in Kim Đông were carried out on Monday, October 13, 2025, between 08:00 and 10:30. Observed salinity values were approximately 8‰. These measurements align with the expected values from the literature for the wet season and were likely influenced by recent typhoon events, which temporarily increased river discharge and thus reduced nearshore salinity.

Table 4.2: Estimated and Measured Salinity Values for Offshore and Nearshore Waters in front of Kim Đông.

Location	Season	Salinity (‰)
Offshore	Annual average	≈ 32
Nearshore	Wet season	5–15
Nearshore	Dry season	25–30
Nearshore (Field measurements)	Wet season	7.6–8.0

4.4. Suspended Sediment Concentration

The suspended sediment concentration (SSC) in the Kim Đông coastal zone is measured to assess sediment dynamics influencing coastal morphology and mangrove development. Two sets of in-situ measurements are carried out: (1) by the Thuyloi University research team in April 2025, and (2) by both the Thuyloi University research team and MDP group in October 2025 during the field trip. Measurements are taken at three locations shown in Figure 4.5. A detailed view of Location 1, where the MDP team collected samples, is provided in Figure 4.6. More information on the field trip can be found in Appendix D.

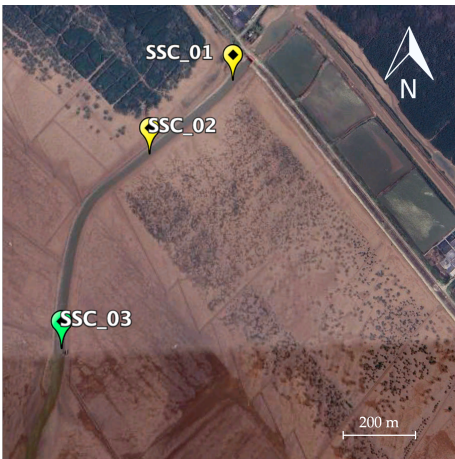


Figure 4.5: Locations of the Suspended Sediment Concentration Measurements



Figure 4.6: Location 1, SSC measurement (Authors, 2025)

Measurement Overview

The MDP group conducted three SSC measurements in October 2025, which are summarised in Table 4.3. A detailed description of the measurement method is provided in Appendix D.4. The values in Table 4.3 represent the raw SSC measurements. The next step is to process the raw data.

Table 4.3: Suspended Sediment Concentration Measurements at Kim Đông — Location 1 (MDP team, October 13th, 2025)

Date	Time	SSC (g/dm ³)
October 13th, 2025	08:12	-0.011
October 13th, 2025	09:24	-0.061
October 13th, 2025	10:24	-0.027

The April 2025 dataset is processed by Thuyloi University using a 3-point rolling mean to reduce short-term fluctuations in SSC. This method smooths the data by averaging each value with its two nearest neighbours, reducing short-term fluctuations and the peaks and troughs. The same method was applied to the October 2025 data by the MDP group. The processed time series for both campaigns are shown in Figure 4.7 and Figure 4.8. For more information on the data processing method using the rolling mean, refer to Appendix B.2.

Results

Figure 4.7 shows that the April 2025 measurements remain within a realistic concentration range after smoothing. By contrast, the October 2025 dataset (Figure 4.8) contains several negative values even after applying the rolling mean. Negative SSC values are physically impossible and likely indicate uncertainty in the filtering, weighing, or drying procedure during laboratory processing.

The persistence of negative values in October suggests potential measurement or drying inconsistencies. It is possible that the filters were already moist before the filtering and drying process, or that the drying method with the oven removed too much moisture, or there may be other uncertainties in the oven calibration or drying procedure. This means this data is not useable for this project, and this should be addressed in future fieldwork.

4.5. Water Density

The estimated water densities of the nearshore and offshore waters at Kim Đông depend on the density and temperature of the freshwater inflow, as well as the salinity level. These parameters vary seasonally. Using the assumed salinities for both nearshore and offshore waters presented in Section 4.3, the resulting water densities are shown in Table 4.4. A more detailed estimation procedure, including the applied formula, is provided in Appendix B.3.

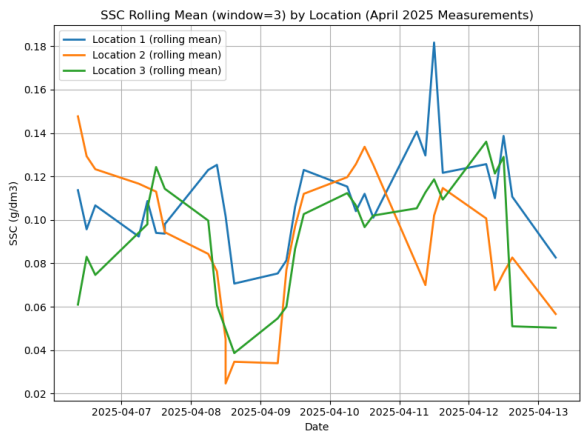


Figure 4.7: Suspended Sediment Concentration at Kim Đông in April, 2025 (processed)

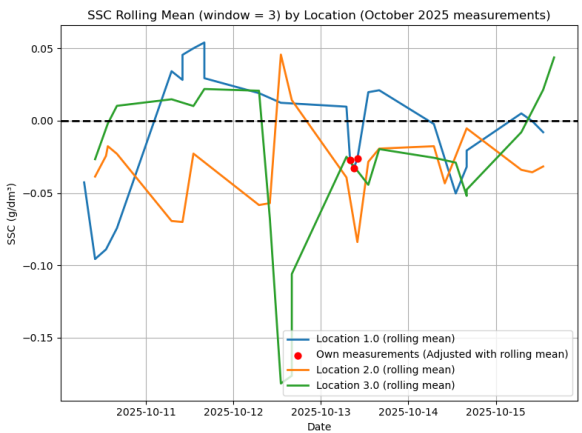


Figure 4.8: Suspended Sediment Concentration at Kim Đông in October, 2025 (processed)

Table 4.4: Estimated Seawater Densities for Nearshore and Offshore Conditions at Kim Đông

Location	Season	Temperature (°C)	Freshwater Density (kg/m ³)	Salinity (‰)	Density (kg/m ³)
Nearshore	Dry	21	997.995	28	1019.0
Nearshore	Wet	29	996.947	8	1003.0
Offshore	Dry	21	997.995	32	1022.0
Offshore	Wet	29	996.947	32	1020.9

These results demonstrate that the seawater density is highly influenced by salinity levels, both spatially and seasonally. This reflects the strong influence from the Đáy River in nearshore waters. These variations in density can alter flow circulation and modify vertical and horizontal mixing patterns, resulting in hydraulic differences between the seasons.

4.6. Water Level

Water levels were recorded hourly for a full month during a measurement campaign in Kim Đông in April 2025. From these measurements, the tidal sequence is characterised by Table 4.5. Appendix B.4 compares the measurement campaign to long-term records at Hòn Dấu (70 km north of Kim Đông). The tidal signal is flood-dominant, meaning that the flow velocity during the flood phase, when water propagates toward the coast, is higher than during the ebb phase, when water retreats from high to low tide. As a result, more sediment is generally transported toward the coast than away from it, since sediment transport scales with flow velocity.

Table 4.5: Tidal Information of Kim Đông (April, 2025)

Characteristic	Value
Mean tidal range (campaign)	1.86 m
Minimum tidal range	1.26 m
Maximum tidal range	2.35 m
Avg. interval between successive high waters	25.8 h
Number of tidal cycles (April)	27
Dominant tidal regime	Predominantly diurnal

4.7. Governing Wave Conditions

This section establishes the wave boundary conditions used in the modelling. The source data and directional filtering are described first, followed by the wave conditions analysed and the assumptions behind them. All methods used are further explained in Appendix B.5.

4.7.1. Modelled Sea-states

Three different sea-states are modelled: two extreme wave regimes and three sea-states that represent average conditions. This is done to adhere to the design conditions of hydraulic structures in the Kim Đông area, to model the effects of yearly storms and monitor day-to-day conditions. These waves are not modelled as monochromatic waves, but are coupled with the JONSWAP (Joint North Sea Wave Project) spectrum, these five sea-states are used to model the hydraulic conditions in Kim Đông. Table 4.6 shows the parameters that correspond to these different sea-states.

Table 4.6: Significant Wave Height and Peak Period for Three Different Sea-states

Sea-state	Calculation Method	H_s [m]	T_p [s]	JONSWAP Parameter γ
Calm	Percentile band	0.47	4.47	3.3
1-year design storm	Extreme Value Analysis	1.65	8.15	3.3
30-year design life	Extreme Value Analysis	4.31	9.30	3.3

4.7.2. Sea-State Derivation

In this section, the offshore wave climate is analysed to later define the boundary conditions for the hydraulic model. The process includes selecting and filtering satellite wave data, identifying representative and extreme sea-states, and translating these into realistic spectral conditions for Delft3D simulations.

Data and Directional Filtering

Hourly wave parameters come from the ERA5 “hourly data on single levels” reanalysis for 1975–2024 over a small sea-only box fronting the site (19.50–19.55° N, 106.00–106.05° E, as seen in Figure 4.9). The variables used are significant wave height (wind sea, swell, and combined), peak wave period, and mean wave direction (wind sea and swell).

Because the present shoreline shelters the bay from the east–north-east, the time series is filtered by wave direction so that only sea-states with unobstructed fetch to the coastline remain. This directional screening removes approximately 64% of the hourly records, leaving 36% for the analysis. Consequently, the effective sample size is reduced, and derived statistics should be interpreted with appropriate uncertainty (see Appendix B.5.2). Figure 4.10 shows the project area and the excluded wave directions now obstructed by the accumulated landmass.



Figure 4.9: Satellite Input Area for Wave Data

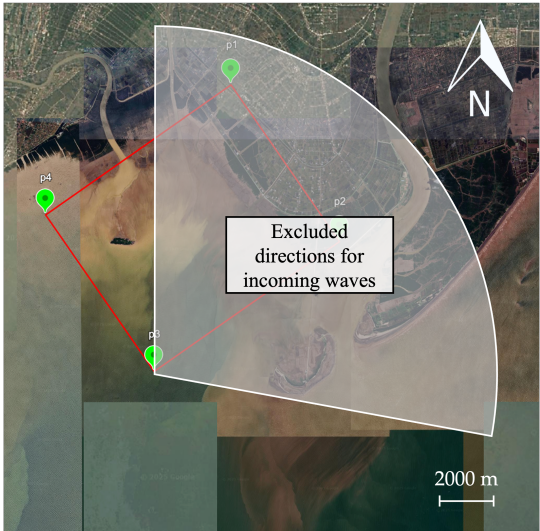


Figure 4.10: Excluded Wave Directions

Sea-states and Assumptions

This study focuses on the combined wave spectrum instead of separately studying the effect of swell and wind-induced waves. With this approach, key coastal processes such as wave-driven currents

are driven by the total wave energy. Furthermore, numerical models like Delft3D typically use a single spectrum for boundary conditions, and using the combined significant wave height (H_s) simplifies model implementation. All sea-states are fitted to the JONSWAP spectrum instead of a monochromatic wave. Monochromatic waves assume every wave is identical, a JONSWAP spectrum captures the natural spread of waves, leading to more representative conditions for modelling.

JONSWAP Spectrum

The wave conditions in Kim Đông are represented by using a wave energy spectrum to provide a more realistic representation of the sea-state rather than using a single monochromatic wave, as it accounts for the distribution of wave energy across various frequencies. For this study, the standard JONSWAP (Joint North Sea Wave Project) spectrum is used, with a peak enhancement factor γ of 3.3, representative for actively growing seas. More information about the JONSWAP spectrum and the assumptions for the peak enhancement factor γ are given in Appendix B.5.3.

Extreme Wave Conditions

To determine extreme wave conditions based on historical data, the direction-filtered ERA5 record is subjected to an Extreme Value Analysis, where extreme wave heights are extracted using the Peak-Over-Threshold method. The threshold is selected from the mean–residual–life (MRL) plot, and threshold exceedances are declustered with a 96-hour window, representative of typhoon-driven events. Appendix B.5.3 explains the method used, the threshold choice and the declustering sensitivity.

Maxima are then fitted to a Weibull competing-risks (mixture) distribution by maximum likelihood. Goodness-of-fit metrics and residual checks are reported in Appendix B.5.3.

Two extreme wave conditions are extracted. First, the national Vietnamese design standard classifies Kim Đông as a Class IV area, corresponding to a 30-year design condition. Using the Weibull competing-risks distribution, this yields a design value for the significant wave height H_s of 4.31 metres, with a corresponding peak period T_p of 9.30 seconds.

Secondly, the 1-year return condition is included to capture the yearly monsoons. Using the same method as for the 30-year design condition, this yields a design value for the significant wave height H_s of 1.65 metres, with a corresponding peak period T_p of 8.15 seconds.

Regular Wave Conditions

Regular forcing is represented by three percentile-based sea-states: *Calm*, *Median*, and *Energetic*, derived from the direction-filtered ERA5 dataset. For each percentile band, the representative median significant wave height H_s and corresponding peak period T_p are taken. Table 4.7 shows the corresponding values for each percentile band. Appendix B.5.3 explains the further process on how these values are obtained.

Table 4.7: Parameters for Representative Regular Sea-states for Wave Modelling

Sea-state	Percentile Band	Rep. Height, H_s^{rep} (m)	Rep. Period, T_p^{rep} (s)	Peak Factor, γ
Calm	20th – 30th	0.47	4.47	3.3
Median	45th – 55th	0.64	4.91	3.3
Energetic	80th – 90th	0.90	5.51	3.3

4.8. Governing Wind Conditions

In the following section, the governing wind conditions will be presented. These winds are obtained in the same manner as in the previous Section 4.7, using the ERA5 'hourly data on single levels' reanalysis for the 1975–2024 dataset. These will serve as input for the conceptual numerical model.

4.8.1. Modelled Wind States

Three different wind states are modelled: two extreme wind states and one wind state that represents average conditions. These are shown in Table 4.8.

Table 4.8: Representative Wind Speed for Three Different Sea-states

Wind State	Calculation Method	U_{wind} (m/s)
Calm	Percentile band	3.87
1-year RP design storm	Extreme Value Analysis	10.23
30-year RP design life storm	Extreme Value Analysis	15.86

Extreme Wind Conditions Derivation

The direction-filtered ERA5 wind dataset is analysed in the same manner as the wave conditions. Extreme events are identified using Extreme Value Analysis, employing the Peak-Over-Threshold method to isolate extreme wind events. The threshold is chosen based on the mean residual life plot, with exceedances declustered using a 96-hour window, which is kept the same as with the wave analysis. Parameter selection is further explained in Appendix B.6.

The identified maxima are then fitted to an Exponential 1P distribution using maximum likelihood estimation. Goodness-of-fit statistics are reported in Appendix B.6.

Two extreme wind conditions are extracted. The National Vietnamese design standard for Kim Đông corresponds to a Class IV area, resulting in a 30-year design condition. For which the Exponential 1P distribution yields a design wind speed of 15.86 m/s. For the 1-year return period, capturing annual wind extremes typically associated with monsoon conditions, the Exponential 1P distribution gives a design wind speed of 10.23 m/s.

Regular Wind Conditions Derivation

Regular wind conditions are represented by three distinct wind states: Calm, Median, and Energetic, based on the direction-filtered ERA5 dataset. For each wind state, the representative wind speed U_{wind}^{rep} is calculated. These values are presented in Table 4.9. The process of deriving these values is explained in Appendix B.6.

Table 4.9: Representative Regular Wind States for Wind Modelling

Wind State	Percentile Band	Rep. Wind Speed, U_{wind}^{rep} (m/s)
Calm	20th – 30th	3.87
Median	45th – 55th	5.60
Energetic	80th – 90th	8.04

5 | Conceptual Numerical Model

This chapter provides an overview of the conceptual Delft3D model developed for this study. The hydraulic analysis described in the Chapter 4 serves as the foundation for the model, providing essential input data for boundary conditions and multiple hydraulic parameters. The objective is to provide a clear understanding of the purpose of the model, how the model is developed, what assumptions are made and what configuration of parameters are applied. Subsequently, the model domain, grid generation, boundary conditions, and physical processes included are discussed. Finally, calibration and validation procedures are explained and results are discussed.

5.1. Model Objective & Scope

As discussed in Chapter 3.3.2, several hydraulic parameters play a crucial role in mangrove development. To gain better understanding about these parameters, a conceptual numerical model is used. In the numerical model, mainly the water depth, inundation time, depth average flow velocity and wave height are the parameters of interest, as they are the main hydraulic parameters influencing mangrove development which can be accurately modelled with the available data. Sedimentation, SSC, salinity and water density are not simulated in the conceptual model, since there is too little data about the bathymetry and river characteristics, which would make the results for these parameters meaningless. However, erosion is addressed in relation to the changing flow conditions during storm events. Due to the limited data availability and the number of assumptions that had to be made regarding boundary conditions, bathymetry, and forcing, the model is considered a conceptual representation of the system rather than a fully reliable predictive tool. The hydraulic analysis, which can be found in Chapter 4, provides the necessary environmental data that serves as input for the numerical model.

Delft3D is used to simulate and analyse the hydrodynamic conditions in the Kim Đông coastal area. Delft3D is a powerful hydrodynamic modelling application capable of accurately simulating key coastal processes. The objective of the conceptual model is to simulate the current hydrodynamic conditions, and a scenario with a fourth dike under representative tidal and wave forcing, including extreme storm conditions. The model compares different sites under current conditions to identify potential differences in hydraulic characteristics between locations. By applying different configurations, it is assessed how these sites are influenced by the construction of the fourth dike, comparing the new situation against the current one. These comparisons are particularly relevant because the different sites represent areas with varying mangrove development, allowing the hydrodynamic conditions associated with good and poor mangrove growth to be identified and better understood. The conclusions of the comparisons are used to integrate the hydrodynamic part into the system diagram, to see how changes in these parameters influence the criteria important for stakeholders in Kim Động.

Important to note is that the mangroves themselves are not included in the conceptual model. Apart from time limitations, this decision was also made due to the complexity of accurately representing vegetation flow interactions within Delft3D. Implementing mangroves would require detailed spatial data on vegetation density, height, stem diameter, and drag coefficients, which highly vary between different sites. Since the primary focus of the model is to compare large scale hydrodynamic patterns between sites and scenarios, excluding mangroves allows for isolating the influence of infrastructure (such as the fourth dike) without introducing additional uncertainty from vegetation modelling.

5.2. Input Model

Selecting an appropriate model domain is an important step in setting up the Delft3D model. The domain should include all the relevant physical boundaries and hydraulic processes that influence the system's behaviour. For this reason, the same domain is used as described in Chapter 4.2. The bathymetry used in the model is an approximation of the real bathymetry, meaning local differences between simulated hydrodynamic conditions and those observed in the field are expected.

5.2.1. Grid and Bathymetry

The produced bathymetry is converted to a computational grid, presented in Figure 5.1. It is common practice in Delft3D applications to use separate grids for the FLOW and WAVE modules, where the hydrodynamic grid is finer to resolve detailed flow patterns, and the wave grid is coarser to efficiently simulate large scale wave propagation. In this study, however, a single grid was adopted to maintain consistency between the two modules and to avoid interpolation errors that can occur when coupling different grids. Moreover, since the model is conceptual and primarily focussed on the comparative analysis between sites rather than high precision local prediction, the use of one shared grid provides sufficient accuracy while significantly reducing setup complexity and computational time.

The grid is created with specific dimensions to ensure sufficient spatial accuracy. The grid cells in front of the coast have a resolution of 12x12 metres, visualised as the red area in Figure 5.1, providing high precision where detailed bathymetric variation and hydrodynamic calculations are important. Further offshore, the grid cells are coarser: 108x12 metres, displayed as the green area in Figure 5.1, where data availability is limited and less accuracy is required, reducing computational time. Furthermore, the FLOW boundaries are visualised at the edge each boundary, clarified in more detail in Section 5.2.2. In Appendix B.1, the creation of the grid is explained, which also includes illustrative figures.

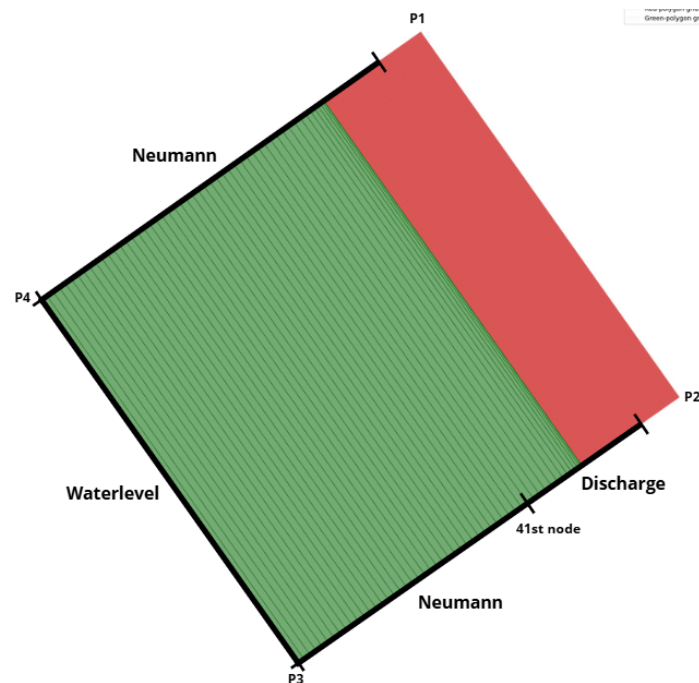


Figure 5.1: Grid Sections with High Resolution (red) and Coarse Resolution (green).

To include the dike in the model, the program QUICKIN in Delft3D is used to draw a polygon. The bed level is increased to 4 metres in the whole area behind the dike. Additionally, the island is drawn into the grid, from which the dimensions are determined by using Google Earth satellite imagery, implemented by increasing the whole island to a height of 4 metres. Since the model does not account for morphodynamics, it is sufficient to represent the dike and island as an impermeable structure by elevating it above the maximum water level and wave height.

5.2.2. Boundaries

The boundaries of the computational domain, previously defined by points P1 to P4, are assigned as open or closed depending on their hydraulic function. The boundaries determine how water can enter or leave the model domain, influencing flow and wave conditions. Incorrect boundary settings can lead to unrealistic simulations or numerical instability. Several combinations of boundary conditions have been tested during model setup, with resulting water levels, flow velocities, wave characteristics, and overall system behaviour analysed to evaluate the model's response. Ultimately, the following boundary conditions are selected for the final model setup, as they resulted in the most realistic simulations.

FLOW Boundaries

In the Delft3D FLOW module, three open boundaries and one closed boundary are defined, of which a visualisation can be found in Figure 5.1. Each boundary condition is selected to represent the hydraulic processes along that boundary as accurately as possible, however, some assumptions are made due to limited data availability. Firstly, the direction of the tidal wave needs to be assumed. In this study, the propagation of the tidal wave is assumed to come from the south-east, travelling toward the north-west. This assumption is made on the topography, tidal propagation and tidal ranges of the Gulf of Tonkin (Pan, Li, Xu, & Wei, 2023). Boundary-specific assumptions are discussed individually below.

- **Open Dirichlet Boundary P3-P4 (south-west):** At the southern boundary, a non-reflective Dirichlet condition is applied. Tidal water levels measured near Gate 10 on Dike 3 are imposed at point P3. The tidal wave is assumed to propagate from P3 to P4, since the propagation direction is from south-east to north-west. This boundary provides the primary tidal forcing for the model domain.
- **Open Neumann Boundary & River Discharge P3-P2 (south-east):** The south-east boundary is divided into two sections. One section of the boundary is assigned to represent the discharge of the Đáy river, represented in Figure 5.1 from the 41st node to halfway through the red area. The exact discharge of this river during different scenarios is further elaborated in Subsection 5.3.3. The second section has been assigned to a Neumann boundary condition, represented in Figure 5.1 from P3 to the 41st node, for which the gradient of the tidal wave is used as input. The derivation of the gradient can be found in Appendix F.1.1
- **Open Neumann Boundary P4 - P1 (north-west):** As discussed in Chapter 4.2, the bathymetry along the land boundary is not known. For this reason, the boundary is placed in front of the landside, in the open sea. Along the entire section of boundary P4 - P1, a Neumann boundary is applied with the same water level gradient as in boundary P2 - P3. In reality, the gradient in these boundaries is slightly different, however, since the assumed gradient is based on a dataset from only 1 point, introducing another assumption into the gradient difference between the two Neumann boundaries will introduce more uncertainty into the model. Furthermore, as discussed in Section 4.1, since there is no available data on the discharge of the rivers near this boundary, the boundary will not include these discharges.
- **Closed Boundary P1-P2:** This boundary is located on the north-west landside, which is why this boundary is assumed to be closed. However, dike number 3 and the partial dike number 4 segment are located in front of this boundary, so no water is actually interacting with this closed boundary.

WAVE Boundaries

For the Delft3D WAVE module, wave boundary conditions are applied along boundary P3 - P4 and partially boundary P2 - P3. The input parameters for these boundaries are derived from the hydraulic wave analysis presented in Chapter 4.7. The input data include significant wave height, peak period, and mean wave direction with standard deviation, which are used to define the incoming wave spectrum at the open boundaries. Specific wave parameters are discussed in more detail in Section 5.3. In Figure 5.2, the exact location of the wave boundaries is visualised.

In order to account for the depth difference along both boundaries, the boundary is divided into sections every 1 meter of depth difference. For each section, the significant wave height is adjusted according to the principles of wave shoaling by taking the depth in the middle of each section, accounting for the increase in wave height into shallower water, for which calculations can be found in Appendix F. This sectional approach ensures a smooth and realistic wave boundary and provides a more realistic nearshore wave field.

5.2.3. Model Settings

In Delft3D, there are several parameters that need to be specified in order to start a simulation. An overview of all input parameters defined in the simulation, including short explanations, is given in Appendix F.2.3. The explanations also describe the iterative process used to calibrate these parameters during the model setup, and which assumptions are made.

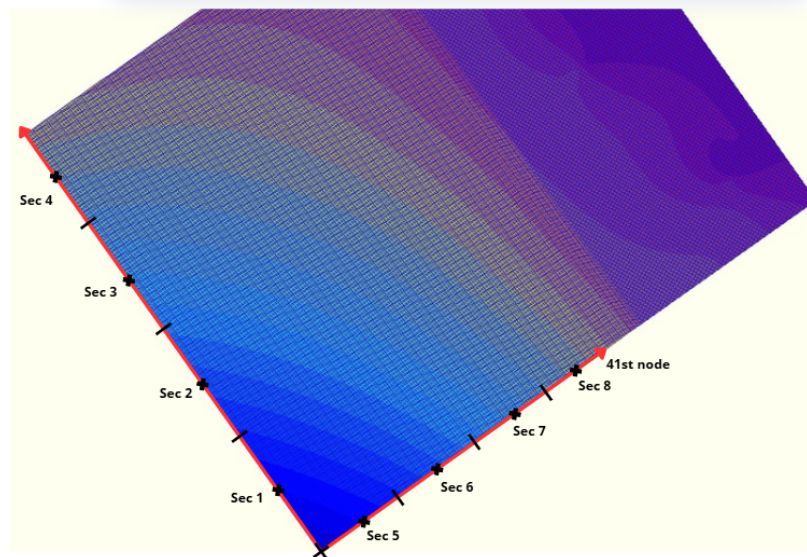


Figure 5.2: WAVE Boundaries Visualised in Red.

The selection of the model run time and time step represents a balance between computational efficiency and numerical stability. To determine an appropriate time step, the maximum stable value is investigated, in order to minimize computational time. The analysis shows that a time step of 1 minute forms the upper limit for maintaining numerical stability, as larger values cause the Courant number to exceed its critical threshold of 1. The Courant number is a measure of numerical stability, showing whether the chosen time step allows information (waves or flow) to move through the computational grid at a physically consistent rate. When this ratio exceeds one, the model can no longer correctly resolve the propagation of waves or flow, resulting in numerical instability and unrealistic outputs. Therefore, a time step of 1 minute is selected to ensure both stability and accuracy.

The total simulation time is set to 3.5 days, with the model starting at low water and ending at high water conditions. For the purpose of this study, this duration is sufficient to identify the main patterns of the system and to meet the model objectives. For other purposes, such as bathymetry changes due to sediment transport, residual currents, or analysing spring-neap tide variations, the model should be run for a longer period, typically at least one spring-neap tide cycle of around 14 days.

The duration of 3.5 days captures several tidal cycles, which is desirable for representing calm (non-storm) conditions and for ensuring that the hydrodynamic system reaches a quasi-steady state, meaning that the system can be analysed for the period of interest. For extreme storm simulations, the same 3.5 days duration is used to maintain consistency in boundary forcing and model spin-up. In numerical models, spin-up time is the initial simulation period during which the model adjusts from simplified starting conditions to a stable, realistic state that aligns with the applied boundary conditions. However, extreme storms generally have a much shorter duration, so conclusions should not be based on the entire simulation period. Instead, only a one-day period around the extreme storm event is analysed.

5.3. Simulation Configurations

In the following section, the different configurations are evaluated for the numerical model, including multiple dike configurations, wind and sea-states.

In order to evaluate the hydrodynamic response of the different configurations, a total of 9 configurations are defined: 3 structural configurations and 3 environmental configurations, of which an overview is given in Table 5.1, which are further elaborated in the following sections. The purpose of defining these 9 scenarios is to assess how the proposed dike segment will influence the hydrodynamic forcing in the domain. By comparing the results, the influence of building a dike is determined, particularly by comparing the water level and flow velocity inside the new dike segment and directly in front of it.

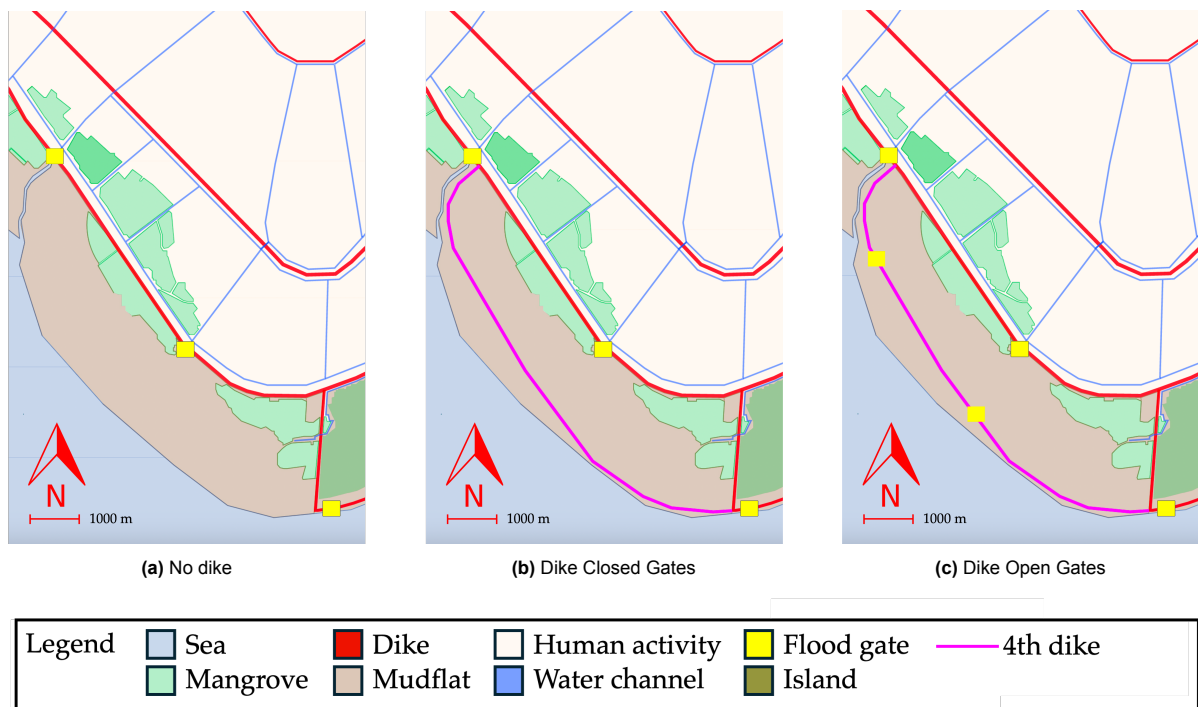
Table 5.1: Overview of Simulated Scenarios for the Delft3D Model

Dike Configuration	Sea-state Scenario	Season / Discharge Condition	Wind Speed (m/s)
No Dike Segment	Calm sea-state	Dry season (low discharge)	3.87
	1-year RP conditions	Wet season (high discharge)	10.23
	30-year RP conditions	Wet season (high discharge)	15.86
Dike Without Gates	Calm sea-state	Dry season (low discharge)	3.87
	1-year RP conditions	Wet season (high discharge)	10.23
	30-year RP conditions	Wet season (high discharge)	15.86
Dike With Two Gates	Calm sea-state	Dry season (low discharge)	3.87
	1-year RP conditions	Wet season (high discharge)	10.23
	30-year RP conditions	Wet season (high discharge)	15.86

5.3.1. Dike Configurations

To systematically assess the hydrodynamic response of the bay, three dike configurations are evaluated, which are visualised in Figure 5.3. The scenarios are outlined below.

1. **No Dike Segment:** Represents the present situation without a dike, providing a baseline of existing hydraulic conditions within the bay.
2. **Dike with Closed Gates:** A fully impermeable dike completing the Binh Ninh fourth dike ring as described in Figure 5.3. This scenario evaluates conditions when gates remain closed for extended periods.
3. **Dike with Two Gates:** Two gates, with dimensions $12W$, $4.9H$ in metres, are installed to facilitate water exchange, and support sediment and water transport for mangroves and aquaculture farms. These dimensions are determined based on the dimensions of the existing gate 10 in dike number 3. The locations of these gates are shown as yellow squares in Figure 5.3c, which are determined by extending the gates already present in dike number 3.

**Figure 5.3:** Dike Configurations (Three Scenarios) including Corresponding Legend

5.3.2. Sea-states

Three representative sea-state scenarios are evaluated using the numerical model. All sea-states and detailed documentation of how the scenarios are obtained is found in Chapter 4. These three scenarios form a representative basis to assess the system's behaviour under both normal and extreme conditions. Furthermore, it is assumed that storm conditions, such as the moderate and extreme sea-states, occur during the wet season (June - October), while calm sea states occur during the dry season (December - April).

1. **Calm Sea-state:** The 20th-30th percentile band, derived from the JONSWAP spectrum.
2. **Moderate: 1-Year Return Period Sea-state:** Obtained using the POT method to evaluate extreme wave conditions.
3. **Extreme: 30-Year Return Period Sea-state:** 30-year return period corresponding to structure class IV. Obtained using the POT method to evaluate extreme wave conditions.

The representative significant wave heights and peak periods per sea-state are given in Table 5.2.

Table 5.2: Sea-state Characteristics

Sea-state	H_s^{rep} (m)	T_p (s)
Calm: 20th-30th percentile	0.47	4.47
Moderate: 1-Year Return Period	1.65	8.15
Extreme: 30-Year Return Period	4.31	9.30

5.3.3. Discharge

To ensure realistic river forcing from the Đáy River, each scenario is coupled with the corresponding hydrological season. The dry season (December–April) or the wet season (June–October). Since the river does not directly discharge inside the model domain, only a fraction of the discharge determined in Chapter 4.1 is actually entering the model domain. Based on the analysis of satellite imagery, field observations, and the model bathymetry, it is assumed that 10% of the total discharge of the Đáy River enters the model domain. The resulting effective discharges, displayed in m^3/s as required by Delft3D, are summarised in Table 5.3. This value is determined by dividing the discharges found in Chapter 4.1 for the wet and dry seasons by the total amount of seconds in the corresponding period.

Table 5.3: Daily Discharge of the Đáy River (Vinh et al., 2014)

Period	Q (m^3/s)
Dry season (Dec to Apr)	36.79
Wet season (Jun to Oct)	147.51

5.3.4. Wind-states

Three distinct wind speed scenarios are modelled. Detailed descriptions of each wind state and the methodology used to derive these scenarios are found in Chapter 4.8, with the corresponding data presented in Table 5.4.

1. **Calm Winds: The 20th - 30th Percentile Range:**
The range is derived from the wind speed cumulative distribution.
2. **Moderate: 1-Year Return Period Wind Conditions:**
Obtained using the Peak Over Threshold method to assess moderate wind speeds.
3. **Extreme: 30-Year Return Period Wind Conditions:**
The 30-year return period corresponds to extreme wind conditions typically expected for infrastructure class IV. Calculated using the POT method to evaluate extreme wind events.

Table 5.5 presents the directional characteristics of the wind, including mean direction and circular standard deviation. These values are used as input parameters for the wind processes in Delft3D.

Table 5.4: Wind Speed Characteristics

Wind State	U_{wind} (m/s)
Calm winds: 20th-30th percentile	3.865
Moderate winds: 1-Year Return Period	10.228
Extreme winds: 30-Year Return Period	15.860

Table 5.5: Wind Directional Characteristics

Characteristic	Value
Mean Direction (°)	173.21°
Circular Standard Deviation (°)	33.27°

5.4. Model Calibration

The constructed model is tested on its performance by measuring its accuracy. This is done by comparing the modelled values to the measured values during the field campaign in April 2025. Due to the limited data availability in the domain and unforeseen complications during the field campaign in October, the available calibration data consists solely of the water depth measurements at a single point. The water depth values extracted from the model simulation are directly compared to the water depth values of these measurements. The location of the calibration location is displayed in Figure 5.4.

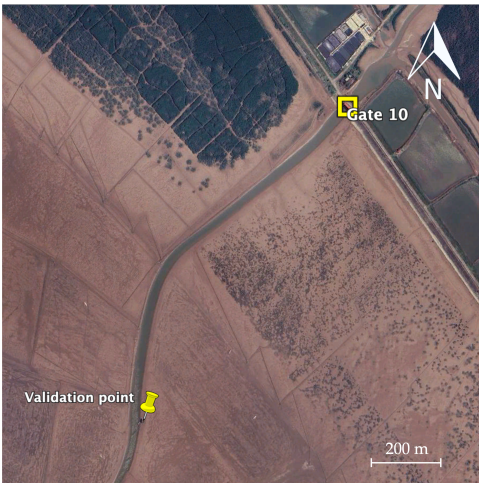


Figure 5.4: Location of the Calibration Point

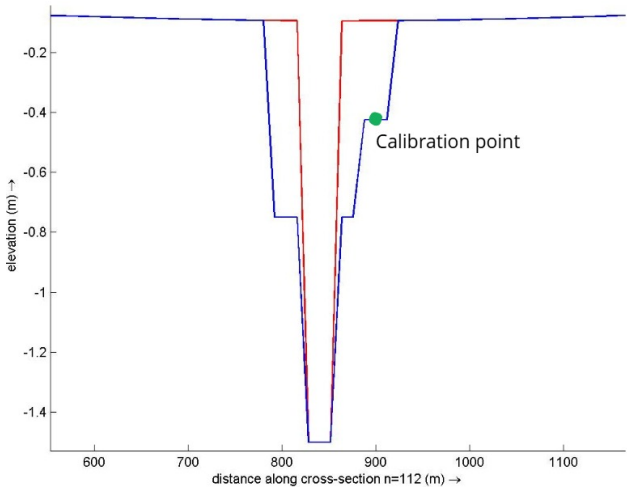


Figure 5.5: Cross-section of Widened Canal and Calibration Point
Red: Original Bathymetry; Blue: Updated Bathymetry

During the initial simulation, the model strongly underestimated the measured water depth. This is caused by the calibration point being measured approximately 35 cm lower during the field campaign than the corresponding elevation obtained from the interpolated bathymetry. This difference is likely related to the influence of the canal leading to Gate 10, which in reality does not have the rectangular shape assumed in the model. Instead, it gradually increases from the deepest point towards the side. The updated bathymetry of the cross section at the calibration point is given in Figure 5.5. The water depth of the initial bed level elevation is indicated with the red line in Figure 5.6, indicating the difference in water depth is significant.

After the updated bed level underestimating the water depth, the model also shows a delay in regions of low water depth, reaching zero water depth later and becoming submerged later than observed. Therefore, the roughness in the FLOW file is adjusted from 0.03 to 0.02 to make up for this lag. The change reduces the lag a little, but it is still present. In Figure 5.6, the simulation with the updated bed level and a bottom roughness of 0.03 is shown by the blue line, while the green line represents the simulation with a bottom roughness of 0.02.

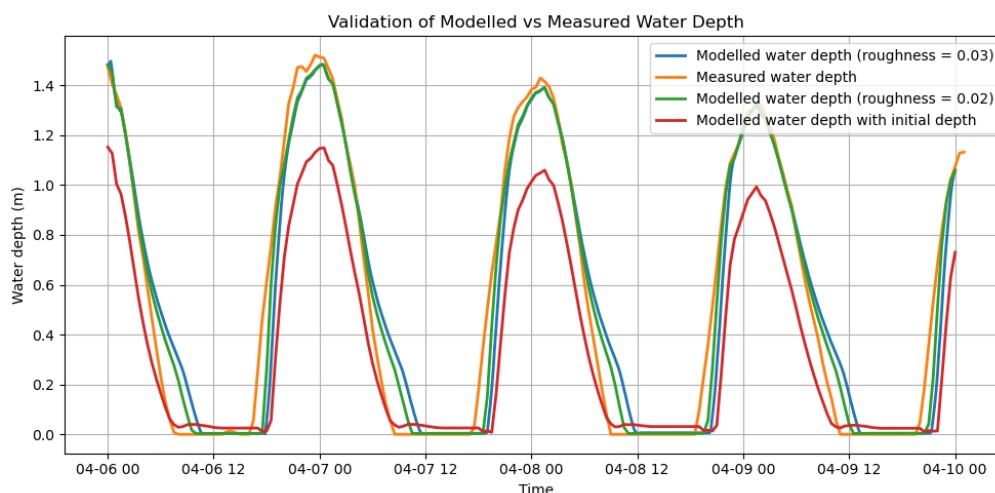


Figure 5.6: Observed and Modelled Water Depth at Validation Location

The simulated water depth at the peak is still a little lower than the observations, even when the newly measured bottom elevation is used. This difference could be caused by several factors. First, the measured tidal signal in the model input might be too weak, resulting in underestimated water levels. This weak tidal signal could be caused by the influence of the canal going through the gate. Second, the pressure sensor used for measuring the water depth may have been positioned too low or could have sunk into the mud, leading to an overestimation of the water depth. Third, the bed elevation at the measurement location may have risen during the six months between the water depth measurement in April and the bed level measurement in October. These three reasons could cause the model to represent a deeper bathymetry than what was actually present at the time of the water level measurement, decreasing the water depth for the simulation.

5.5. Delft3D Model Results

This section presents and discusses the analysis of the simulated hydraulic parameters obtained from the Delft3D model. The focus is on identifying how the different configurations and sea-state scenarios influence the water level, inundation time, depth-averaged flow velocity, and significant wave height inside the model domain. This section highlights the main trends and observations, while a more detailed description of the results can be found in Appendix F.

Table 5.6 summarises the relative changes in the main hydraulic parameters under calm conditions for both dike configurations, compared to the current situation. The table presents the percentage increase or decrease in inundation time, water depth, depth-averaged flow velocity, and significant wave height for scenarios with open and closed gates. These values indicate the general hydraulic response of the system to the different dike layouts. The calm sea state is shown here, as it represents the typical hydrodynamic conditions in Kim Động, and allows for a clear comparison between the configurations. These ranges, along with the storm conditions and location specific information, are further elaborated in the following sections. To help understand the regions and points discussed in more detail, an overview map with all relevant locations is shown in Figure 5.7.

Table 5.6: Relative Results by Configuration (Calm Conditions)

Result	Current Situation (Baseline)	Dike Open Gates in % (3rd Dike Shoreline)	Dike Closed Gates in % (4th Dike Shoreline)
Inundation Time	-	- 10 / + 30	- 20 / - 10
Water Depth	-	- 30 / - 15	0
Depth-Averaged Velocity	-	- 30 / + 30	- 40 / - 10
Significant Wave Height	-	- 25 / - 5	- 25 / - 15

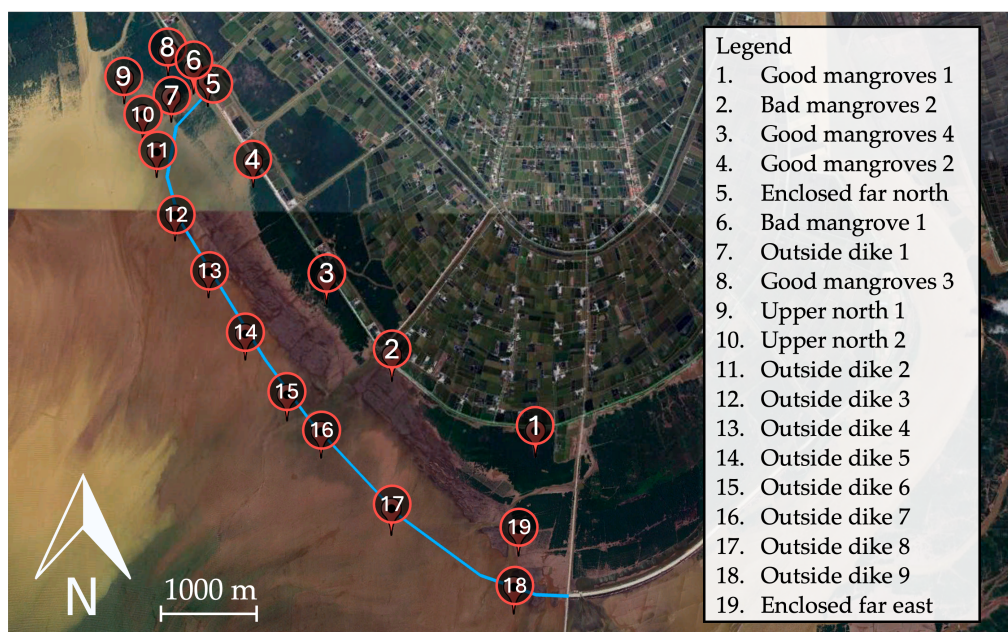


Figure 5.7: Visualisation of the Different Locations of Interest in the Model Domain.

It is important to note that some parameters show unrealistic behaviour. In particular, at the flow and wave boundaries during storm conditions, the waves become unrealistically high and break immediately, while the flow displays irregular patterns with high velocities at the discharge boundary. This is further explained in Appendix F.3.3. Furthermore, the modelled waves show a smooth decrease in height, whereas they should increase due to shoaling. This may be related to the wave angle of incidence with respect to the bathymetry, where refraction can cause a reduction in wave height instead of the expected increase.

5.5.1. Current Situation without the Fourth Dike

First, the simulations of the current situation, without the presence of a fourth dike, are analysed. Here, the focus is concentrated on the nearshore areas, especially the areas where mangroves are thriving and where mangroves are struggling. The locations associated with healthy mangroves are locations 1, 3, 4 and 7, whereas the areas with struggling mangroves are indicated with locations 2 and 6, as presented in the visualisation of the measurement locations in Figure 5.7.

The first key observation is that the healthy mangrove sites experience lower water depths during high tide and have shorter inundation periods compared to the struggling sites, as presented in Figure 5.8 where multiple sites are plotted. This is explained by the fact that good mangrove sites have a higher bed level elevation in the bathymetry used in the model.

To further understand the differences between these sites, the depth-averaged velocity magnitudes are examined at several locations. Under calm conditions, the depth-averaged flow velocities are relatively low, with the highest velocities of around 0.2 m/s occurring when the tide reaches the shore during flood. Interestingly, under the calm sea-state, the areas where mangroves are struggling experience the lowest flow velocities. However, as weather conditions become increasingly more extreme, the same areas experience the highest increase in flow velocities, where they are on average two to three times higher compared to areas where mangroves are doing well during these storm conditions. This indicates more significant erosion during storms in areas where mangroves are struggling.

Lastly, the significant wave height is analysed. Here, the wave height under calm sea conditions increases a little when moving from north to south along the third dike, with waves reaching a 0.1 m wave height. When weather conditions become more extreme, the difference in significant wave height alongshore increases. This can be explained by the wave boundary being located closer to the southern area than to the northern area, while the discharge boundary increases the water depth in the south,

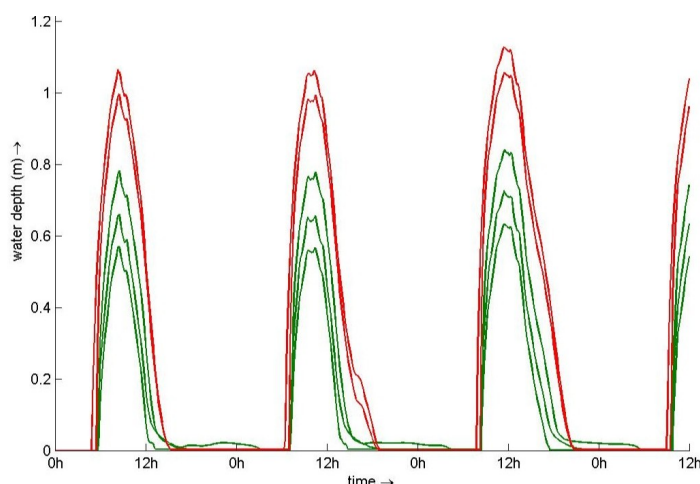


Figure 5.8: Water Depth at Thriving and Failing Mangrove Sites. Calm Conditions.
Red: Failing Mangroves; Green: Thriving Mangroves

allowing higher wave heights to develop. The middle part of the shoreline where, P3 and P4 are located with healthy mangroves, experiences the lowest waves during flood. The areas with bad mangroves at locations P2 and P5 experience from 20%, up to 70% higher wave heights, as can be seen in Appendix F.3.4. Lastly, the most eastward regions around P19 are more sheltered, with significant wave height dropping very quickly to a comparable level of P3 and P4.

5.5.2. The Effect of the Fourth Dike

This subsection discusses the effect of the fourth dike on the hydraulic system. Three areas of interest are identified in the scenario with the fourth dike compared to the current situation: the area enclosed by the dike, the northernmost corner, and the area directly in front of the fourth dike. These areas are of high interest, since they are directly affected by the construction of the fourth dike and hold potential for socio-economic development enabled by the fourth dike. In contrast, hydraulic systems further offshore are less influenced by the completed dike and bring less opportunity.

The Effect of Open Gates Inside the Enclosed Area

Inside the enclosed area by the fourth dike, the hydrodynamic conditions are different compared to the situation without a dike. Since the inflow of water inside the enclosed area is restricted by the dike and can only flow through two gates, the water level response becomes slower, and the high-water peak is reduced and delayed. As the tide recedes, the outflow is again restricted, causing a slower decrease in water level, resulting in an altered inundation time. This pattern is observed across most of the area inside the dike, with water depth reduced by 15% to 30%. Depending on the measurement location, inundation time decreases by approximately 10% at sites close to the gates or increases by up to 30% at sites farther from the gates, such as P19. The general trend regarding mangroves is that the inundation time decreases slightly with 5% at locations where mangroves are currently in good condition, and increases with approximately 20% at locations with poor mangrove conditions. Overall, the decrease at good mangrove sites is lower than the increase at poor mangrove sites. To illustrate the effect of constructing the dike with open gates, Figure 5.9 compares two points in the canal going to the gate near P12: one just outside the gate and one just inside. The point inside shows a slower response at the peaks and the same response in the troughs, an inflow effect whose effects translate to all measurement locations in the enclosed area.

The average reduction in depth-averaged flow velocity is about 30% at locations far from the gates of Dike 4. In contrast, areas close to the gates show an increase of around 30%. Flow velocities near the canals are generally higher than those between canals, which is expected since water flows in and out the enclosed area via these pathways. To give an indication, the flow velocity magnitude 30 metres away from a canal can be 40% higher than a location 100 metres away from a canal.

Because of the blockage of waves by the dike, significant wave heights are reduced, for example in a

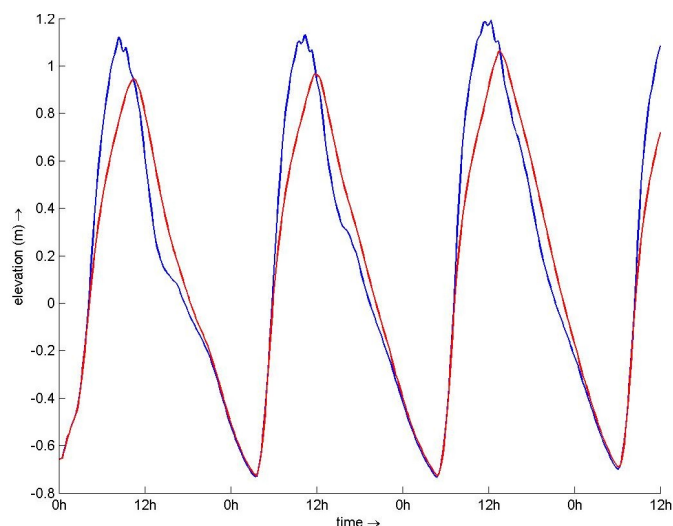


Figure 5.9: Water Depth Inside and Outside Dike. Calm conditions (Red: Inside Dike; Blue: Outside Dike)

transect perpendicular to the dike at P3, by up to 25%, leaving 75% of the original wave to travel into the enclosed area. Only in the area behind the lower gate near P2, the wave height reaches the same height as the situation without the 4th Dike. This is likely caused by the canal being deeper and allowing higher waves heights to travel through the enclosed area. However, during the wave simulations there are some dike sections where waves appear to be travelling through the fourth dike, which is physically not possible. For this reason, the wave results inside the closed compartment should be taken with caution, as they likely are not realistic.

As the sea-state becomes more extreme, the magnitude of all hydraulic parameters increases, and the difference in magnitude of these parameters between the enclosed area and the area outside becomes larger. Under storm conditions, the gates are normally closed. However, in case of failure of the gates, the fourth dike with open gates creates a sheltered environment with calmer hydraulic conditions inside the enclosed area.

The Effect of the Fourth Dike with Closed Gates Outside the Enclosed Area

The effect of the dike on the hydraulic conditions outside the dike ring is assessed with closed gates. The area enclosed by the fourth dike is not considered in this analysis, as no water interaction occurs when the gates are closed. Furthermore, the configuration with closed gates is selected because the gates are assumed to be closed during extreme storm conditions, and the simulation results show no significant differences between open and closed gates under calm conditions. The analysis shows that the water level in the Upper North 1 location slightly decreases by approximately 5% due to the presence of the fourth dike. However, this is only observed in this point, while the surrounding locations 6, 7, 8, and 10 show no water level differences between the different sea-states. Water levels gradually decrease along the seaward side of the dike towards the north during storm conditions. During high water and extreme conditions, the maximum water depth difference between the north part of the dike at P11 and the east part at P18 is around 0.2 m, while during low water the difference rises to 0.4 m, a significant difference. It is visualised in Figure 5.10. Another important pattern is that the bed level in front of Dike 4 is significantly lower than in front of Dike 3, as this area is located further offshore. Because the tidal wave height remains unchanged, the lower bottom elevation causes the inundation time being substantially longer in front of the dike. On average, the inundation time is 250% higher compared to the area in front of Dike 3 before the construction of the fourth dike.

A similar trend of decreasing wave height along the dike to the North is observed, as is also seen for the open gates. The significant wave height along Dike 4 with closed-gates situation is visualised in Figure 5.11. Under extreme storm conditions, the wave-induced forces are highest along the southern section of the dike. This may explain why wave transmission through the dike occurs there, which is also the case during calm conditions.

In addition, the significant wave height along the fourth dike shows a clear spatial trend and response to sea-state conditions. In the configuration with closed gates, the dike acts as an effective barrier to wave propagation, causing most of the wave energy to be reflected or dissipated along the seaward face. As a result, wave heights directly in front of the dike are 20% lower than in the open configuration during calm conditions, and 5% lower during extreme conditions.

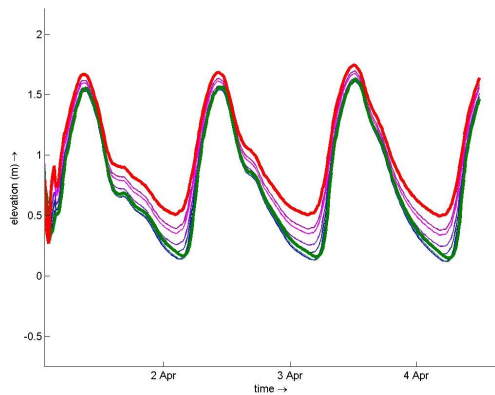


Figure 5.10: Decrease of Water Level under Extreme Conditions along North-to-South Transect
Red: most Southern; Green: most Northern)

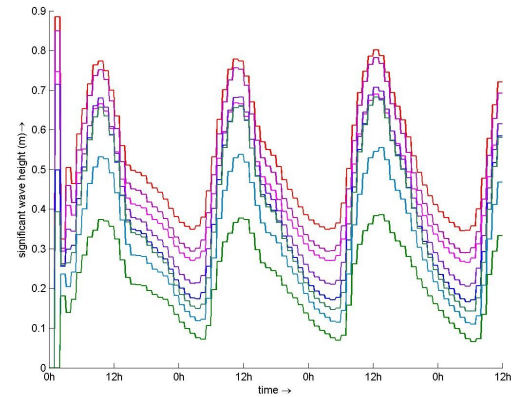


Figure 5.11: Decrease of Wave Height under Extreme Conditions along North-to-South Transect
Red: most Southern; Green: most Northern

Finally, the dike has little effect on flow patterns under calm conditions, with flow velocities slightly decreasing in front of the dike, and increasing in deeper parts further offshore. Similarly to the water level, there is a trend regarding the flow velocity along the fourth dike, only now the maximum is in the north instead of the south. During a calm sea-state, where flow moves from the east side of the dike to the north, the velocity magnitude gradually increases with 70% from P17 until P11. However, when sea-states are excited, this phenomenon flips. During both the 1 year and 30 year extremes, higher velocities are observed at the east side of the dike, with velocities decreasing when following the dike to the north with 40%. This is likely caused by the river discharge being higher at those extreme simulations. Furthermore, by comparing storm conditions between the scenario with dike and without dike, it is observed that in general, the flow velocities in front of the fourth dike during storm conditions are on average 20% higher in the configuration with the dike. This leads to more significant erosion during storms in front of the fourth dike compared to the current situation.

5.6. Model Validation

The goal of the model validation is to assess the accuracy of the calibrated Delft3D model. The model validation is performed using a different dataset than in the calibration, and the water depth is assessed in the same way as during the calibration. The input conditions, in contrary to the calibration phase, originate from October 2025, instead of April 2025. The conditions in October represent the wet season, thus the input for the model should be adjusted accordingly. The difference compared to the calibration data is that, at the validation location, only the water level is measured in October. The water depth is therefore obtained by adding the measured water level to the bottom elevation of 0.424 m.

The wave boundary is adjusted based on comparing the wave measurements done in April and October. The maximum wave height measured in October is 18% higher than in April. Consequently, the significant wave height for the October scenario is obtained by multiplying the wave height of the calm sea-state by a factor of 1.18.

During the April campaign, water level measurements were carried out at Gate 10. This dataset is used for model calibration. However, the measurements of October show irregularities at Gate 10 and are therefore not suitable for use in the validation. Water level measurements at the validation point are therefore used instead. As for the FLOW boundaries, the water level and Neumann boundaries are recalculated in the same way as before, but now based on these new water level measurements dataset.

River discharge is increased for the validation simulation because this time the observations took place during the wet season, increasing the discharge the river flows into the domain. The obtained values for discharge are based on assumptions made in Subsection 5.3.3.

The modelled and observed water depth values are shown in Figure 5.12. The model generally follows the observed water levels well, but at the peaks it tends to overestimate the water depth slightly. This overestimation could be caused by the inclusion of wind and wave effects in the model, while the water level boundary already represents the water level at the validation location. As a result, these effects may be double-counted, leading to an overestimation of the simulated water levels. It also shows a small time lag during other parts of the cycle. From around October, 7th onwards, the observed water depth was not recorded for the entire day. Therefore, only 2.5 days are simulated for this validation period.

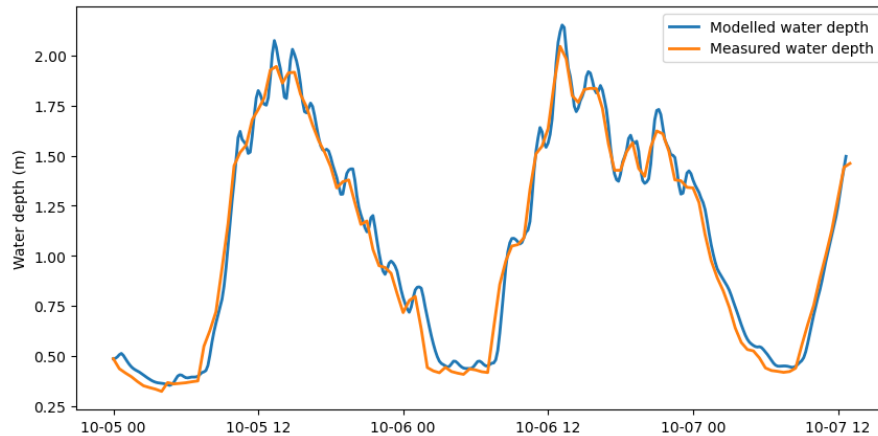


Figure 5.12: Observed and Modelled Water Depth at Validation Location

5.6.1. Validation Criteria

In this study, three validation criteria are applied to quantify the accuracy of the model, which are selected from Moriasi et al. (2007) and are commonly used to evaluate the performance of hydrodynamic models.

- **Nash–Sutcliffe Efficiency (NSE)**

The NSE is commonly used in hydraulic models to evaluate how well simulated variables, such as water level or flow velocity, match the observed data over time. A high value of NSE (close to 1) indicates strong agreement between the simulated and observed data, while values near or below 0 imply poor model performance.

- **Percent Bias (PBIAS)**

The second criterion is the classic PBIAS, which determines the average tendency of the simulation to be larger or smaller than the observed data. A negative sign of PBIAS tells that the model is overestimating, and a positive sign indicates underestimation.

- **RMSE–Observations Standard Deviation Ratio (RSR)**

The third criteria is the Root Mean Square Error (RMSE)-observations standard deviation ratio (RSR), which quantifies the relative error with respect to the standard deviation of the measured signal. Lower values indicate higher model accuracy, with an RSR of 0 representing a perfect fit, and values greater than 0.7 are generally considered unsatisfactory.

By analysing these three criteria in combination with graphical interpretation, the performance of the model can be effectively evaluated and validated (Moriasi et al., 2007). Table 5.7 shows the resulting three criteria, computed in a Python script.

The obtained NSE value of 0.99 indicates that the model reproduces the observed water depth with high reliability and is suitable for practical applications. Since it is well above the threshold value of 0.50, the model can be considered adequate for hydrodynamic applications. The PBIAS value of -2.5% reveals a

Table 5.7: Validation Criteria

Criteria	NSE	PBIAS	RSR
Value Model	0.99	-2.5%	0.10
Value Desired	> 0.50	± 25%	≤ 0.70

very slight overestimation of the simulated water depth compared to the observed water depth. Finally, the RSR value of 0.10 is well below the threshold of 0.7, which is sufficient. This criterion states that the magnitude of the model's residual error is about a tenth of the natural variability of the observed water depth.

This validation process mainly confirms that the water level response at the validation location is highly sensitive and reacts almost instantaneously to external changes. While the boundary data and the observed data are from the same dataset, it is expected that the signals would match. The direct response of the water depth aligns with the characteristics of tidal propagation, which occurs very slowly and has a very long wavelength. As a result, the water levels offshore and nearshore are expected to be nearly identical in both amplitude and phase.

However, this validation provides only limited insight into how accurately the model represents spatial variations or dynamic behaviour in other parts of the system. Since only the water level is validated at one location, any conclusions or recommendations based on other parameters, such as flow velocity or wave height, should be made with great caution. These variables may be influenced by local effects or model uncertainties that are not captured by the water level validation.

5.7. Model Conclusion

The conceptual numerical model successfully provides insight into the main hydraulic parameters influencing mangrove development, as outlined in the model objective. Clear differences in water depth and inundation time are observed between areas with healthy and struggling mangroves. Especially the water level signals provide valuable information, illustrating how these parameters differ between sites and how they respond to the construction of the fourth dike. The storm simulations show that the fourth dike effectively reduces wave energy and flow velocities within the enclosed area, resulting in a calmer hydraulic environment. However, outside the dike, erosion due to storms along the dike could pose a problem.

Several limitations affect the quantitative reliability of the results. Flow velocity results are found to be too variable to identify clear spatial patterns, and therefore no conclusions are drawn regarding sediment transport, as mentioned in the model scope. Wave heights are inconsistent at the boundaries and, in some locations, unrealistically propagate through Dike 4, making the accuracy of the wave height results highly questionable. Nonetheless, the conceptual model provides valuable insight into the effect of the fourth dike on water depth and inundation time at locations where mangroves are currently thriving and where they are struggling.

6 | Results

This chapter presents the results of the hydraulic analysis, governance analysis, and Delft3D modelling. These results are synthesised to assess the expected impacts of completing the fourth dike, followed by an overview of constraints faced by Kim Đông and Ninh Binh. To reduce negative impacts, possible interventions are introduced. A set of alternatives is compared through a multi-criteria analysis to determine the most suitable interventions for Kim Đông, followed by trade-offs and implementation steps. Finally, a conceptual intervention design is proposed to illustrate the potential next steps for Ninh Binh Province.

6.1. Finishing the Fourth Dike

Finishing the fourth dike in Kim Đông has several effects on the local socio-ecological system. Figure 6.1 presents the system diagram, showing the influence of completing the other segment of the dike. The red elements represent the specific influence of completing the fourth dike and are added as an overlay to the original system diagram.

The effects that the dike has are clearly shown in this diagram. In the short term, the dike results in coastal protection and more land to be allocated, which poses a decision-making challenge as choices have to be made between different land purposes. Ultimately, the system diagram shows that the dike results in less sediment deployed from the sea, which is negative for mangrove health. Also, the degradation of mangroves has a negative influence on carbon storage, damages due to floods and economic benefits of mangrove ecosystems. The aquaculture profitability depends on land allocation but also on the choice between mixed mangrove-aquaculture and intensive aquaculture.

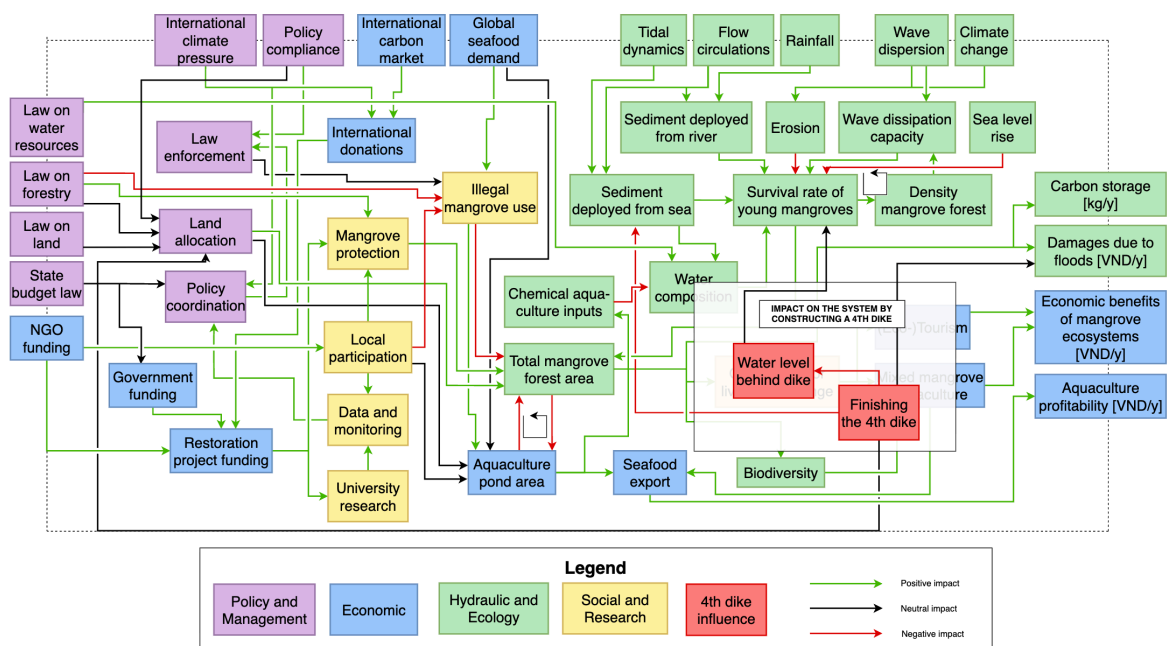


Figure 6.1: System Diagram Including Fourth Dike

6.1.1. Effects on Hydrology and Ecology

Based on the conceptual model results from Chapter 5.5, the completion of the fourth dike ring will substantially alter the hydrodynamic conditions in Kim Đông. These changes are expected to have

varying consequences for different parts of the focus area, both inside and outside the planned fourth dike.

The model configuration with Dike 4 indicates an overall lowering of water levels inside the dike, affecting both thriving and struggling mangrove zones. In the thriving areas (sites 1, 3, 4 and 7 from Figure 5.7), inundation duration becomes shorter, whereas in the struggling zones (such as sites 2 and 6 from Figure 5.7) it increases compared to the situation without a dike. This contrast is clearly illustrated for locations 2 and 4 in Figure 6.2, where water levels decrease in both cases, but the timing of inundation differs between the two mangrove conditions. For both areas, the incoming significant wave height decreases as well compared to the original situation.

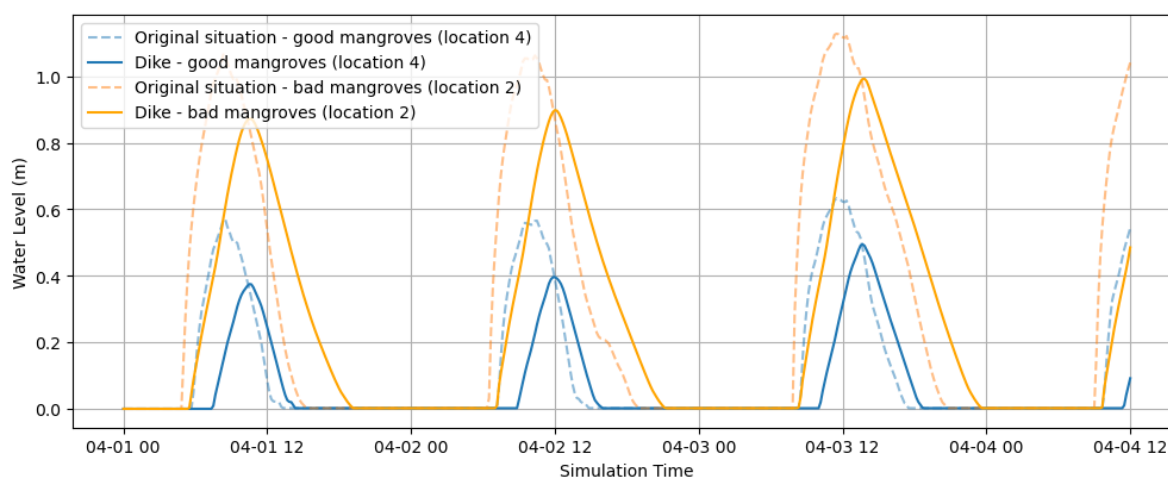


Figure 6.2: Changes in Water Level between Location 2 (Bad Mangroves) and Location 4 (Good mangroves)

These hydrodynamic changes could initially be beneficial for the more stressed mangrove stands, as reduced water levels and wave action lower hydraulic stress on the mangrove roots. However, the decrease in tidal amplitude and exchange also means that less sediment from outside the dike will be transported into these zones. Over time, this limited sediment renewal is expected to restrict natural mangrove expansion, both for struggling and healthy mangrove patches.

Outside and North of Dike 4, there are little differences in the observed hydraulic parameters. As the area is more sheltered from waves and high currents due to the fourth dike, extreme storm impact will be lower, compared to the current situation without a dike. As there are little differences around the outside of Dike 4, few conclusions can be drawn about mangrove performance at this location, as there are currently no mangroves present. The area is exposed to waves however, with limited protection provided by the dike itself. Any potential new mangrove patches here would therefore have to occur without the sheltering effect of existing vegetation or structural protection. Additionally, the initial bed level is low as it is further offshore, drastically increasing the inundation time compared to locations in front of Dike 3 before construction of the fourth dike. This makes it uncertain whether young mangrove seedlings would be able to establish and survive. Furthermore, although there are no significant changes between the configurations under calm sea state conditions, flow velocities increase in the area in front of Dike 4 during storm conditions, increasing the effects of erosion in this area. This further reduces chances for young mangroves to settle outside of Dike 4.

In addition to the effect on mangroves, reduced tidal inflow for the enclosed area will affect the existing aquaculture areas located behind Dike 3. With lower water levels and weaker tidal exchange, less seawater will reach the ponds and channels, which may lead to reduced water renewal and possible shortages in dry periods. As a result, both water quality and productivity of aquaculture farms could decline.

It should also be noted that a major share of sediment entering the area originates from the large river Đáy. The configuration and orientation of the fourth dike will therefore strongly influence how and where this sediment settles. Areas directly in front of the river outlet are likely to experience

continued sediment accretion and potential land formation, whereas sheltered zones along the inner dike alignment may see reduced sediment supply. Consequently, the shape and placement of Dike 4 not only affect tidal exchange and wave exposure, but also play a major role in determining future sediment pathways and opportunities for land acclimation.

While the completion of the fourth dike may locally reduce hydraulic stress on struggling mangroves, it will also limit sediment supply and tidal connectivity for the enclosed area. These combined effects are expected to cause a gradual decline in mangrove health inside the dike, an initial low potential outside it, and additional pressure on aquaculture activities further inland.

6.1.2. Effects on Social, Economic and Management Aspects

As stated in several interviews in Appendix C, the main reasons for finishing the fourth dike are land reclamation and coastal protection. This land can be used for numerous purposes like mangrove forests, aquaculture ponds, mixed mangrove aquaculture and agricultural land. This illustrates the challenge of trade-offs. In the long term, the province and local authorities have to choose between land users and have to determine their long-term goals, like sustainability, economic benefits, livelihood possibilities and maintenance costs. Also, the dike will increase flood safety for the newly reclaimed land and thus reduce damages due to floods. However, there are also concerns about mangrove decrease and loss of biodiversity due to these patterns seen in the past. Additionally, mangroves offer protection against flooding, and a reduction in their numbers could lead to increased flood damage.

Eventually, depending on the decisions that are going to be made, both the area of mangrove forest as the area of aquaculture ponds can either increase or decrease. This will determine what the effects on the criteria in the system diagram (carbon storage, damages due to floods, economic benefit of mangrove ecosystems and aquaculture profitability) will be.

Finally, an interesting development would be a potential fifth dike ring. The river will continue to transport sediment, which will result in larger mudflats. Eventually, even more land could be reclaimed and the process of building dikes could proceed. What the area looks like in a few years will depend on decisions made regarding these potential future developments.

6.2. Interventions

To mitigate the negative effects of the dike on mangrove health, several interventions could be implemented in Kim Đông. To identify which interventions could work best in the current coastal system, different alternatives are compared with each other, using a multi-criteria analysis (MCA). With the results of the MCA, trade-offs are discussed, as well as the implementation process of the alternative.

6.2.1. Alternatives

Based on the described coastal system of Kim Đông and its challenges regarding the construction of the fourth dike on mangrove health, governance and institutional frameworks and development goals (both sustainable as economical), several alternatives have been developed to address these issues. To support this, a morphological chart (Table 6.1) was initially created, which outlines the key problems and potential methods through which they could be resolved. In this chart, the key problems are positioned in the top row, with corresponding solution strategies listed below each category. All alternatives are categorised using a COCD box. This tool helps classify ideas based on their feasibility and originality. How this tool works in detail is explained in Appendix G.

There are three colours in which an idea can be placed. Blue ideas (safe and realistic) are relatively easy to implement within the current system and are often the safer options. Yellow ideas (original but unrealistic) are more creative and innovative, though they may not be immediately feasible. Red ideas (challenging but realistic) combine innovation and feasibility, making them the most valuable for further development.

As shown in the morphological chart, most of the alternatives are 'blue' and 'red' ideas. To assess feasibility, information from the Delft3D model, interviews, the local survey, and literature is combined. The main bottlenecks for implementation include limited financial resources, fragmented responsibilities between administrative levels, and complex approval procedures under the hierarchical governance structure of Vietnam. Additionally, restricted access to border zones and limited local technical capacity

Table 6.1: Morphological Chart – Mitigating the Impacts of the Fourth Dike in Kim Đồng

1. Reduced Tidal Connectivity & Water Quality	2. Mangrove Loss	3. Inefficient Governance	4. Weak Community Involvement	5. Economic Pressure from Aquaculture	6. Security & Research Restrictions
Controlled tidal exchange systems (adjustable gates)	Formal leasing policy (long-term rights)	Clarify institutional procedures	Raise payment for mangrove ground	Sustainable aquaculture certification	Clarify border procedures for research/tourism
Operation plan for gates	Setback zones for future landward migration	Co-management framework	Eco-tourism micro-projects	Mixed mangrove-aquaculture	Research access corridors
Sediment nourishment in front of dike	Replanting native mangroves in degraded zones	Integrate mangrove management into provincial coastal plans	Mobile app for monitoring	Payment for ecosystem services (PES)	Remote sensing drones for monitoring
Floating bioremediation platforms	Mangrove corridors between patches	Legal pilot area for flexible regulations	Technical training and awareness programmes. Water treatment and sediment recycling	Defence–environment dialogue platform	
Digital flow monitoring system	Blue Carbon programs	-	Village-level awards	AI-supported farm optimization tools	-
Legend Safe and Realistic Ideas Challenging but Realistic Ideas Original but Unrealistic Ideas					

make it difficult to execute certain interventions. These factors are taken into account when determining which alternatives are most realistic for further evaluation in the multi-criteria analysis. In Appendix G, the different alternatives and why they are feasible or not are explained in more detail.

As explained earlier, the red alternatives are original and progressive but still realistic. Therefore, the focus lies on those alternatives when deciding which will be analysed in the MCA. Four interventions are selected because they represent a balanced mix between technical, ecological and governance-orientated measures, while directly addressing the main challenges identified in the system analysis, such as reduced tidal connectivity, loss of mangroves, and weak coordination between stakeholders. The selected interventions address multiple alternatives simultaneously, combining ecology, hydrodynamics, social structures and governance.

In addition, one blue alternative is included. Although not yet implemented, it appears to be highly feasible and promising within the local context, making it valuable to compare alongside the more innovative options and serving as a realistic benchmark.

The four chosen interventions are listed below:

1. Adaptive Gate Management

This intervention combines the installation of sluices with an operation plan for gate management. The Delft3D model results indicate that controlled tidal exchange is needed to improve hydraulic connectivity and water quality, and to support sediment transport. It is considered a technically realistic and cost-effective (blue) solution because there are also sluices in all the other dikes. The management of the dike can also quite easily be established. The gate management supports both aquaculture and mangrove health, as both need specific hydrodynamic conditions. The intervention directly targets the most urgent hydraulic imbalance caused by the fourth dike.

2. Mangrove Co-management with Economic Incentives

This is a combination of two interventions. It integrates the formal leasing policy with a co-management framework and payment for ecosystem services. The conservation of mangroves is linked to economic benefits for the local community, making mangrove protection financially attractive. Local households will receive long-term user rights for mangrove areas under the condition that they manage and protect the areas. In return, they can benefit from economic incentives such as direct payments, but also from revenue from mixed mangrove-aquaculture or tourism. This gives communities a direct economic incentive in maintaining healthy mangroves rather than converting them to intensive aquaculture ponds. This intervention could prove very useful, especially in the context of the fourth dike, since finishing the dike will lead to new land being claimed and reallocated. By providing co-management arrangements between authorities and communities and leasing rights, it will be ensured that this land is used in a

way that balances both economic development and ecological restoration. Finally, this intervention will enhance both governance efficiency and community participation, as it creates a shared responsibility between authorities and local residents for managing mangrove areas within the newly enclosed zone.

3. Sustainable Aquaculture (Eco-certification)

Both mangrove protection and local livelihoods are supported by promoting mixed mangrove-aquaculture in combination with eco-certification schemes, as further explained in Chapter 3. By upscaling mixed mangrove-aquaculture, water filtration and carbon storage are maintained, while providing access to premium markets for aquaculture products, increasing the economic benefit. Because land allocation after building the fourth dike is uncertain, land can be allocated to mixed mangrove-aquaculture to combine mangrove health with economic benefit. This also results in eliminating the negative feedback loop in the system diagram, where an increase in aquaculture results in more chemical input, which negatively influences on mangroves, since mixed mangrove-aquaculture uses no or fewer chemicals.

4. Digital Monitoring and Data Sharing Platform

A digital platform for mangrove monitoring can improve transparency and data accessibility. Additionally, it can cause better compliance and understanding between different stakeholders if they all have access to the platform. The platform can provide real-time data for decision-making and thus create a bridge between researchers, (local) authorities, companies and communities. The data shared could include information on mangrove health (species distribution, width of the mangrove belt), hydrological parameters (salinity, water level, sediment and tidal exchange). It could also show land-use changes over time from satellite imagery or field measurements. By combining both, the platform would help track how the fourth dike affects both ecological and hydraulic processes. The intervention is a technologically demanding intervention, but could be very promising in the long term, especially when looking at adaptive governance in the uncertain future where climate change plays a big role. Ultimately, the platform could also provide data which can be used to create financial incentives for conservation by using carbon credit systems. This links local restoration with global climate goals. The hydraulic effects can be modelled, however, the real impact on mangroves will only become clear after monitoring the area. To achieve this, a digital platform could assist well.

6.2.2. Multi-Criteria Analysis

To compare the different interventions proposed for Kim Đông, a Multi Criteria Analysis (MCA) is conducted. A Multi-Criteria analysis is used because it provides a structured and transparent way of evaluating how well each intervention performs across multiple criteria. Since the impact of the fourth dike involves both physical and institutional components, the MCA allows for the integration of quantitative model results while using qualitative governance insights.

To carry out a Multi-Criteria analysis, the criteria first need to be identified. This identification is based on the information collected in the system analysis in Chapter 3. These criteria represent the priorities of the relevant stakeholders within the coastal system, shown in Chapter 3 in both the Power-Interest grid (Figure 3.21) and the Formal Chart (Figure 3.22).

The selected criteria together ultimately determine how good interventions score for mitigating the negative effects of the fourth dike in Kim Đông. Costs, system integration, and implementation complexity indicate whether an intervention is realistic within the system's boundaries and its capacities, which is of importance to the decision-makers. Sustainability and effectiveness show whether it truly contributes to mangrove protection, while it is equally important that the intervention causes minimal disturbance. Those criteria are of importance for all stakeholders involved. Adaptability and durability reflect the ability of an intervention to adjust to a constantly changing system, both now and in the future. Finally, scalability and the local economic benefits are essential for creating support and ensuring broader impact. With all interventions scored using these criteria, a well informed decision can be made about which intervention might be the best one for this specific system.

In the MCA, each criterion is assigned a weight that reflects its importance to the province of Ninh Binh, the main stakeholder for whom the recommendations are intended. If a criterion has sub-criteria, these are also scored based on their importance, adding up to a total of 100%. The overall weight of each sub-criterion is then calculated by multiplying the weight of the main criterion with the importance score of the sub-criterion. Next, the interventions are compared against one specific (sub-)criterion and rated

on a scale from 1 (very poor) to 5 (very good). Finally, the weight of the (sub-)criterion is multiplied by the intervention's score, resulting in a weighted score. All these weighted scores are then aggregated to produce a final score for each intervention. The higher this final score, the stronger the intervention. The substantiation of all values in the MCA is further explained in Appendix G.

In Table 6.2 the final total scores for each intervention are set out. To simplify the table, the weights of the sub-criteria have been added up to show the total weight of the criteria, and the scores on the sub-criteria have been added up to show the final score on the criteria.

Table 6.2: Final MCA Scores per Intervention with Criteria Weighting

Criteria	Weighting	Adaptive Gate Management	Mangrove Co-management with Incentives	Sustainable Aquaculture (Eco-certification)	Digital Monitoring & Data Platform
Costs	0.18	0.36	0.72	0.61	0.43
Effectiveness	0.15	0.75	0.45	0.45	0.30
Sustainability	0.13	0.57	0.44	0.52	0.29
Implementation Complexity	0.12	0.36	0.12	0.48	0.36
Integration into the Coastal System of Kim Đông	0.11	0.31	0.43	0.40	0.42
Adaptability	0.09	0.18	0.36	0.27	0.45
Durability	0.08	0.32	0.08	0.24	0.40
Local Economic Benefit	0.07	0.30	0.50	0.40	0.20
Disturbance	0.04	0.14	0.20	0.14	0.20
Scalability	0.04	0.12	0.08	0.16	0.20
Total Weighted Score	1.00	3.41	3.38	3.67	3.25

The total scores of the four interventions are close to each other, but clear differences can be seen in Table 6.2. The digital platform has the lowest overall score. It does score good on durability, integration into the system and adaptability, but its impact is mostly indirect, which makes it less effective. Mangrove co-management scores a bit better. It scores especially good on social sustainability and economic benefit, but is limited by implementation complexity and durability, because introducing co-management and economic incentives requires large institutional, governance-related transformations. Adaptive gate management scores higher. It scores high on effectiveness and ecological sustainability but low on costs and on adaptability. Sustainable aquaculture has the highest score. It provides a good balance between economic, social and ecological criteria, and thus scores relatively high on many criteria. This makes sense because a mix of different disciplines often results in a good solution since it takes different important elements into account. To get to the final recommendations, a combination of all four could also be implemented.

6.2.3. Implementation Process

The implementation process of the different interventions is important to understand, since this process can show the feasibility of the intervention in the current system, who needs to take action and what the next steps are going to be. Different stakeholders need to coordinate with each other. Whether this coordination is effective will determine if the interventions can actually be realised in practice.

Adaptive Gate Management

Adaptive gate management can be implemented relatively early in the process by adding it to the construction plans of the dike. Since the other dikes in the Kim Đông area also have gates, this lies within the expected plans of the province. The main task, which makes implementation of the intervention more tricky, lies in setting up an operational management plan that balances flood protection with ecological flow. Setting up this plan requires coordination between provincial engineers and local aquaculture farmers, supported by continuous monitoring of water levels and salinity. Also, it could be that farmers require other hydraulic conditions than other stakeholders. Therefore, responsibilities of different stakeholders need to be communicated very clearly.

Mangrove Co-management with Economic Incentives

This intervention needs a stronger institutional framework, since multiple stakeholders need to work together in an iterative way. This should mainly be local authorities and the province in combination

with local communities. This intervention can be built further on the 2017 Forestry Law, which allows community-based management of mangrove plots (Pham et al., 2022). The implementation of this intervention can start with small pilot projects, where local residents can purchase a piece of land with mangroves or where they can earn money to look after it. This pilot could show what a good price is to be an incentive for local residents and how the lands are managed after giving responsibility. Provincial authorities would oversee the process, while the commune facilitates on-site coordination.

Sustainable Aquaculture (Eco-certification)

This intervention requires developing certification criteria, training local farmers and linking them to premium markets. The eco-certifications are provided through a collaboration between the province and NGOs. The government should support farmers through cooperatives or NGOs to teach them how to work in a mixed mangrove-aquaculture system. While this intervention sounds simple, there are risks. It can be difficult for farmers to change their business model, especially if they lack the right knowledge. Finally, institutional risks occur, such as checking aquaculture farms, providing eco-certification, and monitoring the farms. Responsibilities between stakeholders should be clearly defined.

Digital Monitoring and Data Sharing Platform

This intervention depends mostly on collaboration between local authorities, the province and research institutions. It could first be developed as a research-policy tool to improve transparency and data access and later expanded to a broader adaptive management platform on which the local community could eventually also join. Although technologically demanding, it could become a long-term governance instrument linking local action to national and international climate goals, which could also serve as an example for other countries that have similar ecosystems.

In short, while gate management offers the most direct and practical option, the other three interventions require institutional innovation. Combining them, starting with pilots and feedback, would provide both short-term impact and long-term resilience for Kim Đông's coastal system.

6.2.4. Trade-offs

The results from the Multi-Criteria Analysis show clear differences and also show which are the 'best' interventions and which are less feasible. However, none of the interventions are perfect, and each involves certain trade-offs that reflect the complex balance between ecology, economy, governance and practicality in Kim Đông. The trade-offs are listed below.

Adaptive Gate Management

Adaptive gate management addresses the hydraulic imbalances caused by the fourth dike and scores high on ecological effectiveness. It requires continuous operational management and maintenance, especially if it needs to be managed based on real-time data. This creates questions about who will be responsible for the gate management and who decides what gets priority: aquaculture or ecosystems. This increases both costs and the dependency on expertise. Therefore, the intervention is less adaptive and more demanding in the long term, as the whole system keeps depending on the gate management.

Mangrove Co-management

Mangrove co-management performs well socially and economically. It builds local ownership and provides direct benefits for communities. However, it depends heavily on coordination between stakeholders, which can be tricky in the current hierarchical system in Vietnam. The trade-off lies between empowerment and administrative feasibility. It is complex to implement and takes time to succeed.

Sustainable Aquaculture

Sustainable aquaculture represents a good middle ground between ecological protection and economic benefit, a key trade-off in the current system. It supports livelihoods and promotes environmentally friendly practices, but imposes new requirements on farmers through certification and monitoring. This creates tension between short-term profit and long-term sustainability, making it difficult for current aquaculture farmers to rapidly change their business model. Although it requires financial and institutional support, the intervention is feasible within the current system.

Digital Monitoring and Data Sharing Platform

The digital monitoring and data-sharing platform offers long-term potential for transparency and adaptive governance but has limited immediate ecological or social impact. It requires a lot of data which is currently already hard to obtain, and while the long-term effects are promising, its high implementation complexity and initial costs make it unsuitable as a stand-alone intervention.

Overall, the MCA and implementation process do highlight that no single intervention can fully mitigate the negative effects of the fourth dike. A combination of measures could provide the effects needed in the current system. The main trade-off lies between technical and institutional feasibility and social inclusiveness. Interventions that are easier to implement often provide fewer long-term benefits, whereas more inclusive or innovative measures require greater institutional effort and coordination.

6.3. Intervention Design

To translate the research findings into visual and practical next steps, a design is developed for the province of Ninh Binh. This builds further on the results from the system analysis, modelling and multi-criteria assessment. It illustrates how different interventions can be combined to mitigate the negative effects of the construction of the fourth dike while maintaining a balance between flood protection, ecological restoration and local livelihoods. This also relates back to the main research question: 'How can the social, ecological and hydraulic effects of the completion of the fourth dike be addressed to support both sustainable management of ecosystems and the development of the area?'

To do this, a visual roadmap is created first (Figure 6.3) to outline the recommended next steps for the coming years. It shows short-, medium-, and long-term priorities. This roadmap is complemented by an explanatory video that summarises this research, its main findings and the final recommendations. Together, these two products aim to support stakeholders in understanding the problems and proposed recommendations. It translates the outcomes of the research into concrete and coordinated action for the sustainable development of the Kim Đông coastal zone.

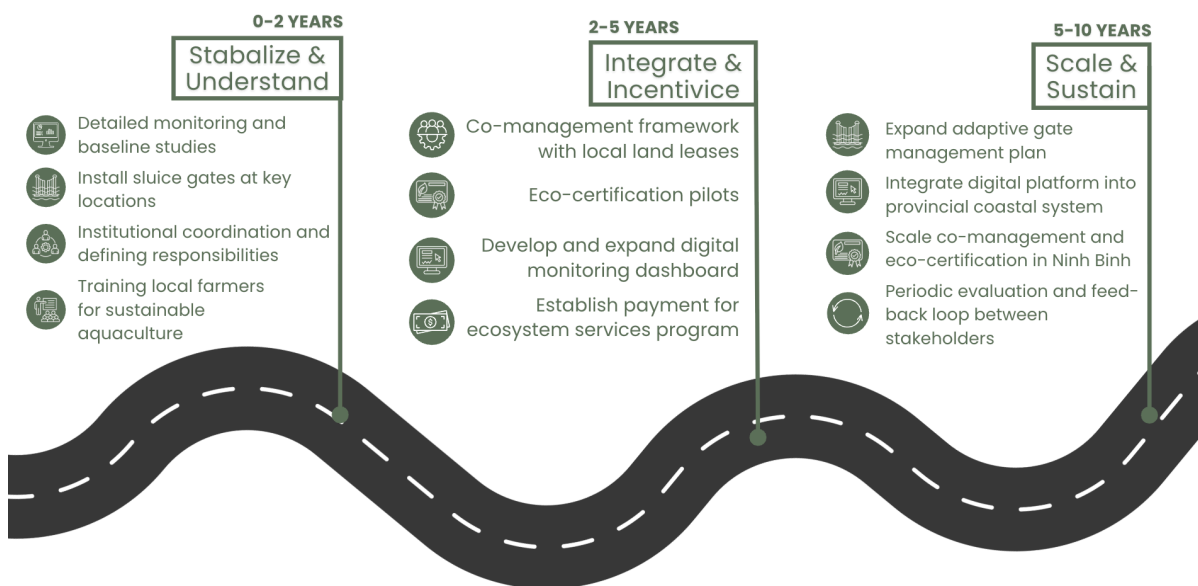


Figure 6.3: Roadmap for the Province of Ninh Binh to Mitigate Negative Effects of the Fourth Dike

In the roadmap, an effective combination of the four interventions is presented, showing once again that no single measure can address all challenges on its own. The first steps focus on the more straightforward actions, which can be implemented relatively easily. After these initial steps, more complex measures can follow, such as adjustments in governance structures, institutional arrangements, and pilot programmes. In the long term, these efforts can evolve into new institutions, management frameworks, a digital monitoring platform, and a continuous feedback loop.

7 | Conclusion

This research investigated how the completion of Dike 4 (Binh Minh 4) will affect the social, ecological and hydraulic dynamics of Kim Đông, and how these effects can be addressed to support both sustainable ecosystem management and economic development. The results show that the dike will significantly alter the area's hydrodynamics by reducing tidal exchange, changing sediment transport, and modifying flow velocities. These shifts directly affect salinity, nutrient circulation, and sediment, factors that are crucial for maintaining healthy mangrove systems. Moreover, the new land created by the dike will need to be allocated carefully, as poor management could disrupt the balance between land use, water movement and ecosystem functioning, reducing mangrove resilience and local livelihoods.

The system analysis revealed that Kim Đông depends strongly on aquaculture, faces rapid land-use change, and operates under a hierarchical governance structure with many stakeholders. Healthy mangroves provide crucial benefits like carbon storage, coastal protection and income generation, which are all closely linked to hydraulic functioning. The system diagram highlights these interconnections between mangrove health, livelihoods and climate goals. However, conflicting priorities between economic development, sustainability and climate adaptation make it difficult to manage these connections effectively, especially given the limited data and technical capacity for adaptive management.

Hydrodynamic modelling confirmed that Dike 4 reduces tidal exchange and flow energy inside the dike, which may slow water exchange and lower sediment input. These hydraulic effects can limit mangrove growth and degrade water quality, which is negative for both mangroves and aquaculture. Field observations, however, showed that mangrove density increased in some areas after partial dike construction, possibly due to local sedimentation patterns and changing flow conditions. Yet, whether this trend will continue depends strongly on long-term hydrological behaviour, sediment balance, and future management decisions. This trend may also be influenced by land-allocation policies and external environmental projects that prioritised mangrove restoration over aquaculture, in contrast to what can be observed behind Dike 3. This underlines that hydrodynamic and policy dynamics both determine ecological outcomes. Continuous monitoring of both physical and institutional changes is therefore essential for informed, adaptive decision-making.

To answer the main research question, *How can the social, ecological and hydraulic effects of the completion of the fourth dike be addressed to support both sustainable management of ecosystems and the development of the area?*, several interventions were identified, of which four were explored to minimise negative impact of the fourth dike: adaptive gate management, mangrove co-management with incentives, sustainable aquaculture certification, and a digital monitoring platform. The multi-criteria analysis indicated that no single intervention can solve all challenges. Still, sustainable aquaculture, co-management, and economic incentives stand out as promising combinations that link ecological restoration with socio-economic benefits. Adaptive gate management and the digital platform could support this by optimising tidal flow behind Dike 4 and improving coordination and transparency between stakeholders. Combining these interventions can form a balanced strategy for the province of Ninh Binh, as outlined in the roadmap describing specific next steps.

In conclusion, sustainable development in Kim Đông depends on maintaining tidal exchange to preserve mangrove functioning and water flow to existing aquaculture, involving local communities through economic incentives, transitioning toward sustainable aquaculture, and ensuring transparent, data-driven management. Integrated, adaptive and participatory governance is therefore essential to achieve a resilient and balanced coastal system in the Kim Đông commune.

8 | Discussion

This research explored the effects of completing the fourth dike in Kim Đông on the coastal system. To do that, methodology steps like literature review, governance analysis, system analysis, hydrodynamic modelling and field-based observations were used. This chapter assesses the methods used for this research. Key insights are shared, the main limitations of the research are identified and lastly, recommendations for further research are made.

8.1. Key Insights

The research shows that there is a strong connection between hydrodynamics, ecology and governance in Kim Đông. Technical insights and measures can mitigate negative effects, but they only become effective when embedded in a strong institutional and participatory framework. This shows the complexity of the system and the need to coordinate with different stakeholders within the system.

Another important insight is that to achieve adaptability to the rapidly changing system, transparent data and knowledge is necessary. However, this is not yet the case for Kim Đông. A lot of data is unreliable and there have not yet been enough measurements to draw solid conclusions. To achieve long-term adaptive governance and knowledge exchange in the future, this should be a key focus point.

8.2. Limitations

Several limitations affected the precision and outcome of the results and can be categorised into four main types: analytical limitations, model limitations, empirical limitations and contextual limitations.

8.2.1. Analytical Limitations (Literature and MCA)

The available literature on some topics was very limited or only accessible in Vietnamese, which made it difficult to draw strong conclusions about key aspects such as mangrove submersion tolerance and the specific decision-making processes in Kim Đông. These knowledge gaps required us to make several assumptions to continue the analysis.

In addition, the MCA introduced a certain degree of subjectivity through the weighting of criteria and sub-criteria, even though these were designed to reflect stakeholder priorities. This was necessary because it was not possible to interview representatives from the Ninh Binh authorities directly. Different weight distributions could have influenced the final ranking of interventions, creating some uncertainty about which measures would be most suitable for Kim Đông. For that reason, a combination of interventions was selected as the final recommendation to balance this uncertainty.

8.2.2. Model Limitations (Delft3D)

The conceptual Delft3D model relied on multiple assumptions due to limited data availability, which drastically increased the uncertainty of the outcomes.

- **Grid:**

In Delft3D, often a finer hydrodynamic grid and a coarser wave grid are used to better resolve the FLOW and WAVE modules. However, in this study, a single computational grid was used for both the modules to ensure consistency and reduce computational effort. Although this approach simplifies the model setup, it likely reduced the accuracy of the simulated wave field.

- **Bathymetry:**

The bathymetry was interpolated and extrapolated using a dataset consisting of only seven cross-shore measurements and two offshore points determined using fishing maps. This introduces uncertainty in the bathymetry, since almost the entire bathymetry is an estimation of the real situation. Furthermore, channel depths were assumed to be around 1.5 m at all places, which can vary locally. Lastly, the mangroves were not included in the simulations. This leads to an

underestimation of the bottom roughness, since vegetation increases this value. Additionally, mangroves dissipate wave energy and introduce drag in the flow, which could alter the flow patterns and significant wave height in the model.

- **Dike Configuration:**

The shape of the fourth dike was determined based on a conversation with Mr. Tri C.2.7, who has contributed to the design and configuration of the first segment of the fourth dike. However, this may not fully represent the final construction plan. Furthermore, the dimensions and locations of the two gates are based on existing gates and the locations of Dike 3. The number of gates in the fourth dike and their dimensions and locations could differ from the final design.

- **Boundaries:**

The boundary conditions in the model are based on several assumptions. Firstly, the offshore water level boundary at P3 is forced to use measurement data retrieved from Gate 10, assuming this signal represents the open sea tidal conditions, which could underestimate the real offshore amplitude. Furthermore, since there was only one water level dataset, the boundaries P2 - P3 and P4 - P1 are defined as Neumann boundaries with identical gradients, although in reality, these gradients differ. Especially the boundary between P4 and P1 is highly doubtful, as in the North a land boundary is present. This could alter flow patterns inside the model compared to the real situation. Additionally, the river inflow into the model domain is estimated to be 10% of the total discharge of the Đáy River, which likely underestimates the actual variability in flow velocities and water levels near the river mouth. Also, the wave boundary conditions are based on ERA5 satellite data, which have uncertainties in nearshore wave direction and height.

- **River Inflows:**

There are three rivers discharging into the bay: the Đáy, Chính Đại, and Lèn rivers. None of these rivers have measured discharge data. The previously mentioned Đáy River discharge is based on a simulation of the entire Red River Delta system during literature review. The inflows from the Chính Đại and Lèn rivers were not included due to a lack of reliable data and their relatively smaller size. These simplifications and assumptions likely result in an underestimation of total freshwater input and local circulation nearshore, particularly during the wet season, when the discharge of all three rivers is significantly higher.

- **Wind:**

Wind forcing was simplified. Although return-period wind speeds were used, the directions were assumed to be equal to that of the waves. This may overestimate wind effects from that direction.

- **Calibration & Validation:**

The calibration and validation of the model were limited by data availability, with only a single water level dataset in April 2025 used for calibration and one dataset in October 2025 at a different location for validation. Normally, both calibration and validation rely on multiple datasets of the same parameter under comparable conditions to make a strong calibration and validation of the modelled parameters. In this case, the calibration and validation are weak, preventing a reliable assessment of the model's accuracy.

Overall, the Delft3D model provides a useful conceptual representation of the hydrodynamic and wave conditions in the study area, but the numerous assumptions introduce significant uncertainty.

Simplifications and assumptions in the boundary forcing, bathymetry, and river inflows, together with limited calibration and validation data, constrain the model's predictive accuracy. Consequently, the results have been interpreted in a comparative rather than an absolute sense, focusing on relative differences between scenarios rather than exact quantitative predictions.

8.2.3. Empirical Limitations (Interviews and Survey)

The interviews and survey resulted in important qualitative insights, but there are quite some limitations that occurred when conducting both the expert interviews as the surveys.

- **Expert interviews:** Most expert interviews were conducted with researchers and academics, as they were willing to participate and could communicate in English. Only one interview was held with a representative from the local authority, which proved quite challenging. The person did not speak English, and the interview had to be conducted in Vietnamese under time constraints and

in an informal setting, meaning it could not be recorded. As a result, input from local authorities and other stakeholder groups in Kim Đông was very limited, making it difficult to fully capture their priorities and perspectives alongside those of the research community. The understanding of higher-level governance dynamics were therefore restricted.

- **Local community survey:** The survey could not be conducted by our team directly and was instead carried out by our supervisors. As a result, the MDP team had no direct insight into how the survey process took place, how respondents were approached, or how they interpreted and reacted to the questions. This limited our ability to evaluate the quality and consistency of the collected responses. Additionally, one page of the survey (25%) was not completed by any participant. The overall number of respondents was also low (18), which makes it difficult to draw any generalised conclusions about the broader community. Therefore, the survey results were mainly used to gain a basic understanding of local demographics and to get an initial impression of how a small group of residents perceives mangrove management and coastal change.

Lastly, it is important to acknowledge the recent governance reforms and how they interacted with the challenges of conducting expert interviews. These reforms were both an advantage and a limitation for the interviews. On one hand, understanding the informal decision-making processes was crucial, yet this could only be done through in-depth conversations with experts and officials. On the other hand, these informal practices may have needed to be redefined or re-established within the new administrative context. As a result, it was not possible to draw firm conclusions about how governance processes in Kim Đông currently function in practice.

8.2.4. Contextual and Practical Limitations (Fieldwork and Governance)

Fieldwork in Vietnam turned out to be quite challenging. It was affected by both logistical and institutional obstacles, such as restricted access to coastal zones, delays in obtaining permits, and the need to coordinate with multiple authorities. These factors limited the available time in the field and created uncertainty and delays throughout the process. Collaboration between the universities and local authorities was essential for conducting the fieldwork but proved to be very time-consuming. The hierarchical nature of the governance system also made open discussions difficult. As a result, parts of the fieldwork could not be carried out by ourselves and had to be completed by our supervisors instead. This led to some unclear data and, in certain cases, results that could not be used. Altogether, these contextual and practical constraints inevitably influenced both the data collection and the way the findings were interpreted.

8.3. Recommendations for Further Research

While these limitations introduce uncertainty, there are also promising opportunities for further research. They are listed below:

One of the most important recommendations is improving the data availability and the frequency of measurements. This includes verifying the bathymetry model used in this research, as it has a major influence on simulated depths and currents, and adding more measurement locations for calibration and validation. Offshore measurements should be taken to better define boundary forcing and wave conditions, while nearshore data along the third dike are needed to assess tidal propagation and flow velocities. This can be realised through participatory monitoring, drone mapping and more frequent measurement campaigns altogether. Additionally, the effect that mangroves have on water level, flow and wave dissipation can be tested with different modelling software such as SWASH to also include local effects in the hydrodynamic analysis. With this approach, ecological predictions will be more realistic. This could be done either by Vietnamese researchers only, or in collaboration with other countries like the Netherlands to share knowledge and practices.

From a modelling perspective, future studies should adopt separate grids for the FLOW and WAVE modules, with a finer hydrodynamic grid and a coarser and more extended wave grid. This could lead to more realistic computations of the WAVE and FLOW fields. Additionally, the FLOW grid should be extended to fully include the Đáy River and the north-western land boundary, allowing for a more realistic representation of the bathymetry and river inflows into the domain and its interaction with the coastal dynamics. By taking this approach, future models can incorporate wave refraction, sediment

transport and full river inflow dynamics.

Funding for pilot projects could also provide valuable insights for further research. Pilot projects which implement the interventions can show whether these interventions have the potential to work on a large scale or not. Also, pilot projects require less funding than changing policy right away. These pilot projects can help bridge the gap between engineering and social systems. Introducing these pilot projects does require strong collaboration between stakeholders though.

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A | Extended Background: Kim Đông Coastal System

This appendix provides background needed to interpret the Kim Đông coastal system. It first covers the evolution of the mangrove area and dike construction over time. Then, additional information about mangroves is given, together with their environmental and societal interactions. Finally, more information about the governance background of Vietnam and Kim Đông is given.

A.1. Mangrove Area Evolution

Figure A.1 shows a map of the area of Kim Đông between 1975 and 2018, particularly, it shows the construction of new dikes and how the mangrove area reacts to this.

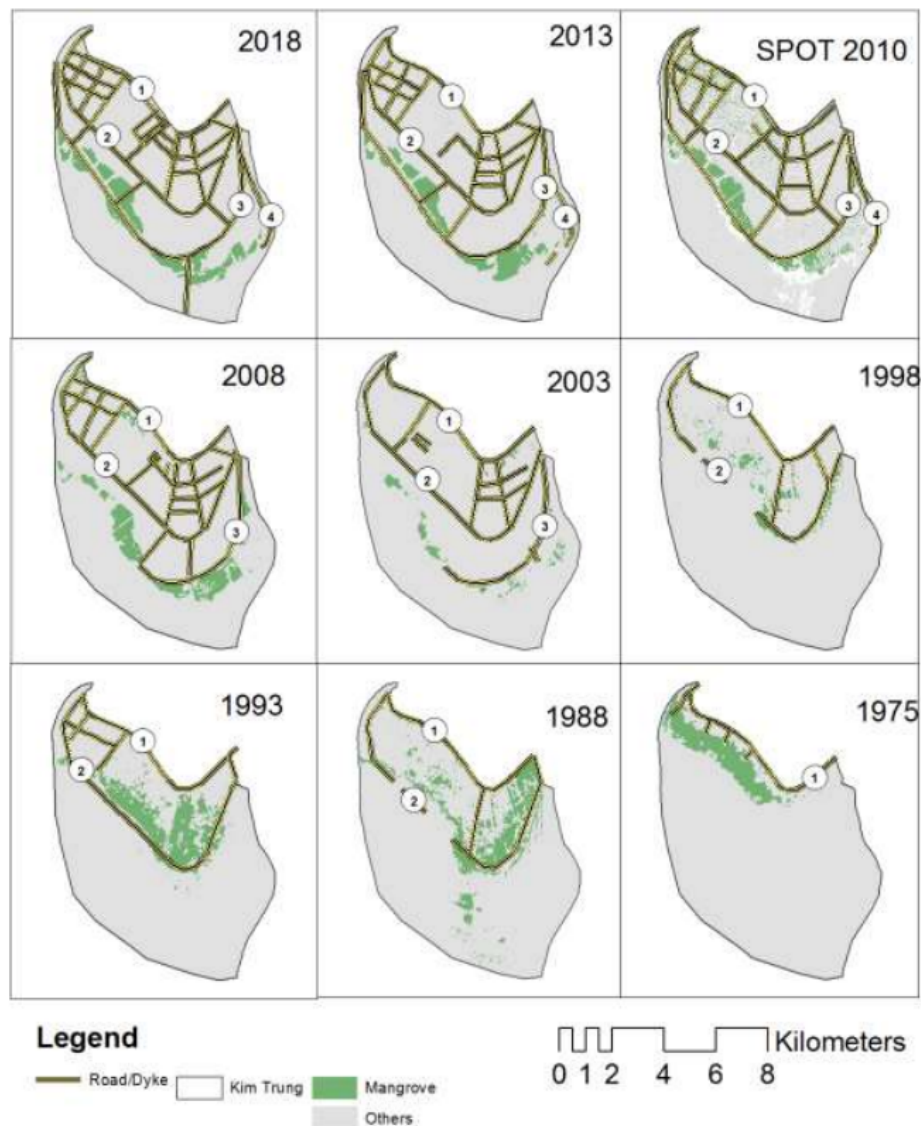


Figure A.1: Mangrove Area Evolution in Kim Đông between 1975 and 2018 (Q. H. Nguyen et al., 2019)

Following the construction of a new sea dike, mangroves located landwards of the dike progressively decline as the tidal cycle and sediment transport are reduced. Seaward of the dike, ongoing accretion at the river mouths creates new intertidal flats that are inhabited by mangroves. The net effect is a redistribution rather than a uniform loss, with the mangrove coverage being spread out more across the length of the outer dike.

A.2. Mangrove Ecology

Mangroves are (sub)tropical forests that reside in the tidal region along sheltered shorelines. There are around 69 species of mangrove trees, all of which are adapted to loose and wet soils, a saline environment and periodic tidal submergence. It is important to note that mangroves do not actually prefer saline water; the reason mangroves are found almost exclusively nearshore is that the location provides a competitive advantage over other plants. Most mangrove species can survive in freshwater conditions but are often outcompeted further inland by truly freshwater species (Marchand, 2008).

One of the most characteristic features of mangroves is their complex root system, which is adapted to oxygen-poor and loose soils. The network of roots dissipates the energy of the water, which offers protection against extreme storms and reduces erosion. By slowing the movement of water, it also promotes land formation as sediments settle and accumulate at the bottom (Marchand, 2008). Understanding these features is important when assessing the protective capacity of mangrove ecosystems.

Mangrove forests are among the most carbon-rich forests in the tropics, containing on average 1 023 Mg carbon per hectare, which is two to three times as high as conifer forests (Daniel et al., 2011). It is estimated that mangrove deforestation contributes up to 10% of global emissions, while mangrove forest area only accounts for just 0.7% of total tropical forest area (Giri et al., 2011; van der Werf et al., 2009).

Beyond their carbon storage capacity, mangrove ecosystems are also vital for biodiversity, providing space for a variety of marine life, like birds, fish and crustaceans, acting as important nursery grounds (Vietnam News, 2024). They also provide nutrients and carbon to nearshore marine ecosystems such as coral reefs and seagrass (Granek, Compton, & Phillips, 2009).

This demonstrates the remarkable sustainability of mangrove forests. Despite their sustainable importance, mangrove forests face threats from various human activities. Historically, wood from mangrove forests has been used for construction and fuel. Aquaculture poses another major threat, being linked to both deforestation and overexploitation of fisheries resources (Alongi, 2002). Additionally, mangrove forests play a crucial role in mitigating pollution, with the ability to remove Nitrogen (N) and Phosphorus (P) from shrimp farming wastewater (N. Ha, The Anh, Thi Tuyet Thu, & Nhat Ha, 2025). Climate change also poses a threat to the survival of mangrove forests. Although mangroves are able to adapt to rising sea levels by migrating inland, a rapid increase in sea level and the limited space for inland migration will have a great impact on mangrove forests worldwide (Gilman, Ellison, Duke, & Field, 2008).

Globally, many restoration projects have failed because they focus on planting mangroves without first restoring the physical conditions required for their growth. Often, insufficient attention is paid to the hydraulic processes that shape the environment, such as sediment transport, tidal exchange, and salinity fluctuations (Lewis, 2005). These conditions not only determine where mangroves can grow but also how resilient they are to environmental stress. In Kim Đông, mangrove growth has been inconsistent, with varying coverage observed across different sites. Therefore, understanding the specific physical conditions of this area is important for the success of restoration efforts.

In the Kim Đông coastal zone, these ecological functions described above are particularly valuable. The commune lies along Vietnam's coastline, which is nationally affected by shoreline erosion, especially in deltaic and muddy coast areas (Phong, 2024). Here, mangroves act as a natural coastal defence system, buffering the energy of waves and tides (Vietnam News, 2024). Their dense root networks trap sediments and stabilise newly formed mudflats, which supports land reclamation efforts. In the past, these mudflats have been diked off three times, and a fourth dike is currently under construction.

Mangroves also contribute to the socio-economic sustainability of Kim Đông by supporting aquaculture activities. Additionally, mangrove forests in Kim Đông are fully capable of removing 100% of the Nitrogen and Phosphorus found in wastewater discharged from shrimp farms, offering significant ecological

and economic value (N. Ha et al., 2025). In addition, they contribute to carbon storage and climate regulation, which aligns with Vietnam's national adaptation priorities for coastal ecosystems and forest restoration (United Nations Development Programme (UNDP), 2024). These combined benefits make mangroves a key component of both ecological resilience and socio-economic sustainability in Kim Đông.

A.3. Environmental Drivers and Mangrove Response

To understand the dynamics of mangrove ecosystems in Kim Đông, it is essential to examine how climatic, hydraulic, and sedimentary processes interact with the mangroves. These environmental factors dictate habitat suitability, growth performance, and long-term resilience of mangrove forests. The evolution of the Kim Đông coastal system, as discussed in Chapter 3.2, highlights the changing landforms and hydrodynamic conditions over time, which have shaped the current state of the mangrove ecosystems.

The Kim Đông commune is situated in an area with favourable conditions for mangrove growth, due to its coastal location within a tropical monsoon climate. The presence of fine-grained mudflats, formed by sediment accumulation, alongside the influence of brackish water from nearby river deltas, provides an ideal environment for mangrove ecosystems. Furthermore, the area is relatively sheltered from open-sea waves by a headland and an offshore island, creating stable shorelines that offer favourable conditions for mangrove trees. The following subsections explore these key natural factors that influence mangrove development.

A.3.1. Key Environmental Factors

Climate and Seasonal Conditions

Vietnam lies within the tropical monsoon climate zone, which is characterised by distinct seasonal variations. The country experiences a hot, wet season from April to October, followed by a cooler, dry season from November to March. The average annual temperature is around 24°C and the average annual rainfall reaches 1 760 mm, with the heaviest rainfall occurring in August and September (V. K. Nguyen, Nguyen, Phan, & Nguyen, 2000).

During the monsoon season, the region is often subject to heavy rainfall, strong winds, and occasional typhoons, which can bring extreme weather conditions (Vinpearl, 2024). These seasonal weather patterns influence tidal dynamics. Increased rainfall causes higher river discharge and alters salinity levels, both of which can significantly affect mangrove ecosystems. Typhoons can also cause extreme storm surges, flooding, and erosion, further impacting the stability of the coastal zone.

The stable and warm temperature throughout the year due to the tropical climate in Vietnam is essential for mangrove survival. Freezing temperatures are lethal to mangroves, so the warm climate ensures their thriving. This temperature stability is a key reason why mangroves are found in tropical and subtropical regions (Alongi, 2008).

Location Influence

The project area in Kim Đông is located at the mouths of the Đáy, Chính Đại, and Lèn rivers, placing it within a river delta. This location provides ideal conditions for mangrove growth due to the constant flow of fine-grained sediments carried by the rivers. These sediments accumulate in intertidal zones, forming mudflats that are perfect for mangrove establishment (Gijssman et al., 2024).

The shores are also relatively protected from extreme open-sea waves by an offshore island and a headland, which shield the area from the open sea, allowing the mangrove roots to establish and anchor themselves. This can be seen in Figure A.2.

In addition to the rich sediment supply and wave protection, the project area benefits from brackish conditions created by the mixing of freshwater from the rivers and seawater from the coastal zone.

Water Conditions: Salinity

Mangroves thrive in brackish environments, where saltwater and freshwater mix, providing the ideal conditions for their growth. The fluctuating salinity levels in areas like Kim Đông create a suitable environment for mangrove species like *Sonneratia* and *Rhizophora*, which have evolved adaptations to



Figure A.2: Area Overview of Kim Đông

survive in such environments. The combination of fresh and saltwater, especially during tidal inundation, brings nutrients necessary for mangrove growth (Alongi, 2022).

However, saltwater intrusion due to changing weather patterns and tidal dynamics can stress mangrove ecosystems, particularly in areas affected by seasonal changes such as the monsoon season. This season results in increased salinity levels and fluctuating water levels caused by extreme storms and tidal changes. Mangroves are adapted to a specific salinity range, and fluctuations, but especially increases in salinity during saltwater intrusion can reduce their growth and resilience (Alongi, 2022).

A.3.2. Hydraulic Processes

The favourable environmental conditions in Kim Đông are shaped and sustained by four hydraulic processes that control how water moves, how sediments are transported, and how mangroves interact with their surrounding environment. These processes, including sediment transport, wave energy, tidal dynamics, and water flow, play a key role in sediment deposition, the frequency of mangrove inundation, and the exposure of mangrove roots to stress. The following subsections detail the key hydraulic processes governing mangrove dynamics in Kim Đông.

Sedimentation Transport

Sediment transport is one of the most important hydraulic processes influencing mangrove ecosystems, as it directly affects their development, health, and long-term survival. The continuous delivery of fine sediments to intertidal zones allows mangroves to maintain their elevation relative to sea level, to improve soil fertility, and to sustain the balance between land accretion and erosion.

The location of the project area at the mouths of the Đáy, Chính Đại, and Lèn rivers ensures high sediment availability, which has driven the natural expansion of the coastline and the formation of new mudflats suitable for mangrove development (Q. H. Nguyen et al., 2019).

The sedimentary conditions in Kim Đông, particularly the fine-grained mudflats with high sediment accretion, create an ideal environment for mangroves to grow. Mangroves are adapted to low-oxygen soils and can thrive in waterlogged environments where they anchor their roots. Fine sediment provides the stability and nutrients necessary for root establishment (Ruiz-Fernández et al., 2017).

According to Ms. Trần Thị Lợi (2025; Appendix C.2.2), researcher at Thuyloi University, it is emphasised that mangroves require this continuous input of fresh sediment, and that those located behind sea dikes gradually die off due to the lack of fresh sediments. This statement is supported by Nguyen et al. (2019), who explain that the construction of dikes restricts tidal exchange between ponds and surrounding areas, leading to water pollution and soil degradation. The lack of fresh sediments and reduced tidal water flow behind the dike cause toxic conditions. Litter decomposition depletes oxygen in the soil, resulting in an increase of the accumulation of toxic substances such as hydrogen sulphide (H_2S) and ferric hydroxide ($Fe(OH)_3$), which ultimately leads to gradual dieback of mangroves in the enclosed areas due to these toxic substances (Q. H. Nguyen et al., 2019). In Kim Đông, it is unclear if this is also the case, since there is no clear evidence of mangrove degradation solely because of the changing hydrodynamics because of the dike.

The dynamics of sediment transport are influenced by other hydraulic processes such as wave dispersion, tidal movement, and flow dynamics. These processes determine the distribution and deposition of sediment, directly impacting mangrove growth and stability.

Wave Dispersion

Mangroves act as natural buffers against wave energy, significantly reducing coastal erosion and protecting the land. The roots, trunks, and canopies of mangrove trees serve as roughness elements that dissipate incoming waves, reducing their intensity and preventing shoreline damage. The degree of wave attenuation depends on the type of mangrove species and the density of the vegetation.

During the mangrove restoration campaign in Kim Đông, four mangrove species are planted: *Sonneratia caseolaris*, *Sonneratia apetala*, *Bruguiera gymnorhiza*, and *Rhizophora stylosa* (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2). Each of these species displays distinct root structures and hydrodynamic behaviour, influencing the way they dissipate wave energy and stabilise sediments (Table A.1).

Table A.1: Mangrove Species planted in Kim Đông and their Dissipative Effectiveness during Tidal Cycle (McIvor et al., 2012)

Species	Root Type	Effectiveness During Tidal Cycle
<i>Sonneratia caseolaris</i>	Pneumatophores (upright pencil-like roots)	Highly effective at low tide; attenuates short-period waves and enhances sediment deposition.
<i>Sonneratia apetala</i>	Pneumatophores (vertical air roots)	Most effective during low to mid-tide; supports rapid colonisation and sediment build-up.
<i>Bruguiera gymnorhiza</i>	Knee roots (arched above-ground loops)	Provides moderate damping at mid-tide; stabilises soil and traps fine sediments.
<i>Rhizophora stylosa</i>	Prop roots (stilt-like supports)	Strong attenuation at low tide; stabilises exposed coasts and dissipates wave energy.

Mangrove roots, trunks, and canopies act as natural roughness elements that dissipate incoming wave energy. In addition to reducing wave intensity, wave energy attenuation also leads to sediment deposition. As the wave energy is dissipated, sediments suspended in the water column are allowed to settle, contributing to the formation and stability of mudflats that are essential for mangrove root establishment. This process not only supports mangrove growth but also helps create a stable foundation for other coastal ecosystems.

Flow Circulation

Water flow and current velocity are key drivers of sediment movement, erosion, and deposition within mangrove ecosystems.

In mangrove forests, however, the presence of roots, trunks, and canopies creates resistance to flow, reducing the velocity of water and increasing sediment deposition.

Mangroves enhance sediment accumulation by increasing drag, which slows down water flow and allows fine sediments to settle and accumulate. This is also explained by Stokes's law (Moran, 2018). This gradual deposition leads to the formation of stable mudflats, which support root establishment and

provide a solid foundation for further mangrove growth. The role of mangroves in stabilising sediments is vital, as it helps reduce coastal erosion and promote shoreline stability (Horstman et al., 2014; Quartel et al., 2007).

Tidal Dynamics

The tidal cycle also plays an important factor in shaping mangrove ecosystems. Tidal dynamics, including the frequency and amplitude of inundation, determine the exposure of mangrove roots to air and water, regulate salinity levels, and influence sediment transport.

Kim Đông, located in the Red River Delta, experiences a diurnal tidal cycle, with one high tide and one low tide every lunar day (approximately 24 hours and 50 minutes) (Trinh et al., 2020). This regular tidal movement influences the availability of oxygen to mangrove roots, as well as the salinity levels that mangroves are adapted to tolerate (Alongi, 2022).

Mangroves, however, cannot remain submerged for long periods, as their roots require exposure to oxygen for respiration. Prolonged inundation may lead to hypoxia in the root zone, limiting the ability to thrive (Alongi, 2022). Excessive flooding, particularly during extreme storms or due to altered tidal dynamics, can suffocate mangrove roots, leading to stress, reduced growth, or even dieback.

The tidal influence also plays a significant role in nutrient delivery and saltwater flushing, which are crucial for maintaining a healthy mangrove ecosystem. However, disrupted tidal flow caused by human interventions such as the construction of dikes can lead to impaired nutrient exchange and salt accumulation, which can stress mangroves and reduce their resilience (Q. H. Nguyen et al., 2019).

Understanding the tidal dynamics in Kim Đông helps identify areas of hydraulic stress and supports the evaluation of mangrove restoration strategies, such as reconnecting tidal channels that could restore a balanced tidal cycle for mangrove regeneration.

A.4. Societal Drivers and Mangrove Response

In this section, the societal interactions with mangrove ecosystems are mapped out. Besides hydraulic and environmental influences, people also have a major influence on how well the mangrove ecosystems perform in different areas.

A.4.1. Mangrove squeeze

When civil constructions are used for coastal protection and economic benefits, this can clash with mangrove preservation. The concept often recurring in these areas is called mangrove squeeze. In the Kim Đông commune this problem also occurs, because several dikes have been built to protect the coast and reclaim land for aquaculture use, ultimately squeezing out mangroves.

The practice of building dikes restricts the natural landward migration of mangroves, which is referred to as mangrove squeeze. When mangroves are blocked from expanding inland, and the mudflat is not wide enough, their natural buffer against coastal erosion and waves is reduced.

The stability of mangrove forests is closely linked to the shape of the underlying mudflat. Under natural conditions, mangroves typically develop on gently sloping, convex-up profiles that provide a relatively stable substrate (Figure A.3). However, when vegetation is lost due to the construction of a dike for land reclamation, this balance is disturbed. The absence of root structures that normally trap and stabilise sediment accelerates erosion, and the convex-up profile gradually transforms into a concave-up profile. When a dike (grey rectangle) is constructed for land reclamation, the mangroves in front of the dike are squeezed out, and the mangroves behind the dike can be exchanged for aquaculture ponds (Figure A.4).

As the bed deepens and the slope steepens near the shoreline, incoming waves can propagate further inland. This results in higher wave energy reaching the forest edge, which in turn causes more erosion and additional tree loss. The process thus reinforces itself: erosion leads to mangrove dieback, which further destabilises the profile, allowing even stronger hydrodynamic forces to penetrate.

Furthermore, research on mangrove belt stability suggests that there is a critical minimum width below which mangroves become unstable and cannot maintain their regenerative capacity. Although estimates

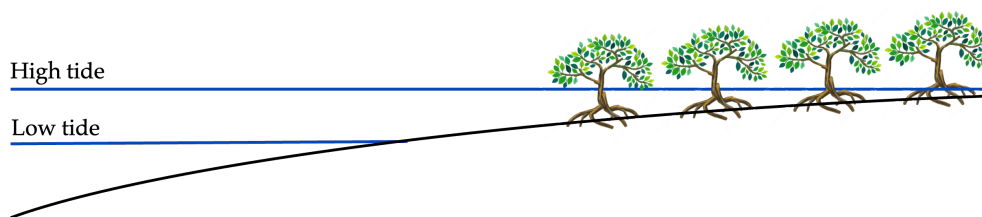


Figure A.3: Original Situation for Mangrove Forests showing a Convex-up Mudflat Profile

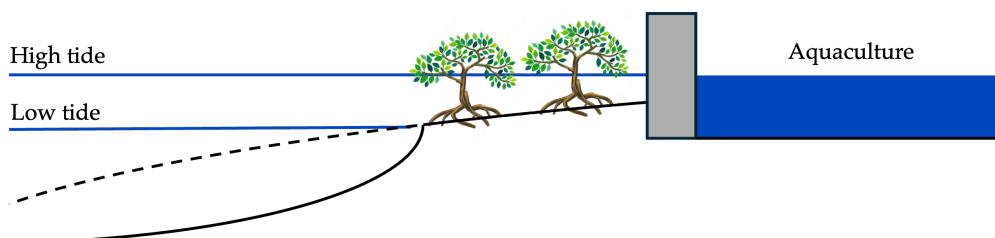


Figure A.4: Mudflat Changes into a Concave-up Profile due to the Presence of a Hydraulic Structure

vary in different environments, two studies in the Mekong Delta found a critical width of 80 metres along bank protections (Truong et al., 2017) and 140 metres for coastal wave dissipation (Phan et al., 2014). The larger the width of a forest, the more efficient the dissipation of waves and currents will be, offering both a successful seedling and sedimentary environment (Phan et al., 2014). Below this critical value, the mangrove belt will fail to provide sufficient resistance against strong currents, waves, and river discharge. The reduced width limits the sediment deposition process, leaving trees vulnerable and the shoreline exposed to erosion. This makes the mangrove belt even more unstable, eventually making it prone to collapse.

A.4.2. Economic Activities in Kim Đông

Aquaculture can depend on mangroves. Mangrove roots and sediments filter nutrients, organic matter and suspended solids. This results in clean water entering aquaculture ponds and reduces algal blooms and disease risk. Mangroves also provide detritus, plankton and organic matter from litterfall. Many shrimp and fish species naturally depend on these. Lastly, mangrove belts buffer ponds and farms against waves, extreme storms and erosion. Without this natural protection, aquaculture ponds near the coast often fail after a few years due to embankment collapse. Healthy mangroves reduce farm maintenance costs and increase pond longevity (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2).

The recent economic growth, resulting in aquaculture expansion and infrastructural development, brings both opportunities and challenges for mangrove management in Kim Đông, depending on the management strategy chosen. On the one hand, the expansion of aquaculture ponds is putting pressure on the space for mangrove forests. Ponds take up a lot of space for which mangrove areas can be cleared. Also, the wastewater from ponds can create eutrophication and sulphide toxicity in nearby mangrove creeks (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2). The economic benefits of aquaculture can therefore come at the cost of the mangrove ecosystem, reducing carbon storage capacity and weakening coastal protection. Additionally, the infrastructural development where roads are constructed and dikes are built further contributes to this land-use competition. Also, these developments can change hydrological conditions that are needed for mangroves to survive, such as the tidal flow (Interview Ms. Trần Thị Lợi, 2025; Appendix C.2.2).

On the other hand, the expansion of aquaculture can also be an opportunity for mixed mangrove aquaculture systems. Economic benefit can be gained from aquaculture while maintaining ecological functions, promoting the balance between both.

Additionally, tourism is expected to play a bigger role in Kim Đông in the near future. This proposes mainly opportunities for both the preservation of mangrove forests and the economy. Tourism is a

relatively new form of livelihood in Kim Đông, and thus, a lot of economic benefit can be gained, paired with mangrove preservation, since tourists will come to see the mangroves.

A.5. Governance Background

This appendix presents governance background based on literature analysis and several interviews. It begins with a background analysis of the governance in Vietnam, after which the institutional environment is described, followed by a detailed stakeholder analysis.

A.5.1. Background Governance Vietnam

The background analysis starts with the history timeline of Vietnam, after which the four pillars are explained and the political participation is described.

History Timeline

The formation of the first states in what is now North Vietnam dates back to around 3000 BC. Early agrarian societies were formed during the Phung Nguyen and Dong Son culture (Whitmore, n.d.).

Over time, Chinese dynasties gained influence in these states, imposing a more centralised form of governance. For more than 1000 years, Vietnamese were subjected to Chinese rule (the Bắc thuộc periods), which introduced imperial institutions, bureaucratic norms, tax systems and administrative models (Jamieson & Buttinger, 2025). Despite centuries under Chinese control, Vietnamese continuously resisted, preserving cultural and local governance practices. In 939, Ngo Quyen defeated the Southern Han at the Battle of Bach Dang River. This ended nearly a millennium of Chinese political domination (Whitmore, n.d.).

A period of stability entered Vietnam during the Ly Dynasty (first golden age). Thang Long (Hanoi) became the capital of a unified Vietnam. During the Ming occupation, China reoccupied Vietnam and attempted to impose Chinese customs. The rebellion led by Le Loi ended the occupation, starting the Le Dynasty (second golden age). Vietnam flourished economically, culturally and administratively. After 1539, the Trinh family ruled the north while the Nguyen controlled the south (Whitmore, n.d.). Their rivalry divided the country into two power zones. In 1802, the emperor Gia Long reunified Vietnam after centuries of division (Osborne & Duiker, 2025).

French colonialism disrupted this stability in 1857. They began conquering Vietnam and made it part of French Indochina. They introduced new legal systems, centralised administrative bodies, and altered land ownership structures. They transformed the way authority was organised and exercised. However, the French oppression also had a dark side, oppressing many Vietnamese people. This sparked resistance among the Vietnamese. Ultimately, Ho Chi Minh established the party to fight for independence from France. This was the beginning of the organised communist movement in Vietnam (Whitmore, n.d.). France was ultimately defeated at Dien Bien Phu in 1954, and Vietnam was split into two parts again (Osborne & Duiker, 2025). The North adopted a socialist model, with central planning and single-party rule, while the South was still more under Western influences (Osborne & Duiker, 2025).

In 1956, a devastating conflict between North and South Vietnam began. The North, supported by the Communist Party of Ho Chi Minh and the Vietcong (a resistance movement against foreign influence), fought to liberate the South and reunify the country, while the South was backed by Western countries, primarily the United States (Whitmore, n.d.). The war caused immense hardship and loss for the Vietnamese people, but it also demonstrated their determination and resilience (Spector, 2025). The war ultimately ended with the fall of Saigon. The US and its allies withdrew after South Vietnam's collapse. North Vietnam reunified the country under communist rule (Whitmore, n.d.).

North and South were officially unified under one central government in 1976, the Socialist Republic of Vietnam (Whitmore, n.d.). The communist regime implemented centralised economic control. However, in 1986, the Đổi Mới ("Renovation") reforms began and the governance model changed. Although political power remained with the CPV, there was a gradual decentralisation of administrative authority, introduction of market mechanisms, greater attention to legal frameworks, and greater space for local initiative (Giang, 2025).

Today, Vietnam operates in a socialist orientation with a market economy. The Communist Party continues to dominate politically, but the mechanisms of governance are more complex: multi-layered administration (central, provincial, commune), public administration reforms, legal reforms, and increasing pressures for accountability and citizen input in governance.

Four Pillars

The Communist Party of Vietnam remains the central political party. Under the central party, there are also many departments and organisations involved. The structure of the national government is illustrated in Figure A.5

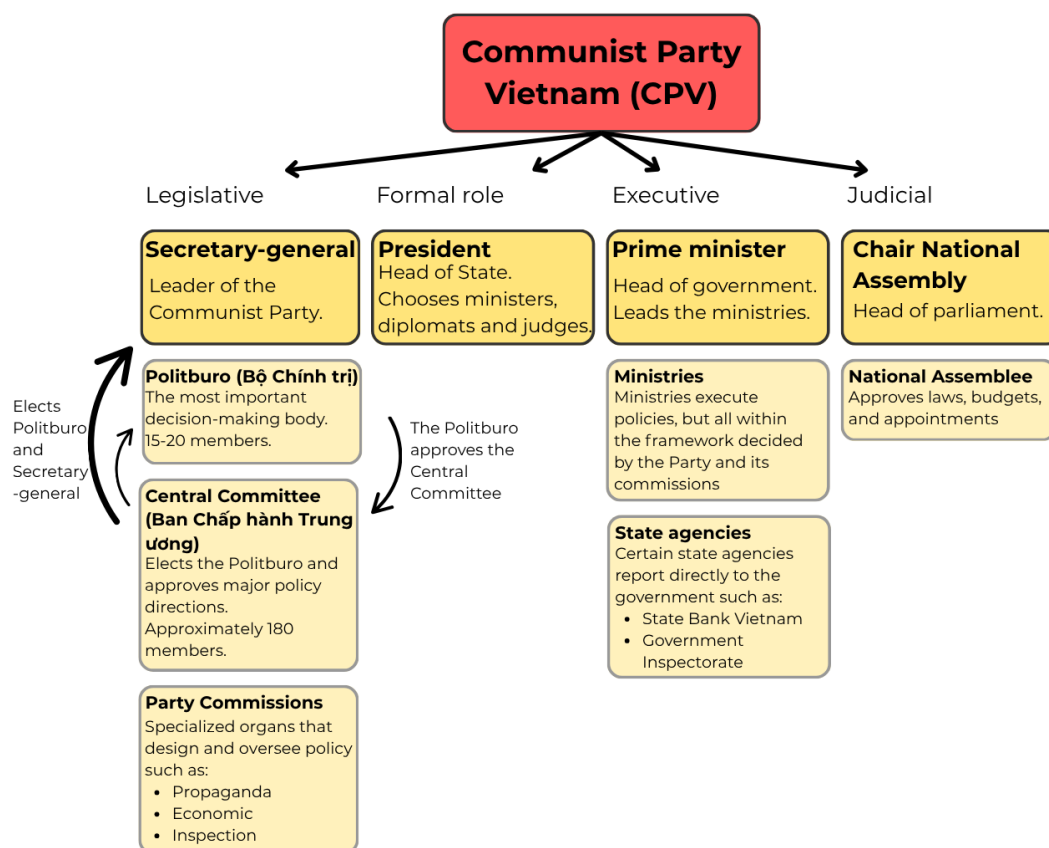


Figure A.5: Formal Governance Structure Vietnam

In Vietnam, there are “four pillars” (tứ trụ), which are the most powerful leaders in the country. These are the secretary-general (Tô Lâm), the president (Lương Cường), the prime minister (Phạm Minh Chính) and the chair of the National Assembly (Trần Thanh Mẫn). All four of them are also members of the Politburo (Stiftung et al., 2024). Most of the time, the secretary-general is the most powerful of all four. However, it depends on the people holding the positions if this is true. The secretary-general has leadership over the Politburo, Central Committee and the Party Commissions. The Politburo approves the Central Committee, which in turn elects the Secretary-General and the Politburo (Stiftung et al., 2024). Together, they set the direction for future policy. All other ‘pillars’ have to follow this course as well. The president holds mostly a formal role as head of state. This means he formally represents the country at foreign events or meetings, for instance. Formally, he chooses the ministers, diplomats and judges, but this has to be approved by the CPV as well. The prime minister holds the executive power. It is the responsibility of the ministries to make sure the direction the secretary-general and the commissions have set, is actually executed. Lastly, the chair of the National Assembly holds the legislative power. The National Assembly approves laws, budgets and appointments. In practice, they often just ratify Party decisions as candidates are pre-screened by the Party. Formally, the legislative, executive, and judicial powers are separated, but in practice, the CPV has the power over all three, though the power is still spread over four different people.

Besides the central government, there are also provinces and communes. They have, almost always, the same departments as the ministries and work directly with the policies the ministries, and thus the CPV, have come up with. All heads of government ministries, ministerial agencies and provincial party committees must be members of the Central Committee (Stiftung et al., 2024). Before July 1st 2025, there were provinces, districts and communes, way more ministries and a lot of other departments. However, Vietnam has implemented its largest administrative reform since reunification, consolidating provinces, abolishing districts and streamlining bureaucracy (T. H. Nguyen & Le, 2025). Vietnam had 63 provinces, which are now 34 provinces (T. Nguyen, n.d.).

As a result of this reorganisation, also described in 3, the Kim Đông Commune falls within Ninh Bình Province and now includes the project area. The previous 125 communes in this province have been reformed to 39 communes since August 1st 2025 (T. Nguyen, n.d.).

Political Participation

In Vietnam, elections are held every five years. They are meant to choose the people of the National Assembly and the local people's council (T. M. Nguyen, 2021). The next election for the 16th National Assembly and for the People's Councils at all levels will be on March 15th, 2026 (Vietnam Plus, 2025).

The consultation process to nominate candidates for the election takes a few steps and is fully coordinated by the Communist Party (Stiftung et al., 2024). Candidates are first nominated, then screened by looking into their background but also reconsulting people who know them well. After that, the CPV has to finalise the candidate list (T. M. Nguyen, 2021).

Once the list is approved, people receive the list of people in their commune they can choose from. Most of the time, there are as many candidates as seats, so the outcomes are predetermined. In conclusion, there are elections, but these are mostly formal and already predetermined by the CPV, thus a representative democracy.

A.5.2. Institutional Environment

Nature and the use of nature are important when it comes to mangroves. The laws regarding nature and use of nature can decide whether mangroves will have an environment to live in or not. The following formal rules are applicable in the Kim Đông area regarding nature and use of nature:

- **Vietnam Land Law 2024:** The Land Law is a comprehensive piece of legislation implemented by the national government, covering all matters related to land ownership. At the local level, people's committees in the communes are authorised to allocate land. In the Kim Đông area, the Department of Forestry (also a government institution) has the authority to allocate land which consists of protected forests like mangroves (Interview Dr. Tung Dao, 2025; Appendix C.2.4). In the case of mangroves, this authority can work both positively and negatively, as the government ultimately decides whether land is designated for environmentally sustainable use or for economic purposes. The Land Law also states that there is a quota on land ownership for households, and the commune's people committee has to see to it (Viet An Law, 2024).
- **Law on Forestry 2017 (No. 16/2017/QH14):** The Law on Forestry establishes that the state retains ownership of natural forests, with the authority to allocate forest land to organisations, households, individuals or communities. In the case of Kim Đông, this is the Department of Forestry. Thus, this also applies to mangroves, which are even classified as coastal protection forests (National Assembly, 2017). The law also prohibits illegal logging, deforestation, and changes in land use, such as the clearance of mangroves for aquaculture (National Assembly, 2017). However, when the government has allocated land to an organisation for planting mangroves, that organisation practically owns that land, and the law applies less strictly (Interview Dr. Tung Dao, 2025; Appendix C.2.4). Finally, the law encourages cooperation with international organisations in the areas of forest management and climate adaptation (National Assembly, 2017). In article 90 of the law, the state encourages organisations and individuals to expand international cooperation in forest protection, development, biodiversity conservation and response to climate change.
- **Decree 08/2022/NĐ-CP implementing the Law on Environmental Protection 2020:** In addition to the Law on Forestry, any project affecting mangrove forests or coastal wetlands must undergo environmental screening leading to registration, an environmental licence, or a full Environmental

Impact Assessment (EIA), depending on scale and risk. Works such as discharges, dredging, dike or road construction, aquaculture expansion, and tourism facilities must meet water-quality standards, maintain tidal connectivity, and avoid significant habitat loss; where impacts remain, mitigation and monitoring are mandatory. Appraisal and enforcement sit with provincial authorities (led by the Department of Agriculture and Environment), with public consultation and disclosure required (Government of Viet Nam, 2022; Viet Nam National Assembly, 2022).

- **Law on Water Resources 2023 (No. 28/2023/QH15):** Wastewater discharges are allowed under the Environmental Protection Law, but they must also fit within the capacity of the local water system so that mangrove wetlands do not get damaged. Significant abstraction of surface water or groundwater for aquaculture or visitor facilities requires registration or a water-use licence aligned with basin plans and environmental flow needs. The way sluices are used and the way water flows in and out of the ponds must keep good water quality, control salt levels, and maintain tidal connections that are important for healthy mangroves (Viet Nam National Assembly, 2023). In Kim Đông the regulation of water has to be done using the sluices and gates.
- **UNESCO Red River Delta Biosphere Reserve (2004):** The Kim Đông area lies within a UNESCO-designated biosphere reserve. The designation functions as ‘soft law’ (Soft law refers to guidelines, declarations, or principles that are not legally binding but can influence or shape legal and political practices). Destructive activities are prohibited in core zones. In buffer zones, activities (including aquaculture) may be licensed provided they do not degrade water quality, tidal connectivity or overall mangrove condition, and remain consistent with reserve management objectives (Ninh Binh Conservation Alliance (NBCA), 2025; UNESCO, 2025).

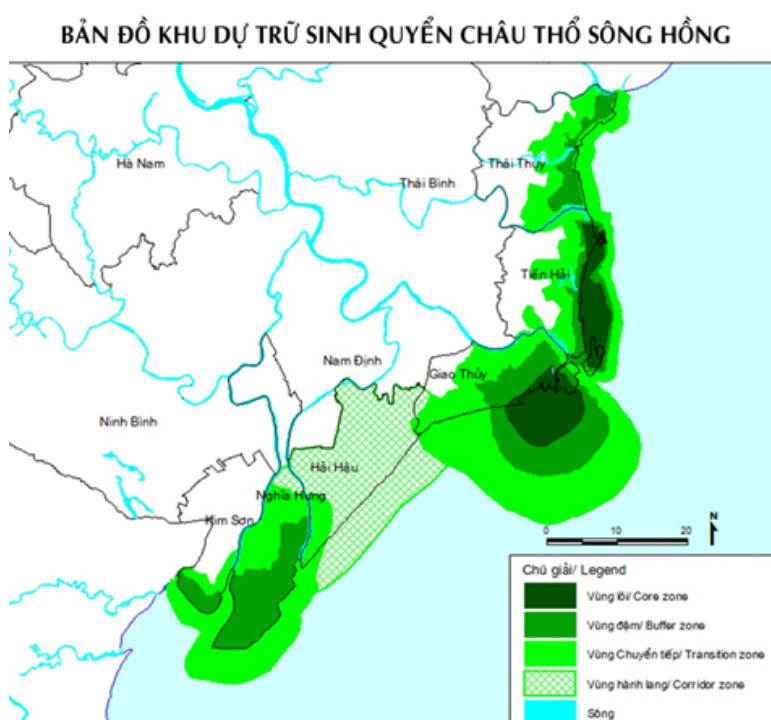


Figure A.6: Red River Delta Biosphere Reserve: Core (dark green) and Buffer (green) Zones (Ninh Binh Conservation Alliance (NBCA), 2025).

- **Decision No. 1662/QĐ-TTg:** In the project '*Protecting and developing coastal forests in response to climate change and promoting green growth for the period of 2021-2030*', the Vietnamese government proposed a plan to plant 20 000 hectares of forest. This also includes 9 800 hectares of mangrove area along the coastline (Kiet, 2021).
- **Law on Fisheries 18/2017/QH14:** The law addresses the challenge of illegal, unregulated, and unreported (IUU) fishing (in both fresh and salt water), while placing emphasis on the conservation of marine protected areas, including mangrove ecosystems (Thu Vien Phap Luat, 2017). In Kim

Đông it encourages mixed mangrove-aquaculture systems.

- **Kim Sơn Protection Forest Ecotourism Scheme (to 2025, orientation to 2030):** The former Kim Sơn now falls under the Kim Đông commune. For Kim Đông, the scheme permits tightly controlled ecotourism within the coastal protection forest, with conservation and the forest's protective function taking precedence. Activities must remain small-scale and low-impact, use designated routes and sites, and comply with licensing, environmental appraisal and monitoring. Management prioritises maintenance of water quality, tidal connectivity and habitat integrity, and favours projects that support local livelihoods and education (Xuân Mai JSC, 2024). However, as of right now, ecotourism in the Kim Đông area is almost zero and thus not so important (Dr. Tung Dao, 2025; Appendix C.2.4).
- **Decree No. 34/2014:** This decree regulates border areas in Vietnam (communes, wards and townships that are located at the national borders). They are assigned as land border areas. The law states which people, organisations and transport can be active. Activities often require extra permits or control, which is also the case for tourism in Kim Đông (Dat, 2023).
- **Law on National Defence:** Since January 8th, this Law is active. The state can declare areas for national defence and safety. Projects or activities in those areas will have to adhere to special rules. This can mean that tourism or commercial activities are restricted in those areas. Kim Đông is part of a strategic coastal zone, which means there are special safety and defence measures (Government of the Socialist Republic of Vietnam, 2014).

Public Investment Management is also very important when it comes to mangroves. Mangrove planting, monitoring and coastal protection projects are mostly funded by the government. Also, the dikes in the Kim Đông area fall under public investment. How the government allocates investment capital determines whether mangroves will survive as a natural defence system or continue to be squeezed out by aquaculture or other constructions like dikes. The following formal rules are applicable in the Kim Đông area regarding Public Investment Management:

- **Law on Public Investment (No. 58/2024/QH15):** This is the central law that governs public investment. This law states when an investment can count as a public investment. Also, the law allocates the responsibility to either the central government, a ministry or a People's Committee of either the province or the commune. It determines whether restoration projects like planting mangroves or construction projects like those of the dikes in Kim Đông can receive state funds and who will be responsible for the project (LuatVietnam, 2024).
- **Law on Construction (Law No. 50/2014/QH13):** This law is related to the Law on Public Investment and regulates the design, planning and execution of projects. Also, the responsibilities of different organisations and individuals are stated, as well as the technical standards that must be met (Vietnam National Assembly, 2014). For the Kim Dong area, this law ensures compliance in coastal protection works like dikes.
- **Law on Investment (Law No. 61/2020/QH14):** This law regulates both domestic and foreign business investments and sets conditions for involvement including public-private partnerships (PPPs) (UNCTAD Investment Policy Hub, 2020). In the case of mangrove projects, this regulates the involvement of international companies to co-finance these projects, like mentioned in international laws and projects further in this appendix.
- **State Budget Law:** This law regulates how public funds are raised in Vietnam, but also how they are allocated and managed (Vietnam National Assembly, 2015). The State Budget Law decides whether funds can be allocated from local or central budgets to finance coastal defence and restoration. In Kim Đông, mangrove initiatives depend on provincial and external co-funding

Besides the formal rules explained above, there are also informal rules that have a great influence on the way the institutional system works. The following informal rules are applicable in the Kim Đông area:

- **Corruption:** Unchecked provincial power was considered a major source of corruption in Vietnam. Since 2021, members of the Central Committee of the Communist Party of Vietnam have been removed due to corruption. Half of them were provincial leaders, resulting in a decrease in provincial representation in the Central Committee from 40 percent to 28 percent (Khac Giang,

2024). This anti-corruption movement does have an effect and leads to a real decrease in corruption. However, the anti-corruption efforts focus mostly on the province and national government. Local communes are a different story. In practice, family members or friends of government officials often gain privileges in relation to the application of rules (The Shiv, 2023). Regulations that limit the amount of land a single household may own, or those intended to protect forests, are frequently circumvented by local residents. Wealthier families, in particular, are able to retain more than the legally permitted share through government connections or by simply purchasing additional land. At the same time, some local residents disregard forest protection laws in favour of their own economic interests. This is most commonly associated with aquaculture activities, which in turn have negative impacts on mangrove ecosystems (Viet An Law, 2024).

- **Informal land use practices:** Local farmers often convert more mangroves into aquaculture farms than the law permits. Such practices are frequently tolerated by regulators as long as they generate profit, meaning that economic gain is prioritised over the preservation of mangrove forests. Interviews with 120 small-scale shrimp farmers in the Mekong Delta revealed that more than half had expanded their farms beyond the legal limits, thereby clearing more mangroves than officially allowed (efeedlink, 2024).
- **Unequal laws:** Laws are applied unfairly to local communities. Small-scale operators, such as fishers and farmers, as well as low-income households, are more frequently subject to strict monitoring, whereas larger aquaculture companies can often commit violations without facing severe consequences. This exacerbates the imbalance between large and small enterprises. Moreover, this focus on minor infractions often means that large-scale mangrove degradation goes unnoticed (Anh, Beaulieu, Da Hanh, & Tru, 2024).
- **Transparency:** In Vietnam, doing research is very different than in other countries. One particular observation is that there is a lack of transparency regarding local policy documents or previously done research (CECODES, RTA, & Vietnam, 2023). This makes it harder for researchers to investigate certain problems and systems. Also, data is way more limited than elsewhere. In the Kim Đông area as well, there is limited data available on the mangrove forests.
- **Public Investment Management law complexity:** Projects that rely on public funding or shared funding (such as dike upgrades, access roads, small visitor facilities, and sluices that affect mangrove health) move slowly because responsibilities are divided across several laws and levels of government. Once a project is added to the five-year Medium-Term Public Investment Plan, it is hard to remove, so weakly prepared proposals can still go forward and later need long adjustments, often leading to slow spending and higher costs. For conservation and small-scale projects this means longer preparation times and more coordination problems between districts and provinces. Careful early studies, early planning for resettlement, and clear documentation are needed to avoid delays and keep mangrove restoration on schedule (Chi, 2025).
- **Signature-linked liability and administrative risk aversion:** Projects that require routine approvals stall when officials fear personal responsibility under intensified anti-corruption scrutiny. Extra countersigning and audit steps increase documentation loads and shift risk to individual signatories, slowing public investment disbursement across ministries and provinces. For mangrove restoration and other small works, this yields longer preparation times, repeated resubmissions, and coordination problems between districts and provinces unless responsibilities are clarified early and files are fully documented (K. G. Nguyen, 2023).

As stated before, there are also a lot of international influences in the Kim Đông area. They are primarily focused on mangrove projects (Vietnam News, 2024), but certain international laws also do have an influence on the mangrove systems in Vietnam. The following international laws and projects have an influence in the Kim Đông area:

- **Korea Forest Service:** The Korea Forest Service has set project requirements stipulating the restoration of 250 hectares of mangroves in the Kim Đông area (Vietnam News, 2024). They have donated 3.79 million dollars of non-refundable aid to support this project (Vietnam News, 2023). The goal of the project was the preservation of the environment and biodiversity, the reduction of emissions and climate adaptation. South Korea does this for several reasons, namely to maintain good relations with Vietnam, but also to gain CO₂ certificates so that they can compensate for

the CO₂ they produced in their own country or with their own companies (Interview Dr. Tung Dao, 2025; Appendix C.2.4).

- **Provincial Red Cross:** The Red Cross located in Ninh Binh launched the Mangrove Forest Plantation, a disaster risk reduction project, in 2015. In addition to this project, they have been planting and protecting mangrove forests since 1994. Their main goal is saving people's lives from floods and extreme storms (Vietnam Red Cross Society, International Federation of Red Cross, Red Crescent Societies, & Japanese Red Cross Society, 2016).
- **The Green Climate Fund (GCF) and United Nations Development Programme (UNDP):** In 2015, Vietnam proposed a project *'Improving the resilience of vulnerable coastal communities to climate change-related impacts in Vietnam'*, and sought funding from the Green Climate Fund through the United Nations Development Programme (ReliefWeb, 2021). One of the outputs of the project was regeneration of 4,000 hectares of coastal mangrove extreme storm surge buffer zones (United Nations Development Programme, 2016).
- **Japan:** In many projects in Vietnam, part of it is financed by Official Development Assistance (ODA). Japan is one of Vietnam's most important ODA donors, especially in the case of climate adaptation and forestry (United Nations Development Programme, 2016). They have the same reasons for investing as South Korea.
- **EU Deforestation Regulation (EUDR, Regulation (EU) 2023/1115):** The law covers seven commodities: cattle, cocoa, coffee, oil palm, rubber, soy and wood. If companies want to sell these goods or products made from them in the EU, they have to do their research first. This includes finding out where the plots are located, showing proof that no trees will be cut down after December 31, 2020, and showing proof that the goods were legally made in the country where they came from. Aquaculture products such as shrimp and clams are outside the scope. Wood from mangroves is within scope, so any mangrove timber or wood-derived products entering the EU must meet the deforestation-free and legality requirements (European Commission, 2023).

A.5.3. Stakeholder Background Information

In Kim Đông, there are numerous stakeholders who are involved in the coastal system. In the power-interest grid in Figure 3.21 it is important to note that the most critical stakeholders are positioned in the top-right quadrant, as they both have significant influence and a strong interest in the problem. Stakeholders in the top-left quadrant may have the power to make important decisions or shape policy but are less directly engaged with the issue. Those in the bottom-right quadrant are highly engaged but lack the authority to implement policy or make strategic decisions.

For each stakeholder the values, needs and interests will be discussed.

There are a lot of governing bodies involved in the coastal system of Kim Đông, which will be listed in the list below.

- **Vietnam Communist Party (CPV):** The CPV opts for maintaining authority over all policy directions, which also includes mangrove conservation and economic growth. One of their main values is national unity and centralised control. To do that, they need reliable information and alignment between ministries without conflicting goals.
- **Ministry of Agriculture and Environment (MAE):** The ministry responsible for mangrove development and aquaculture in Vietnam is the Ministry of Agriculture and Environment (MAE) (Vietnam Law & legal forum, 2025). Previously, this ministry was divided into two separate bodies: the Ministry of Agriculture and Rural Development (MARD) and the Ministry of Natural Resources and Environment (MONRE). These opposing policy orientations often undermined each other, hindering effective efforts to address mangrove deforestation and degradation (Orchard, Stringer, & Quinn, 2015). As of February 18th 2025, however, the two ministries have been merged into MAE, with the aim of reducing contradictions and improving efficiency in policy making (Vietnam Law & legal forum, 2025). The ultimate goal of MAE is to find clear coordination between environmental and agricultural divisions to avoid internal policy contradictions and come up with the best results.
- **Ministry of Planning and Investment (MPI):** Another ministry that is involved in Kim Đông is the Ministry of Planning and Investment, since they oversee the planning and funds for the dikes

built in Kim Đông together with the MAE (Interview Mr. Mai Cao Tri, 2025; Appendix C.2.7). They want to ensure public investment aligns with national targets, using investment planning.

- **Department of Agriculture and Environment (DAE):** At the provincial level (Ninh Binh), the Department of Agriculture and Environment (DAE) carries out the policy set by MAE. The department has a lot of power in Kim Đông, since a lot of decisions have to go through them. For example, when foreigners want to go into the area, the province needs to give a signature. Their needs are mainly clear communication with both central and commune levels, access to project funding and administrative capacity.
- **Commune People's Committee:** At the local level, policy shaped by MAE and DAE is executed by the Commune People's Committee of Kim Đông. They manage daily governance, licensing and small-scale development. All governing bodies, and thus the commune as well, have to follow the policy and direction set out by the CPV (Vietnam National Assembly, 2015).
- **Vietnam Administration of Forestry:** VNFOREST is part of MAE. They are responsible for provincial-level forest management, biodiversity protection and managing projects. They monitor and enforce mangrove restoration activities (Vietnam National Forestry Association, n.d.). To do this, they need funding and coordination with local authorities to effectively enforce regulations.
- **Department of Forestry:** The Department of Forestry is part of the Vietnam Administration of Forestry (VNFOREST), and executes their policy on a provincial level. They mostly oversee reforestation and protection projects in Kim Đông. They cooperate with NGOs, researchers and the local authorities.
- **Border Guard:** The border guard sees to the law enforcement when it comes to coastal areas. The border guard is part of the military and cares about safety and security in the Kim Đông area (Interview Dr. Tung Dao, 2025; Appendix C.2.6). They coordinate with civilian authorities to balance security with sustainable tourism and research access.

Besides governing bodies, there are a lot of other stakeholders involved within the coastal system of Kim Đông, which are listed below.

- **International countries that donate, e.g., Korea and Japan:** Donors often provide funding for restoration efforts. For example, the donation from the Republic of Korea in Kim Đông (Vietnam News, 2023), and donations from Japan elsewhere in Vietnam. One of the incentives for donors to donate for these kinds of projects is the CO₂ certificates that can be obtained. These can be used by companies to reach carbon neutrality. They need transparent project reporting and, most importantly, measurable environmental outcomes.
- **Multilateral ODA:** Besides those countries, other donors like the Green Climate Fund, the United Nations Development Programme and the Worldbank have also donated a lot of money to mangrove projects, some of which are in Kim Đông (MARD, 2020). They want to finance projects that combine climate adaptation with poverty reduction.
- **Provincial Red Cross:** NGOs like the Red Cross Vietnam have supported mangrove projects elsewhere in the Ninh Binh Province (Pham et al., 2022) for human safety and disaster risk reduction. This indicates that they can be a potential stakeholder in Kim Đông restoration efforts. They want to use mangroves to protect communities from storms and floods.
- **Mass Organisations, e.g., Women's Union, Youth Union:** Mass organisations value community well-being and social participation and are therefore important for community mobilisation. They represent citizens in restoration and livelihood projects.
- **Researchers:** Researchers collect data and monitor developments in the area, providing evidence that can serve as a reference point for policy-making. In Kim Đông this also happens through Thuyloi University and Hanoi University of Civil Engineering. Ultimate authority rests with the government, and thus, researchers lack formal decision-making power. However, they are able to offer advice and recommendations. To do research, they need access to field sites, research permits and good collaboration with government agencies.
- **Contractors:** Contractors want profit and project completion. They do this by winning tenders for infrastructure and restoration works. To do this, they need stable contracts and clear technical guidelines.

- **Local (aquaculture) entrepreneurs:** Local entrepreneurs value economic security. They want as much profit as possible. Therefore, they need balanced regulations that allow economic activity while maintaining environmental aspects.
- **Local residents:** Local residents value livelihood stability and access to land and research. They want to maintain a stable income while ensuring protection from possible extreme storms. They need participation in decision-making, fair law enforcement and (financial) incentives to protect mangroves.

B | Extension of Hydraulic Analysis

This appendix provides detailed documentation of the methods and processes used to support the hydraulic analysis presented in Chapter 4, focusing on the Kim Đông coastal area. It covers the estimation of bathymetry, including grid creation, analysis of tidal information, estimation of water density and wave data processing. The aim is to transparently present the data sources, processing steps, and assumptions underlying the numerical simulations used in this study.

B.1. Bathymetry Estimation and Grid Creation

This appendix describes the steps taken to estimate the bathymetry of the Kim Đông area in Vietnam. In this area, bathymetric data are sparse and are only available at a few locations in the form of cross-shore measurements, primarily close to the shore. Due to the limited measurements of (offshore) data, the bathymetry for the remainder of the area has been estimated using a combination of interpolation and extrapolation techniques.

It is important to note that the results presented in this appendix are based on several assumptions, which may simplify the complexity of real-world conditions.

The purpose of generating this bathymetry is to provide input for the Delft3D model, where simulations of flow, sediment transport, and other hydrodynamic processes can be performed. This explains the choice of file formats of the bathymetry used for export, which are compatible with Delft3D.

To integrate the bathymetric data into Delft3D, a grid with corresponding bathymetric values across the study area is required. This grid is the spatial framework and must be carefully constructed.

The bathymetry is generated using a Python script, which performs the grid creation, and the interpolation and extrapolation processes. Once the bathymetric values are generated, they are exported as a DEC file, which can be directly imported into Delft3D for further analysis and modelling. Additionally, the grid itself is exported as a GRD file, providing the spatial structure needed for the simulations.

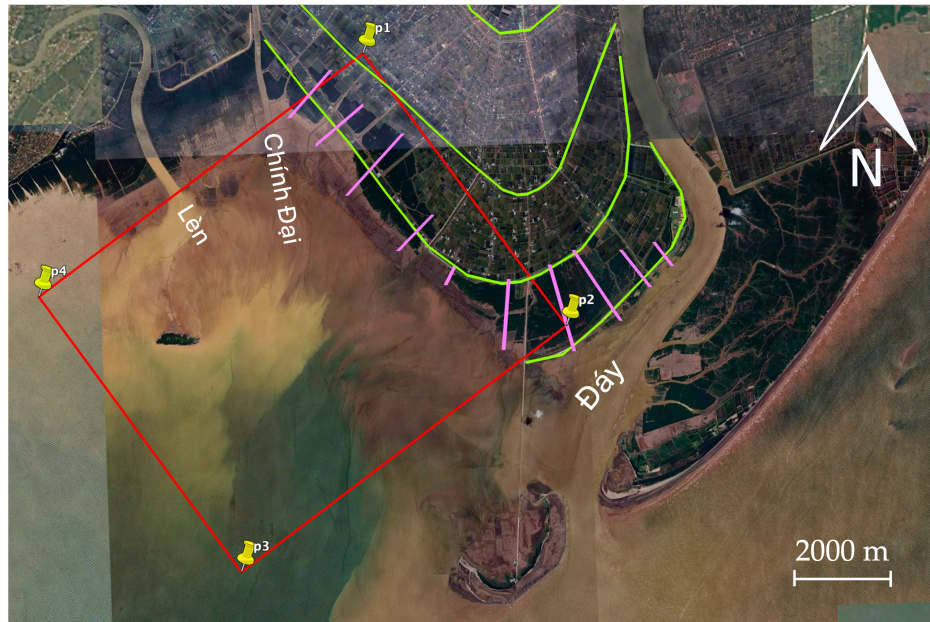


Figure B.1: Selected Area (Google LLC, 2024)

B.1.1. Selected Area

Selecting the area is an important step in setting up this model. The area needs to contain all relevant boundaries and processes. In Figure B.1 the selected area is visualised using Google Earth. The measurements (yellow lines) and dikes (green lines) are also included.

A few aspects in the area are included in the model to better represent the hydraulic conditions. First, the end of the fourth dike segment, at the bottom right near P2. This area is elevated compared to the rest of the nearby area. Including this end allows for the simulation of the effects of finishing the fourth dike. A second aspect that should be included in the model is the island just of the coast of Kim Đông, because of the unknown effects it has on currents and wave propagation. To include these aspects, the green rectangular area in Figure B.1 is chosen as the modelled area. This shape is most convenient when generating the grid and depth files for the input of Delft3D.

B.1.2. Grid Creation

The spatial component of the bathymetry model is represented by a grid that consists of 280 rows and 547 columns, and has two subgrids: one for the near-shore region and one for the offshore area. These subgrids allow for different resolutions, based on the desired accuracy of the bathymetric model.

Figure B.2 shows a visualisation of the outlines of both subgrids. The red outline represents the near-shore grid, while the green outline represents the offshore grid. Furthermore, the corner points of both grids are shown.

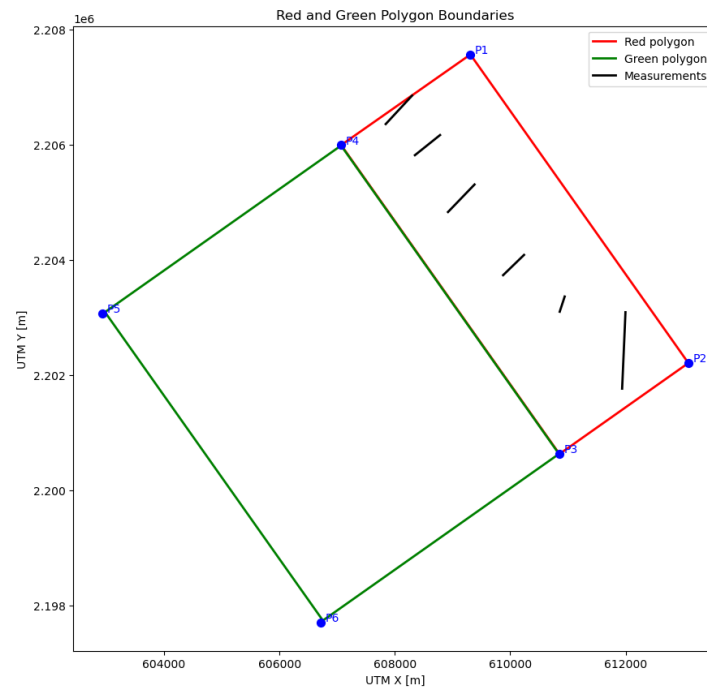


Figure B.2: Outlines of the Subgrids

- **Near Shore Grid:** The first subgrid consists of 229 rows, with a constant cell size of 12 x 12 metres. This fine resolution is used because measurements are only available in the near-shore region, unlike the offshore areas where data are sparse and therefore estimated. The higher resolution allows for a more precise representation of the bathymetric values, hydrodynamic and morphodynamic output.
- **Offshore Grid:** The offshore grid has 51 rows with a varying cell height, starting at 24 metres and gradually increasing to 108 metres in steps of 12 metres. This change in cell height for the green grid is visible in Figure B.3 close to the red grid. This approach reduces computational demand, as the offshore areas are more sparsely sampled and do not require the same level of resolution as the near-shore region.

The grid is created in Python. First the direction of the grid is determined by creating a unit vector from P1 to P2, and from P1 to P5. Using these vectors, the coordinates of the nodes can be created, including the specifications of the offshore grid cell sizes and the stepwise increase towards it. After storing all these coordinates in arrays for X and Y coordinates, the coordinates are flipped in order to start the counting at P5. The grid is now counting anticlockwise, which is required when using Delft3D. The complete grid layout is displayed in Figure B.3.

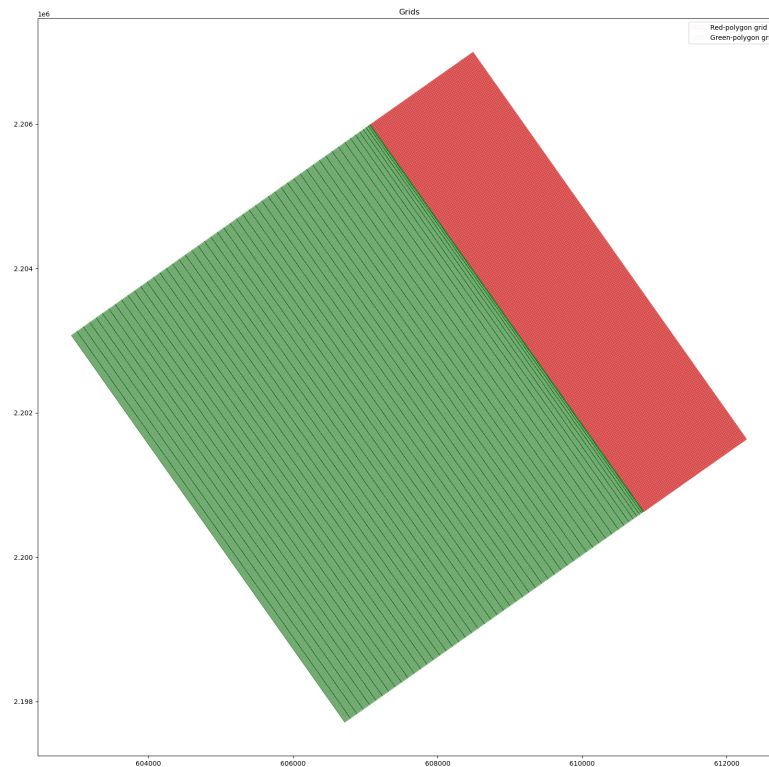


Figure B.3: Complete Grid Layout

B.1.3. Measurement Data

The first measurement campaign done by the government, Thuyloi University (TLU) and Hanoi University of Civil Engineering (HUCE) provides six cross-section measurements in the selected bathymetry area and are shown in B.1 with the white lines. The data of these measurements are stored in AutoCAD and are extracted by hand into Excel sheets. Only data starting from the dike are used, because the points behind the dike are not relevant for the interpolation. The coordinates of the start and end points of each measurement are known, allowing the measurements to be represented as straight lines. The starting coordinates are adjusted to begin at the dike.

The measurements are taken with respect to Mean Sea Surface (MSS), which is the average sea level over a long period of time, usually over several years. MSS provides a reference level that accounts for long-term variations in sea level, such as seasonal and tidal changes.

The obtained Excel file, which contains the distance from the dike and the corresponding bathymetry values, is used as input for the Python notebook. Each measurement is assigned to the nearest grid cell to align the data with the bathymetric grid. In order to maintain the accuracy of the model and avoid skewing the results, measurements with values above 1 meter are excluded from the interpolation. This is done to minimise the influence of measurements of the dike on the bathymetric results, as the dike's height could otherwise disproportionately affect the model output. These dike measurements are later manually incorporated back into the final bathymetry model in Delft3D.

B.1.4. Interpolation and Extrapolation

To estimate the bathymetry for regions without direct measurements, interpolation and extrapolation techniques are applied. These methods help generate a continuous bathymetric surface, even for areas where no direct data exists. Below is a detailed breakdown of the methods used:

1. Interpolation within the Convex Hull

One of the key steps in the process is to interpolate bathymetric values within the near-shore grid, specifically inside the smallest region covered by the available measurement points. This region, also called the convex hull, is the smallest convex boundary that encloses all the data points.

This method estimates the bathymetric values at unmeasured locations based on the surrounding data points. The `griddata` function from the interpolation package in SciPy is used in Python for the interpolation. This function employs linear interpolation, which is selected for its simplicity and efficiency, especially given the relatively small dataset available.

Linear interpolation is chosen because bathymetric data often varies smoothly, and this method provides a straightforward way to estimate the bathymetry between known data points. It assumes that the change in bathymetric values between two points is constant, which is a reasonable assumption when no complex trends or patterns are expected. The result of this interpolation within the convex hull is shown in Figure B.4.

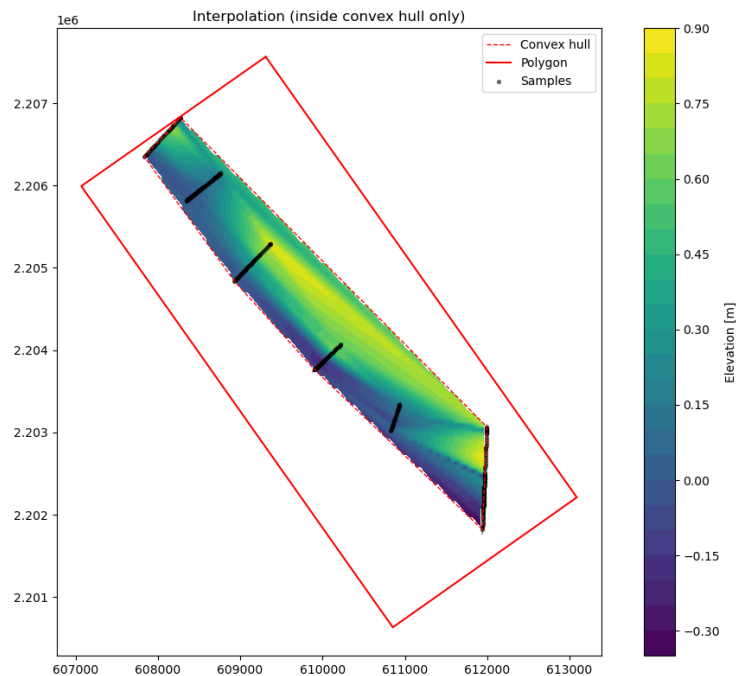


Figure B.4: Interpolation (Inside Convex Hull Only) of the Bathymetry in Kim Đông.

2. Extrapolation Beyond the Convex Hull

For areas outside the convex hull, extrapolation is applied to estimate bathymetric values. Extrapolation extends the known data into regions where no direct measurements exist under the assumption that bathymetric features such as slopes or depth contours continue in a manner similar to that observed in the measured regions.

In the Python notebook, two methods are combined to achieve a smooth and realistic extrapolation over the near-shore grid:

- **Radial Basis Function (RBF):** This method handles irregularly distributed data well and captures local variations in bathymetry. The RBF is used to predict values near and slightly beyond the measurement points. It provides a smooth, continuous surface that can accurately represent bathymetric features even with sparse or unevenly distributed measurements (Tang et al., 2022).

- **Linear RBF:** This is a simpler, linear version of RBF used as a background trend for areas farther from the measurements. While the multiquadric RBF captures local variations, the linear RBF ensures a stable, smooth extrapolation in regions with little or no data. It acts as a baseline that prevents unrealistic oscillations or extreme values in sparsely sampled areas.

The final bathymetric values are computed as a weighted combination of the RBF and linear extrapolation, where the weight depends on the distance to the convex hull of the measurement points. Near the measured points, the RBF dominates, preserving local detail, while farther from the data, the linear component dominates, preventing unrealistic variations in sparsely sampled areas. This resulting extrapolated bathymetry is visualised in Figure B.5.

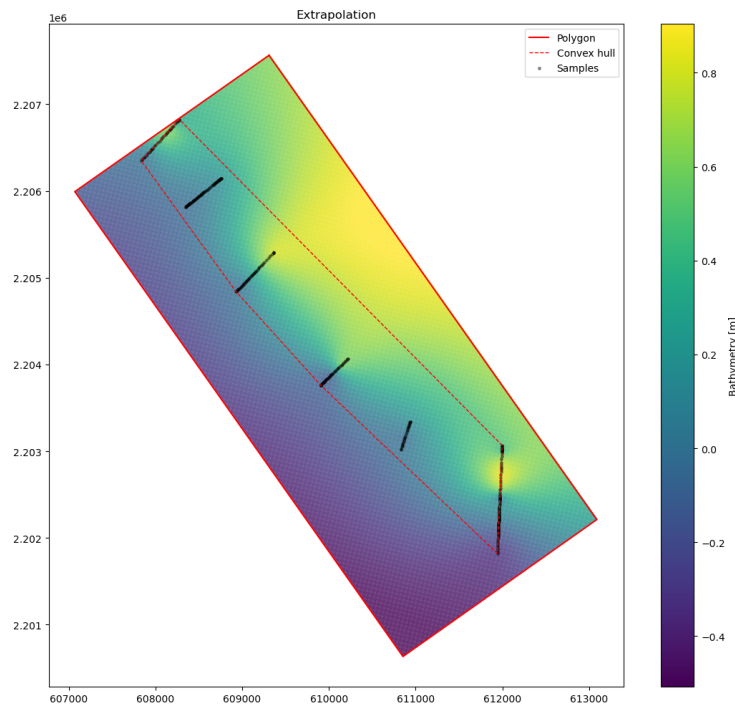


Figure B.5: Extrapolation of the Bathymetry in Kim Đông.

3. Offshore Extrapolation: Linear Slope Assumption

For the offshore region (Subgrid 2), where there is a lack of bathymetric data, a linear slope assumption is applied to estimate the bathymetric values. This assumption is necessary to extend the model beyond the measurement areas.

The bathymetric values from the last row of the near-shore grid (Subgrid 1) are used as the starting points for the linear interpolation.

To estimate the bathymetry in the offshore area, nautical charts from fishermen are used (GPS Nautical Charts, 2025a). Specifically, the bathymetric value of the grid cell near P5 is assigned a depth of -1.2 metres. This shallow value is due to the continuing coastline nearby. The depth at the grid cell at P6, located at the farthest south-west point of the grid, is -5.4 metres.

Linear interpolation is applied in two stages:

- From P5 to P6, to establish the offshore boundary values.
- From the last row of the near-shore grid (Subgrid 1) to this offshore boundary, to ensure a smooth transition.

This approach assumes that the bathymetric slope remains consistent between these points, allowing for a smooth and continuous bathymetric model.

B.1.5. Visualisation of Results

After the interpolation and extrapolation processes are completed, the resulting bathymetry is visualised to provide a clear representation of the estimated seabed. Visualisation is performed using contour plots and colour maps (Figure B.6), which help to illustrate both the spatial distribution and variation in bathymetric values across the project area. The values are with relation to the Mean Sea State (MSS), also called Mean Sea Level (MSL).

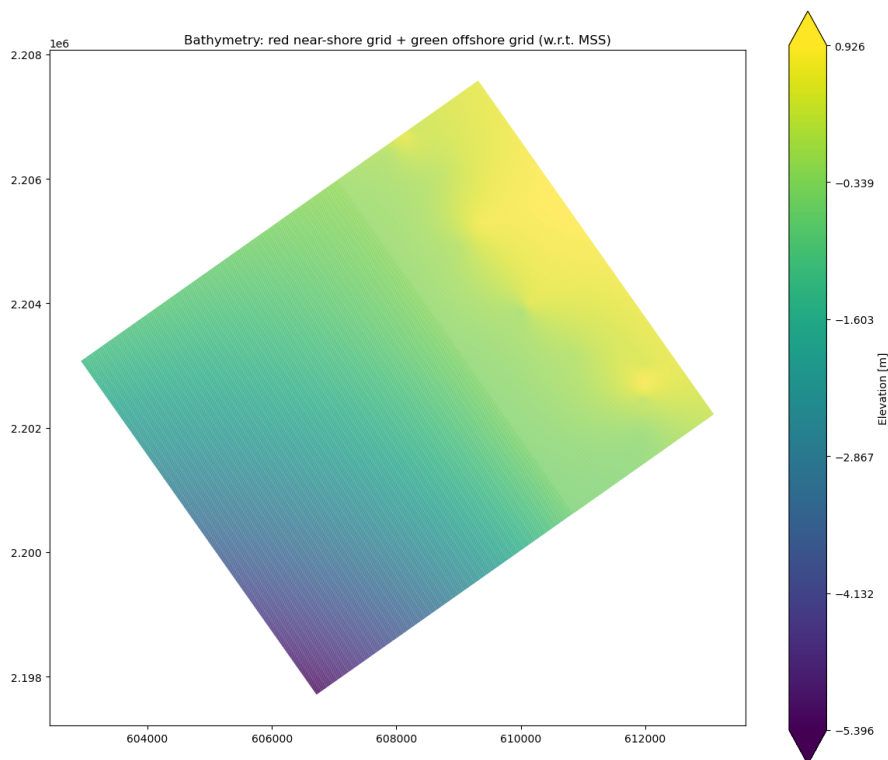


Figure B.6: Visualisation of the Resulting Bathymetry

Manual Additions

In addition to Dike 3, the nearby island is manually incorporated into the Delft3D model, with an assigned elevation of MSL +4 metres, serving as an obstacle in the hydrodynamic model. This represents a simplification, as the island is more complex in reality. The canals connected to the gates are modelled with a depth of MSL -1.5 metres, based on water depth estimations at Gate 10 during the October 2025 field trip. Additionally, an extra bathymetric model is created to include the extension of Dike 4.

These adjustments result in a revised bathymetric representation, as shown in Figures B.7 and B.8. The new red lines indicate the canals, the dark blue area to the left represents the island, the dark blue line marks Dike 4, and the other dark blue area corresponds to Dike 3.

B.2. Suspended Sediment Concentration Data Processing

Suspended Sediment Concentration (SSC) plays an important role in understanding the sediment dynamics of the Kim Đông coastal zone, which influences coastal morphology and the growth of mangroves. Two sets of SSC measurements are obtained during different periods:

1. April 2025: The Thuyloi University research team conducted measurements at three locations in the coastal zone in Kim Đông. These measurements are displayed in Figure 4.7.
2. October 2025: The MDP group, in collaboration with the Thuyloi University team, carried out additional measurements at the same three locations during the field trip. For further details about these measurements, including the field trip methods, refer to Appendix D.

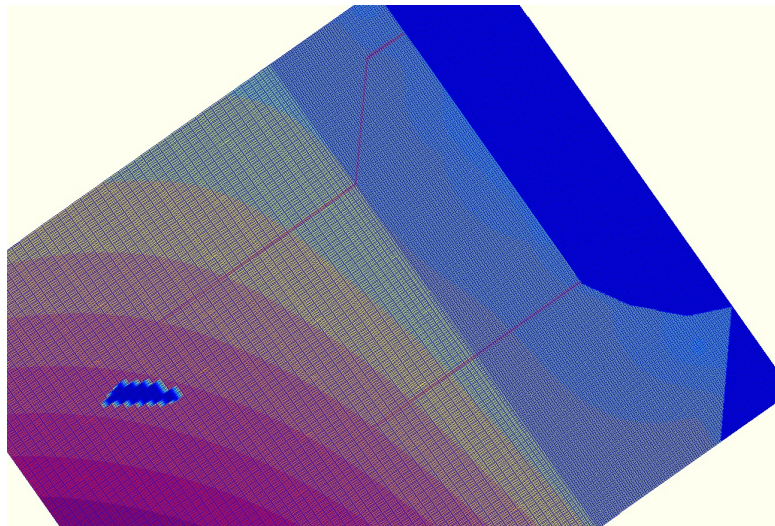


Figure B.7: Resulting Bathymetry With Additions

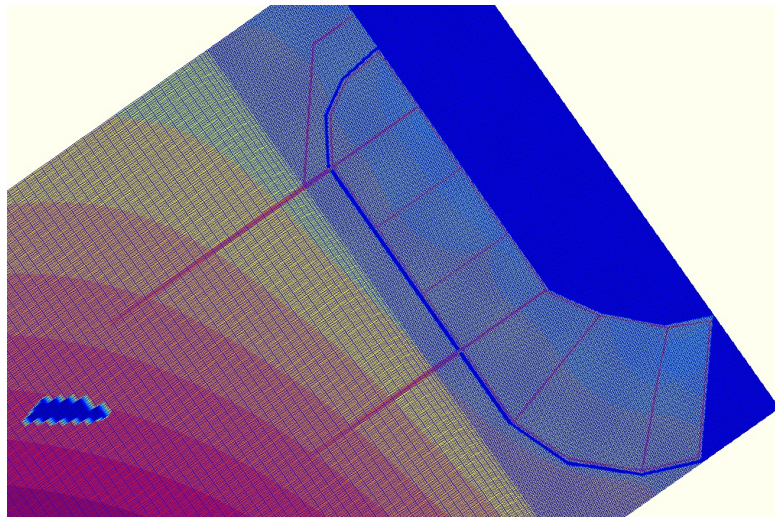


Figure B.8: Resulting Bathymetry With Additions and Dike 4

B.2.1. Data Processing Methodology

To make the SSC data easier to interpret, a 3-point rolling mean was applied to the time series data. This method smooths out sudden, short-term changes by replacing each data point with the average of itself and its two closest neighbours. This helps highlight the larger, more consistent patterns in the data while reducing the impact of temporary spikes and drops.

However, this method has a limitation: it cannot smooth the first and last data points because they do not have enough neighbouring points. As a result, these points are excluded from the final processed data.

The processing for the April 2025 measurements was carried out by Thuyloi University, and the results, including the scatter plots of the raw data, the distribution of the measurements and the smoothed values, are shown in the figures below:

- Figure B.9: A scatter plot of the raw SSC measurements from April 2025.
- Figure B.10: A distribution plot showing the spread of SSC values for April.
- Figure B.11: The same data processed using the 3-point rolling mean to smooth short-term fluctuations.

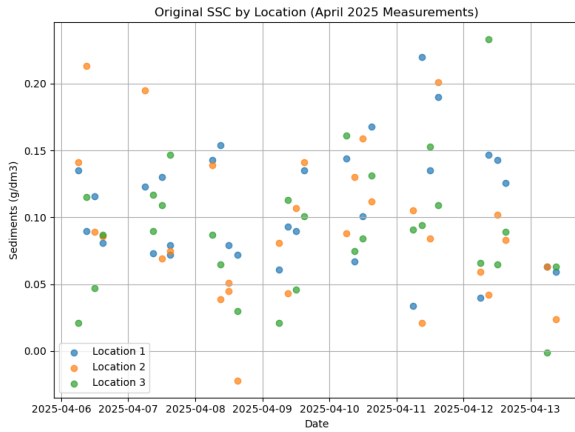


Figure B.9: Scatter Plot of Suspended Sediment Concentration (SSC) Measurements - April 2025, Kim Đông

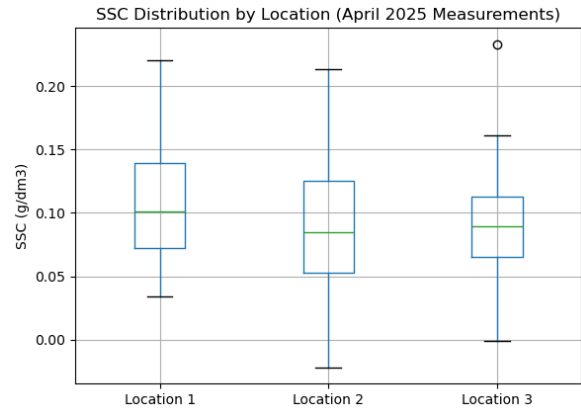


Figure B.10: Distribution of SSC Measurements - April 2025, Kim Đông

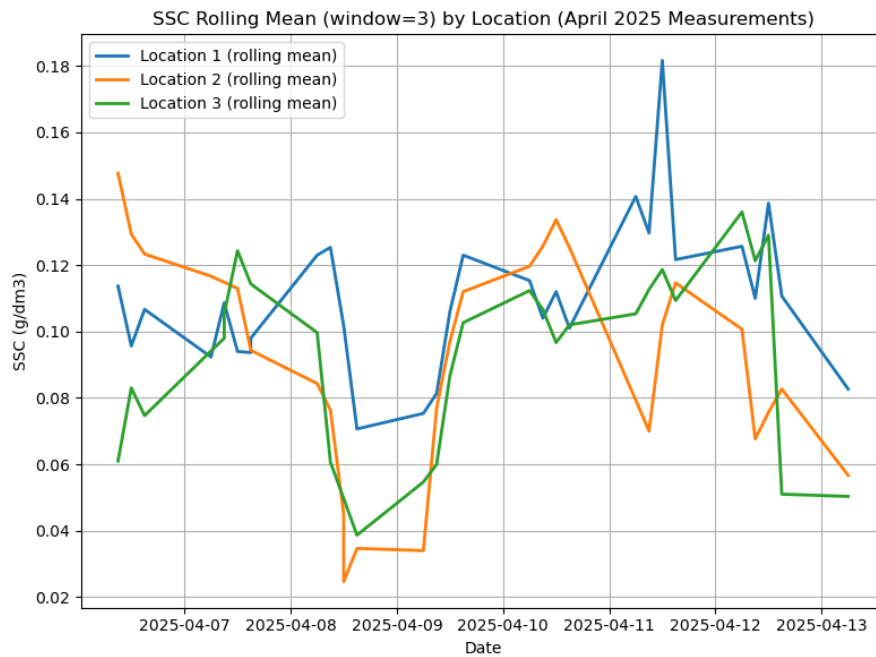


Figure B.11: Suspended Sediment Concentration (SSC) with 3-Point Rolling Mean - April 2025, Kim Đông

For the measurements of October 2025, the MDP group applied the same methodology, with the processed data shown in Figures B.12, B.13, and B.14.

This data processing approach allows for a clearer understanding of the trends in SSC over time, filtering out noise that may arise from environmental factors or measurement errors. It also helps to correct unrealistic negative values in the dataset, which likely resulted from small weighing errors or moisture differences before and after filtering.

B.3. Estimation of Water Density

The water density can be assumed according to Formula B.1. This equation is a simplified version from Millero and Poisson (1981), where the correction for non-linear salinity effects is left out, since only an estimate of the water density is needed.

$$\rho = \rho_{\text{fresh water}}(T) + \Delta\rho_{\text{salinity}}$$

B.1

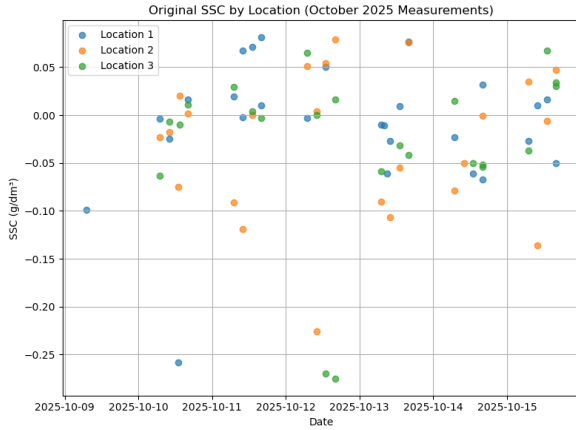


Figure B.12: Scatter Plot of Suspended Sediment Concentration (SSC) Measurements - October 2025, Kim Đông

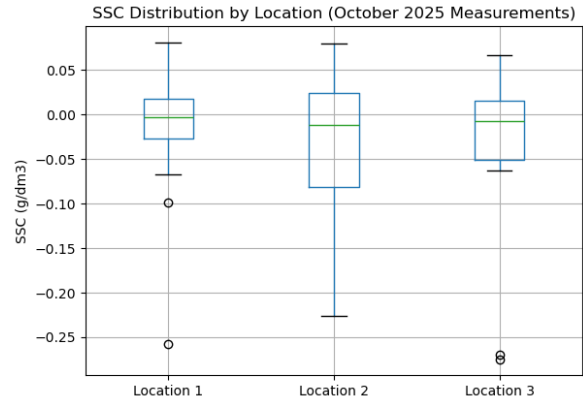


Figure B.13: Distribution of SSC Measurements - October 2025, Kim Đông

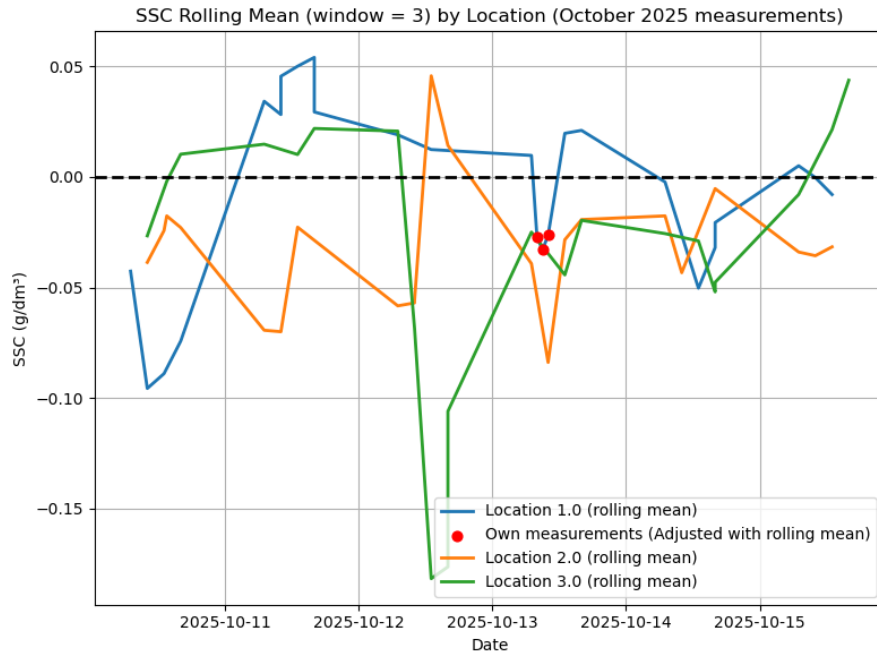


Figure B.14: Suspended Sediment Concentration (SSC) with 3-Point Rolling Mean - October 2025, Kim Đông

This equation expresses the density of seawater (ρ) as the sum of two components:

- $\rho_{\text{fresh water}}(T)$: the density of fresh water, which depends on temperature T .
- $\Delta\rho_{\text{salinity}}$: the increase in density caused by dissolved salts in water. This factor is estimated at 0.75 kg/m^3 per ‰ (Millero & Poisson, 1981).

The average temperature in the Gulf of Tonkin varies from 21°C in February to 29°C in June and August (Zavala-Garay et al., 2022). The corresponding freshwater densities are 997.995 kg/m^3 (dry season) and 996.947 kg/m^3 (wet season) (NIST, 2008; Wagner & Pruß, 2002). Using the assumed salinities for both nearshore (8 or 30 ‰) and offshore waters (32 ‰), the resulting water densities are summarised in Table B.1.

Table B.1: Estimated Seawater Densities for Nearshore and Offshore Conditions at Kim Đông

Location	Season	Temperature (°C)	Freshwater Density (kg/m ³)	Salinity (‰)	Density (kg/m ³)
Nearshore	Dry	21	997.995	30	1020.5
Nearshore	Wet	29	996.947	8	1003.0
Offshore	Dry	21	997.995	32	1022.0
Offshore	Wet	29	996.947	32	1020.9

B.4. Tidal Information

This section examines the comparison between hourly water level measurements recorded in front of the Kim Đông coast and available tidal data from the region of Hòn Dấu, approximately 70 km north of Kim Đông.

During the Kim Đông measurement campaign in April, water levels are recorded hourly for the full month, as shown in Figure B.15. The tidal sequence is characterised by a mean tidal range of approximately 1.86 m. The smallest observed range between high and low water is 1.26 m, while the largest reaches 2.35 m.

The spacing between successive high waters averages 25.8 hours, and a total of 27 tidal cycles were identified during the observation period. This aligns with expectations for the northern Gulf of Tonkin, where the tidal regime is predominantly diurnal, typically producing one high and one low water each day (Trinh et al., 2020).

For comparison, long-term records at Hòn Dấu, located about 70 km from the Kim Đông area, show a mean tidal range of 3–4 m (Trinh et al., 2020). The discrepancy with the April measurements may be due to the limited one-month observation window of this study.

Additionally, the Hòn Dấu measurement station is located further north in the Gulf of Tonkin, which can amplify differences in tidal range relative to the Kim Đông site. Furthermore, the presence of intertidal mudflats and the exact measurement location strongly influence the recorded values.

After reviewing the differences with the field supervisor of the measurement campaign from Thuyloi University, the measured data is chosen as the most representative. Table B.2 summarises this tidal sequence.

Table B.2: Tidal information of Kim Đông (April, 2025)

Characteristic	Value
Mean tidal range (campaign)	1.86 m
Minimum tidal range	1.26 m
Maximum tidal range	2.35 m
Avg. interval between successive high waters	25.8 h
Number of tidal cycles (April)	27
Dominant tidal regime	Predominantly diurnal
Regional mean range (Hòn Dấu)	3–4 meters

B.5. Wave Analysis

This section explains the derivation of the wave boundary conditions used in the study. It begins by describing the ERA5 reanalysis data and the spatial extraction window, followed by the process of filtering the dataset to retain only the wave directions that can physically reach the site under the current spatial conditions. Next, the filtered dataset is analysed to characterise governing wave conditions.

For extreme wave conditions, the peaks-over-threshold (POT) method is applied: the threshold selection, declustering time choice and distribution fitting are shown, leading to both the 30-year and 1-year design significant wave height and an associated period. In addition to the extreme conditions, three

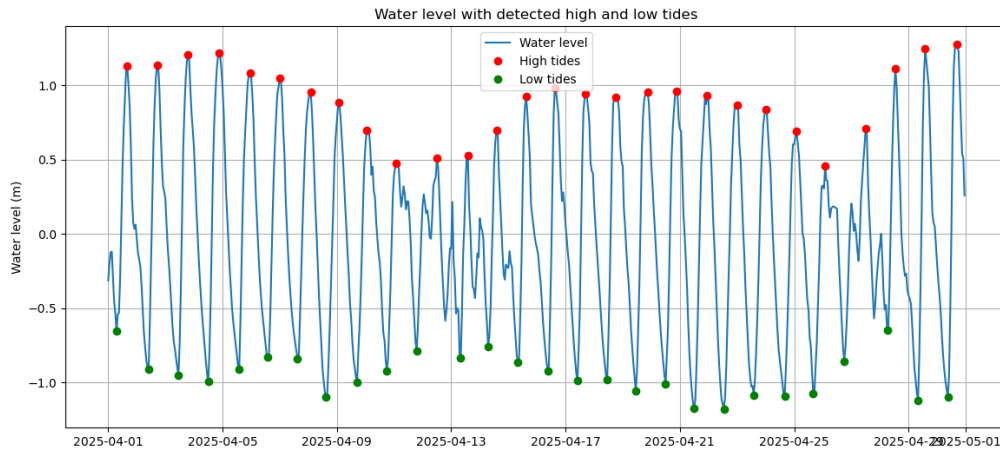


Figure B.15: Water Level over Time during the Measurement Campaign in Kim Đông

representative regular or average sea-states (calm, median, and energetic) are defined directly from the time series using percentile bands and conditional period estimates, providing inputs for the Delft3D model.

B.5.1. Data Input Copernicus Satellite

Wave conditions are assessed using hourly output from the ERA5 reanalysis dataset (The Copernicus Climate Change Service, 2025), taken between the years 1975 and 2024. This time is chosen to include all data following the construction of the first dike (as mentioned in Section 3.2). The variables included in the analysis are the wave direction, peak wave period (T_p), and the significant wave height (H_s), separated into:

- Wind-sea (locally generated waves)
- Swell (waves generated remotely)
- Combined significant wave height

Data extraction is performed in a rectangular domain defined by the following coordinates (WGS84 geographic coordinate system, EPSG:4326):

- Northern boundary: 19.55°N
- Southern boundary: 19.50°N
- Western boundary: 106.05°E
- Eastern boundary: 106.00°E

This rectangular domain covers the bay in front of the mangrove area and is shown in Figure B.16. The bounds are chosen in a way that the grid covers only water, not land surface. For the analysis, only surface level data was used (called: single level data).

Table B.3 provides an overview of the settings applied when retrieving wave data for Kim Đông. As outlined in Section B.5.1, information is obtained from the ERA5 reanalysis dataset, which provides hourly data on single levels from 1975 to 2024 (The Copernicus Climate Change Service, 2025).

B.5.2. Filtering Wave Dataset

As mentioned in Section 3.2, the shoreline of Kim Đông has changed significantly since the construction of the first dike. A substantial accumulated slab now protrudes into the bay, sheltering the bay from sectors in the east and north-east. This difference can be seen in Figure B.17 and Figure B.18.

The original dataset is comprised of 146 104 entries for both wind-waves and swell. The directional distribution of these waves, depicted in Figure B.19, shows a main direction for wind-waves of 35° and a main direction for swell of 130°, indicating a system dominated by north-easterly and south-easterly approaches. To create a dataset that more accurately represents the current wave climate for the model area in Kim Đông, a directional filter must be applied to the historical data.

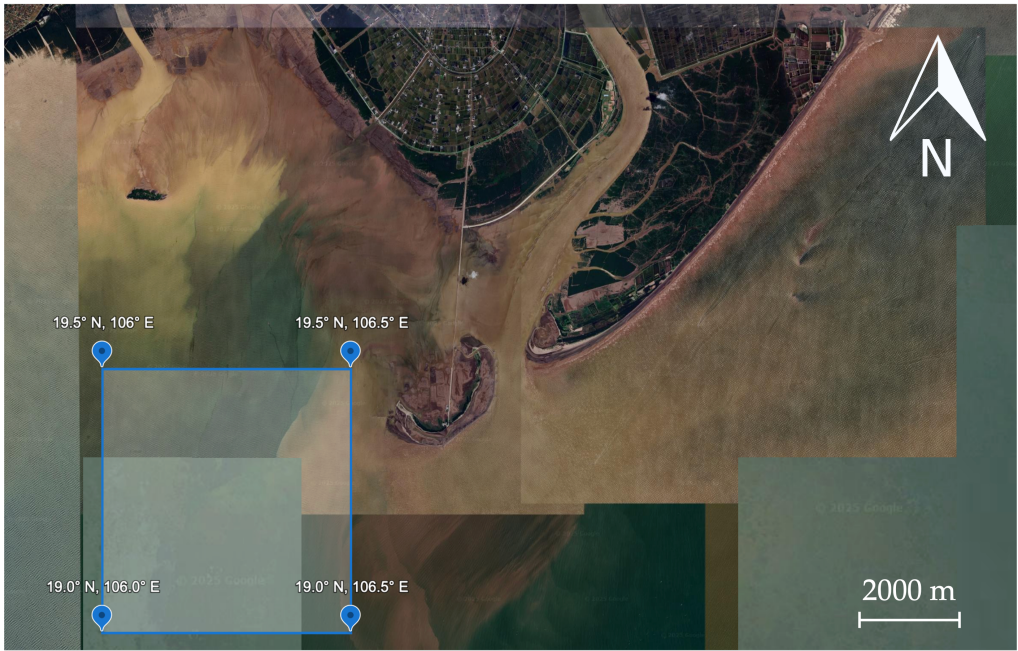


Figure B.16: Project Area (Google, 2015)

Table B.3: Overview of ERA5 Dataset Used for Wave Analysis

Dataset	ERA5 hourly data on single levels (1940–present)
Product type	Reanalysis
Variables	Significant wave height (swell, wind waves, total combined) Peak wave period Direction waves (swell, wind waves)
Time span	1975 - 2024
Months	All
Days	All
Time resolution	3-hourly (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00)
Geographical area	19.50 - 19.55 °N, 106.00 – 106.05°E
Data format	NetCDF4 (Experimental)

A filter is applied where incoming waves from 0° - 100° are excluded. This range is selected based on the orientation of the model grid and to exclude wave directions that are now obstructed by the accumulated landmass. This is illustrated in Figure B.20.

The number of valid entries for both wind-waves and swell is now reduced to 52 949. This corresponds to a reduction of 63.76%. The filtering process not only reduces the data volume but also shifts the prevailing wave directions. For the filtered data, the main direction for wind-waves is 174 °, while the main direction for swell is 130 °. The directional distribution of this final, filtered dataset is visualised in the polar plots in Figure B.21.

Summary Wave Conditions

A final summary of the remaining wave events, illustrating the frequency and directional distribution of the filtered wave climate, is presented in the heatmap in Figure B.22.

This study focuses on the combined wave spectrum instead of separately studying the effect of swell and wind-induced waves. This approach is taken because key coastal processes, such as sediment transport and erosion, are driven by the total wave energy arriving at the shoreline, making the distinction between wind-sea and swell origins less critical for assessing hydraulic forcing. Furthermore, numerical models like Delft3D typically use a single spectrum for boundary conditions, and using the combined

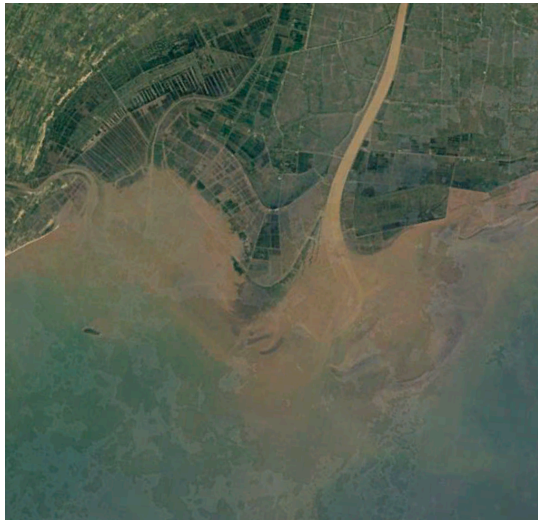


Figure B.17: Satellite Imagery of Kim Đông in 1984
(Google LLC, 2024)

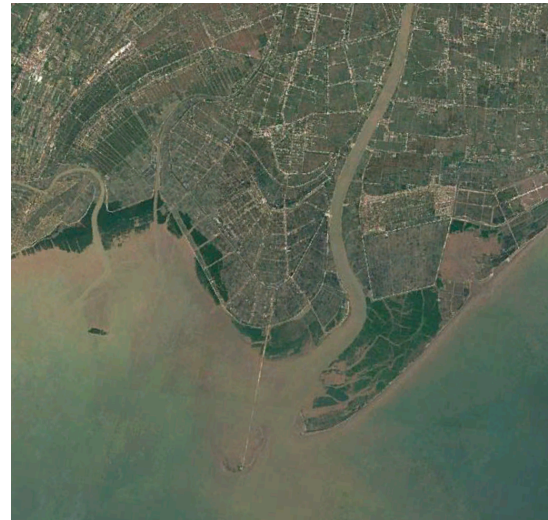


Figure B.18: Satellite imagery of Kim Đông in 2020
(Google LLC, 2024)

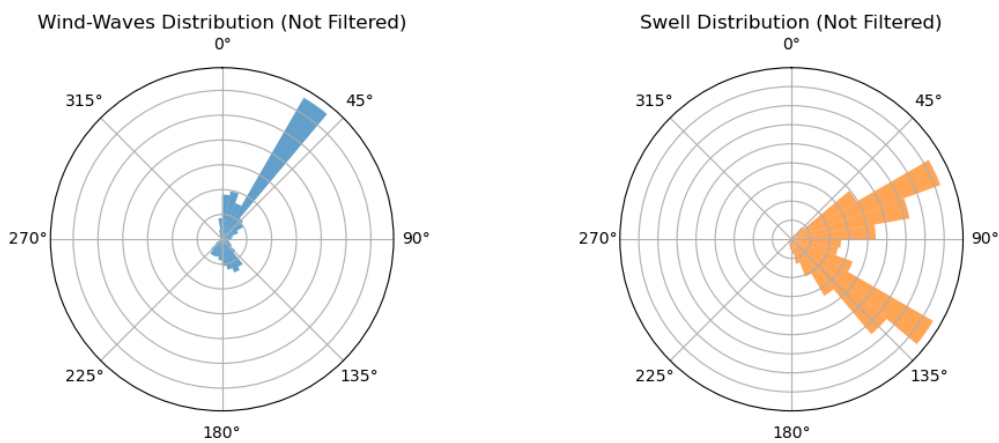


Figure B.19: Directional Distribution of Wind-waves and Swell in the Original Dataset

significant wave height (H_s) simplifies model implementation.

B.5.3. Sea-states for Model Input

Following the data filtering, a set of representative sea-states is defined to serve as boundary conditions for the Delft3D model. To assess the system's response to a full range of hydraulic forcing, both extreme and operational wave conditions are required. First, two extreme design waves are derived through statistical analysis to represent extreme storm events. Second, a set of more common, or 'regular', sea-states is defined to characterise the typical conditions that drive long-term morphological processes. The following subsections detail the methodology used to derive these distinct wave conditions for the model input.

JONSWAP Spectrum

The wave conditions in Kim Đông will be represented by using a wave energy spectrum. A spectrum provides a more realistic representation of the sea-state than a single, monochromatic wave, as it accounts for the distribution of wave energy across various frequencies and directions. For this model, the JONSWAP spectrum has been selected as the most appropriate spectral model for the regular wave conditions.

The JONSWAP (Joint North Sea Wave Project) spectrum describes the distribution of wave energy over different frequencies in a wind-generated sea-state for fetch-limited seas. It is a modification

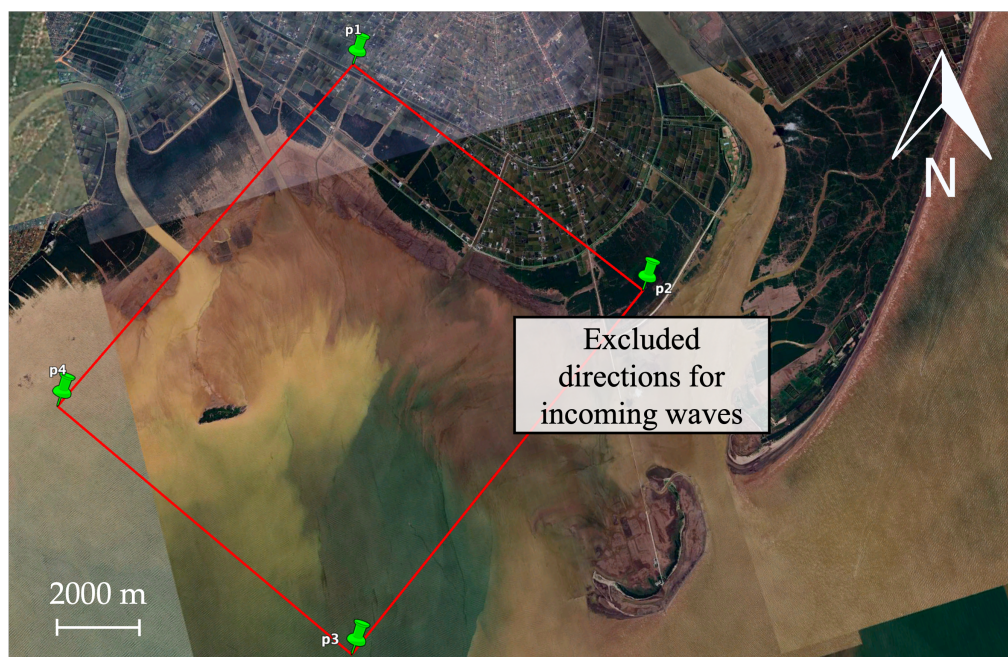


Figure B.20: Reduced Range for Incoming Waves

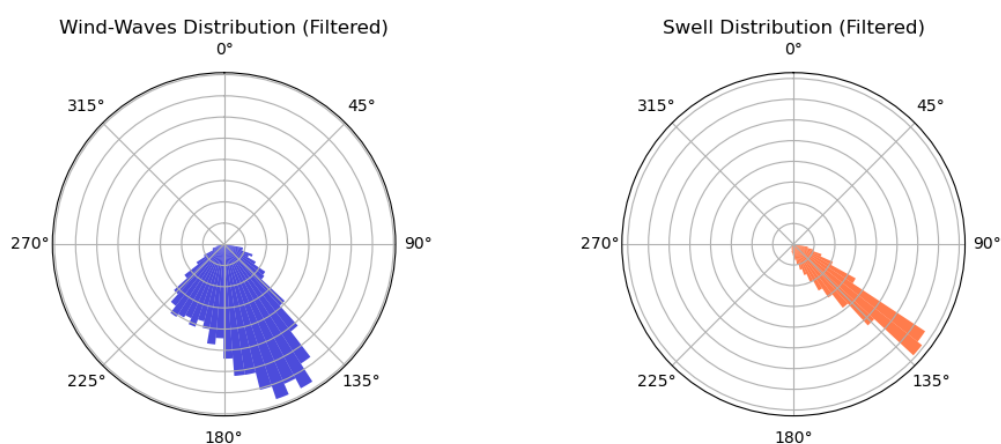


Figure B.21: Directional Distribution of Wind-waves and Swell after filtering for the Current Shoreline

of the Pierson-Moskowitz spectrum, which is a less peaked spectrum for fully developed seas. The JONSWAP spectrum was developed to better represent regions where wave growth is constrained by the distance over which wind blows with extensive measurements in the North Sea but can also be used in other fetch-limited seas (Hasselmann et al., 1973). Therefore, this model is particularly suitable for enclosed or semi-enclosed basins and coastal areas like Kim Đông, which is situated in the Gulf of Tonkin.

The Gulf of Tonkin, including the Kim Đông area, is a fetch-limited sea due to its semi-enclosed nature. Waves here are primarily generated by regional winds, particularly the summer monsoon (a rainy period in South and Southeast Asia between May and September), where winds come from the south and south-south-west. For example, for a south wind, the maximum fetch across the Gulf of Tonkin is approximately 180 kilometres (determined with Google Earth).

The use of the JONSWAP spectrum for this area is further validated by a study on wind-wave characteristics

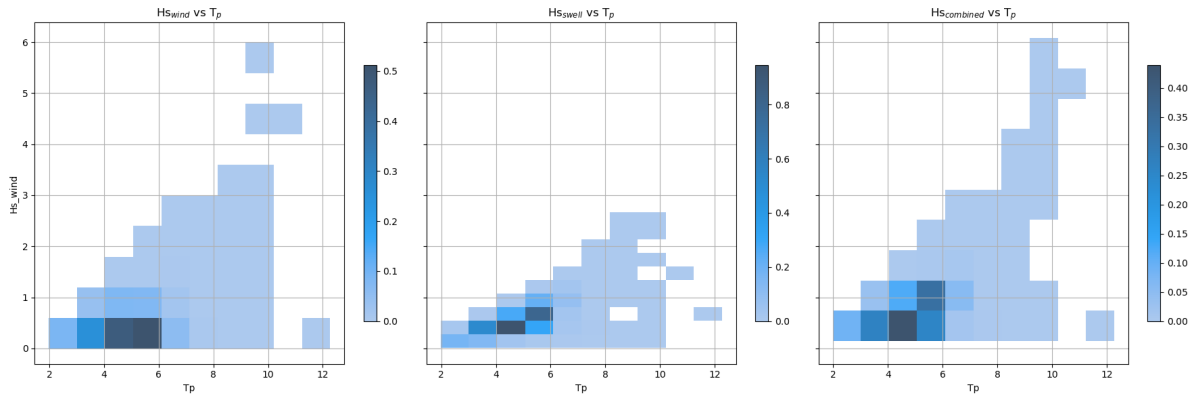


Figure B.22: Heatmap of Wave Occurrence based on the Filtered dataset, showing the Final Distribution of Wave Energy

in the South China Sea (De Silva, De Silva, & De Silva, 2013). This paper makes use of the JONSWAP spectrum and shows a strong positive correlation between modelled and observed significant wave heights in the region (De Silva et al., 2013). This provides evidence that the JONSWAP spectrum is an appropriate and validated choice for modelling wave conditions in the Gulf of Tonkin.

The peak enhancement factor, γ , is a crucial parameter in the JONSWAP spectrum that quantifies how peaked or narrow the wave energy spectrum is. It is the ratio of the maximum spectral energy density to the energy density of a Pierson-Moskowitz spectrum at the same peak frequency. A higher γ value indicates a narrower spectrum with more energy concentrated at the peak frequency, typical of actively growing seas. A value of $\gamma = 1$ reduces the JONSWAP spectrum to the Pierson-Moskowitz form (a fully developed sea). The original JONSWAP study, developed in the North sea, found a mean value of $\gamma = 3.3$ (Hasselmann et al., 1973), but later studies have shown that this parameter is highly variable and often lower for coastal, fetch-limited conditions (Kim, Ryu, Kim, & Kim, 2021). Typical peak enhancement factors for fetch-limited coastal areas range from 1 to 3.3, and selecting a value within this range is suitable for the model. Figure B.23 shows the standard JONSWAP spectrum for different values of γ .

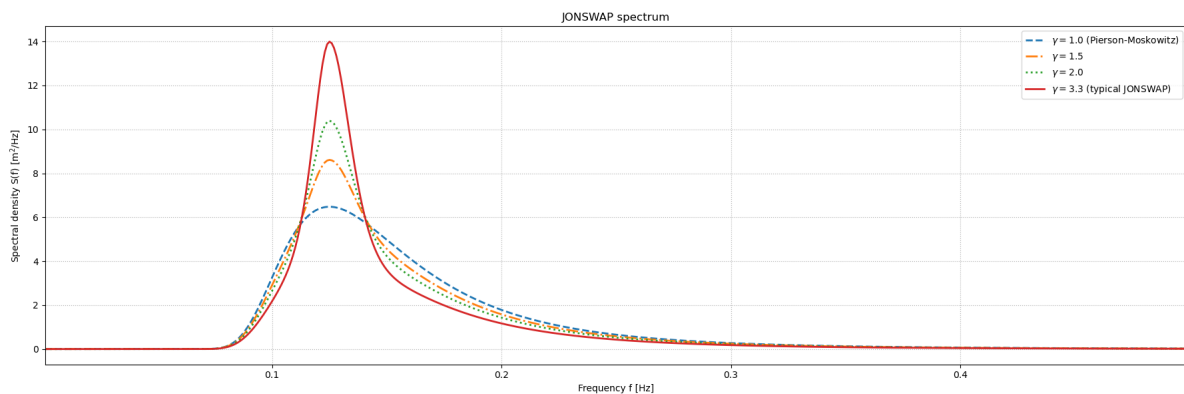


Figure B.23: JONSWAP Spectrum for Different Peak-Enhancement-Factors (γ)

Extreme Wave Conditions

To evaluate the extreme wave climate of the total spectrum, a Peak-Over-Threshold (POT) approach is used. This method is a widely used method in extreme value analysis and is often preferred over methods like Block Maxima because of its ability to capture relevant seasonal influences. With the POT method, all events that exceed a predetermined threshold are considered for the analysis. A key advantage of this approach is its ability to include multiple, independent extreme events within a single year or season. Simultaneously, it avoids the issue of selecting non-extreme maxima during periods with low extreme storm activity, ensuring that every data point in the analysis is genuinely significant. The method requires two key parameters to be defined: a threshold value (u) to identify extreme events

and a declustering time (dl) to ensure that events are statistically independent.

A critical step in the POT analysis is the selection of an appropriate threshold. The threshold must be high enough for the statistical theory to be valid, yet low enough to retain a sufficient number of events for a reliable analysis. To help with this selection, the Mean Residual Life (MRL) plot is used. An MRL plot is a tool that shows the average excess of the data over a given threshold. The selection of an appropriate threshold is done by identifying a range in the plot where a clear linear relationship appears. As shown in Figure B.24, this linearity occurs between 1.5 m and 2 m of significant wave height. Based on this trend, a threshold u of 1.65 m is chosen for the POT analysis.

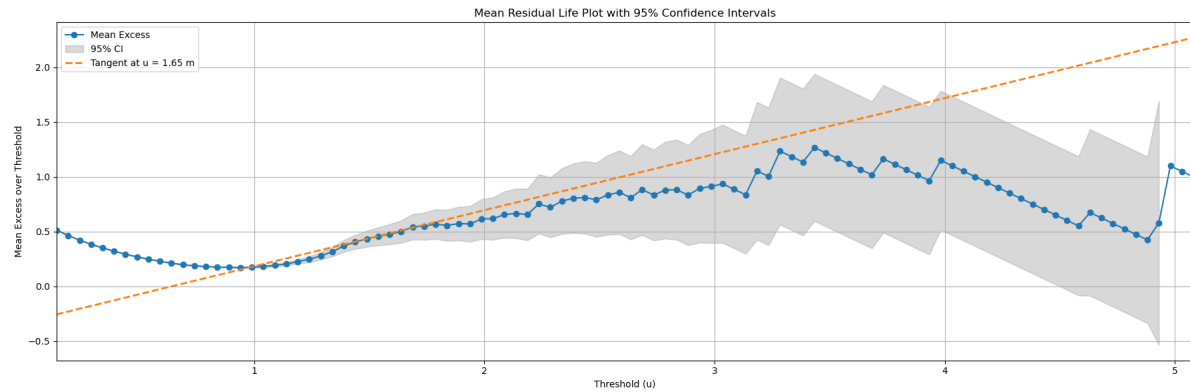


Figure B.24: Mean Residual Life (Declustering Time = 96 hours)

With this configuration, where the threshold value is set at 1.65 m and the declustering time is 96 hours (typical for typhoon-induced storms, according to McElman, Verma, and Goupee (2025)), the POT method is implemented as illustrated in Figure B.25.

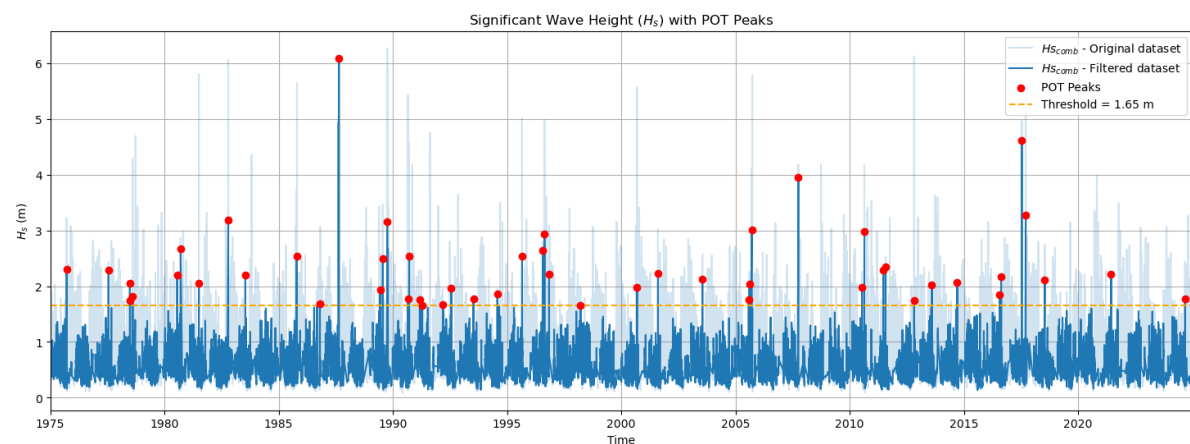


Figure B.25: Identification of Independent Extreme Events using the POT Method for the Total Wave Spectrum

To estimate the magnitude of rare extreme storm events for design purposes, a probability distribution is fitted to the identified extreme wave heights. This statistical model allows for extrapolation beyond the observed data to calculate design values for specific return periods.

The analysis is conducted using the 'Reliability' Python library, which fits several probability distributions to the data using the Maximum Likelihood Estimation (MLE) method. To select the most appropriate model, the goodness-of-fit of each distribution is evaluated using several statistical criteria. For these tests—Log-likelihood, AICc, BIC, and Anderson–Darling—a lower score indicates a better fit to the data. The results of this comparison are summarised below.

- Log-likelihood: Gumbel 2P (−80.42)
- AICc: Weibull Competing risks (46.89)
- BIC: Weibull Competing risks (53.65)
- Anderson–Darling: Exponential 1P (0.58)

Because the Weibull Competing Risks achieves the best performance across the statistical tests, it is selected as the most representative model for this dataset. The fitted distribution is displayed in Figure B.26, and it forms the basis for estimating design values of significant wave height.

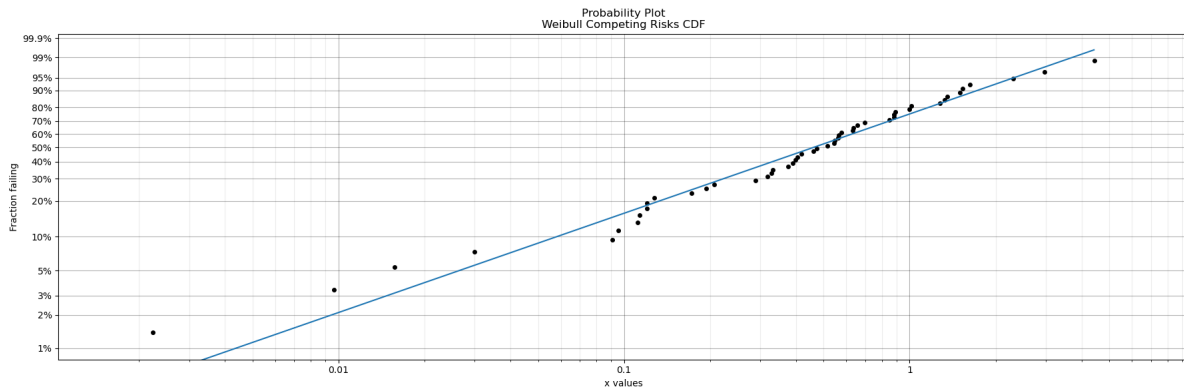


Figure B.26: Weibull Competing Risks Distribution fitted to the Extracted Extreme Wave Events

Now that a reliable statistical model for extreme wave heights is established with the Weibull Competing Risks distribution, it can be used to determine the design wave height for the project. For the required level of safety, and thus the design return period, the significant wave height is determined by local engineering standards. With this design wave height, also the statistical yearly returning wave is calculated to simulate the impact these extreme storms have on the project area.

According to the Vietnamese national standards for coastal protection structures, the Kim Đông coastal area is classified as a Class IV structure (Ministry of Science and Technology, 2023). This classification dictates the design frequency that the structure must be able to withstand. As shown in Table B.4, a Class IV structure corresponds to a design frequency of 3.33%, which translates to a required return period of 30 years.

Table B.4: Design Frequency for Waves and Water Level by Structure Class (Ministry of Science and Technology, 2023)

Structure class	I	II	III	IV	V
Design frequency, %	0.67	1.00	2.00	3.33	< 10.0
Corresponding return period n , years	150	100	50	30	> 10

This 30-year return period is now used as input for the fitted Weibull Competing Risks distribution to calculate the corresponding significant wave height. A 30-year return level yields a significant wave height H_s of 4.31 m. The corresponding peak period T_p is taken from the heatmap for $H_{s,combined}$, and is determined to be 9.30 seconds. The 1-year return level yields a significant wave height H_s of 1.65 m and a peak period T_p of 8.15 s. This is shown in Figure B.27.

Regular Wave Conditions

To complement the extreme design case, a small set of representative regular (monochromatic) sea-states is defined to characterise day-to-day conditions for nearshore process studies and sensitivity tests.

To do this, instead of computing a Significant Wave Height value (H_s) and Peak Period value (T_p) by fitting a probabilistic distribution and using a return level value, the entire wave spectrum is divided into three different sea-states: a calm, median and energetic sea-state.

The three sea-states will be taken directly from the time series and are split up in the following percentile bands: Calm sea-state (20th–30th percentile), Median sea-state (45th–55th percentile) and an Energetic

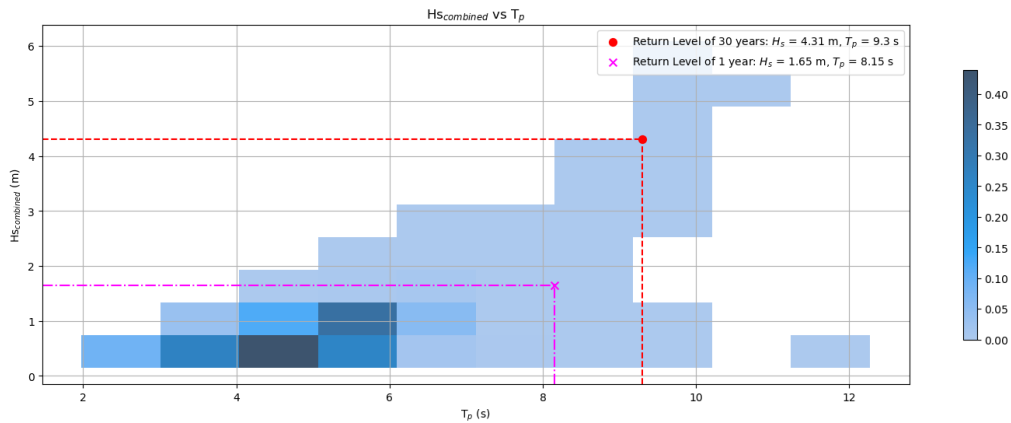


Figure B.27: Determining T_p for a 30-year and 1-year Return Period

sea-state (80th-90th percentile). This method is supported by Roelvink (2006), which outlines the need to reduce complex and variable boundary conditions into a simplified scenario to make long-term simulations computationally feasible.

For each band, the representative height (H_s^{rep}) is taken as the median of the wave heights within that band. The corresponding representative peak period (T_p^{rep}) is calculated as the maximum period associated with the same wave events, ensuring that the peak period remains within the constraints of Kim Đông Bay. The peak period is selected here instead of the more commonly used mean period, as Delft3D uses this as an input parameter. The final parameters used for modelling are summarised in Table B.5.

Table B.5: Parameters for Representative Regular Sea-states for Wave Modelling

Sea-state	Percentile Band	Rep. Height, H_s^{rep} (m)	Rep. Period, T_p^{rep} (s)	Peak Factor, γ
Calm	20th – 30th	0.47	4.47	3.3
Median	45th – 55th	0.64	4.91	3.3
Energetic	80th – 90th	0.90	5.51	3.3

By using these three sea-states in combination with a JONSWAP spectrum in a model, an accurate representation of the regular wave spectrum can be used in Delft3D.

B.6. Wind analyses

In this appendix the process of obtaining the model input will be evaluated. The method for obtaining the governing wind conditions follows the same steps as outlined in Appendix B.5.

B.6.1. Filtering Wind Dataset

A directional filter, identical to the one used for waves, is applied to exclude winds that do not coincide with the incoming waves. This ensures that wind directions that would produce non-existent wind-wave combinations are removed. Figure B.28 and Figure B.29 show the distributions of incoming wind directions for both the filtered and unfiltered datasets.

B.6.2. Wind States for Model Input

After filtering the data, representative wind states are defined for the Delft3D model. Both extreme and typical wind conditions are needed to assess the system's response. Extreme wind states are derived through Extreme Value- and Peak-Over-Treshold Analysis to represent extreme storm events, while regular wind states characterise typical conditions for long-term processes, for which its methodology is explained in more detail in Appendix B.5.

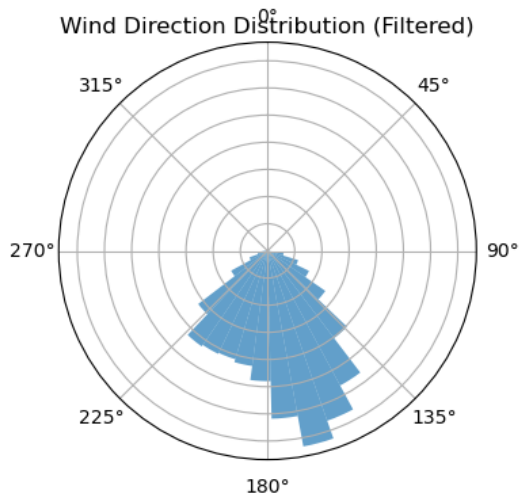


Figure B.28: Wind Direction Distribution (Filtered)

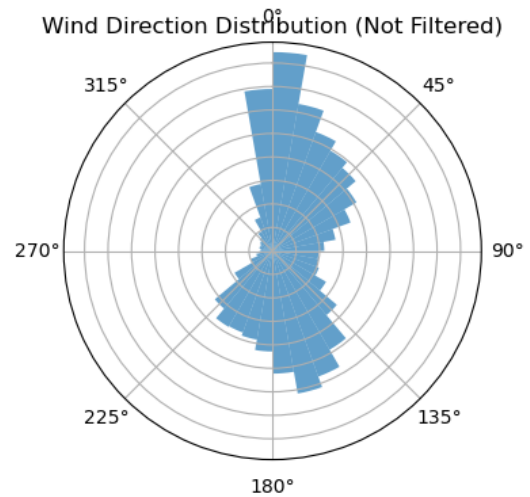


Figure B.29: Wind Direction Distribution (Not Filtered)

Extreme Wind Conditions

Following the same methodology outlined for wave conditions in Appendix B.5, the Peak-Over-Threshold method is used to identify extreme wind events. The threshold for extreme wind is selected based on the mean residual life plot, with declustering performed over a 96-hour window to capture significant typhoon-related events. The threshold is set at 10 m/s, resulting in 62 peaks.

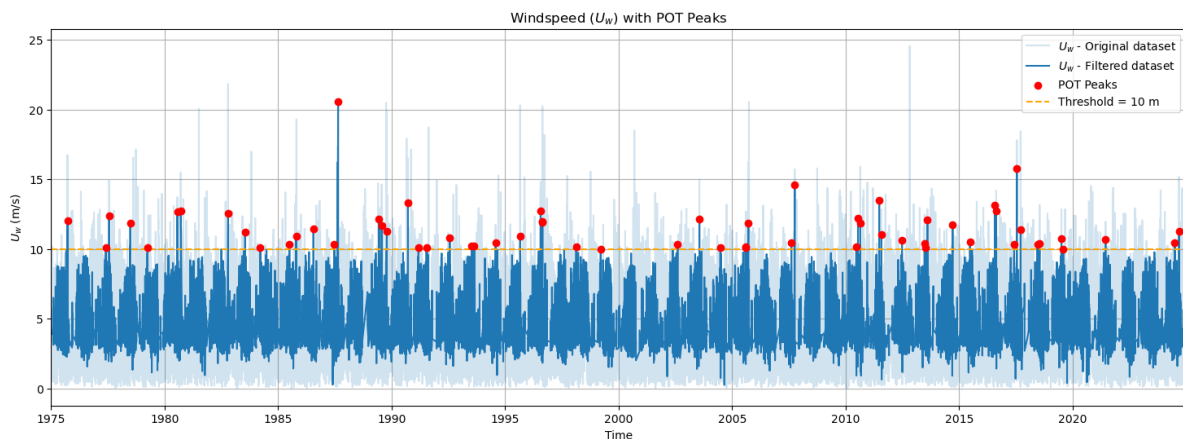


Figure B.30: Identification of Independent Extreme Events using the POT Method for the Total Wind Spectrum

Figure B.30 illustrates the identification of independent extreme wind events using the POT method for the total wind spectrum, while Figure B.31 shows the exponential distribution fitted to the extracted extreme wind events.

Because the Exponential Distribution (1P) achieves the best performance across the statistical tests, it is selected as the most representative model for this dataset. The fitted distribution is displayed in Figure B.31, and it forms the basis for estimating design values of the return period wind speed.

With a statistical model for extreme wind speeds based on the exponential one-parameter distribution now established, the project's design wind speed can be derived. The annually recurring wind speed is computed to represent more frequent extreme storms, and the 30-year recurring wind speed is in line with the design life of the structure, as presented in Table B.4 in Appendix B.5.

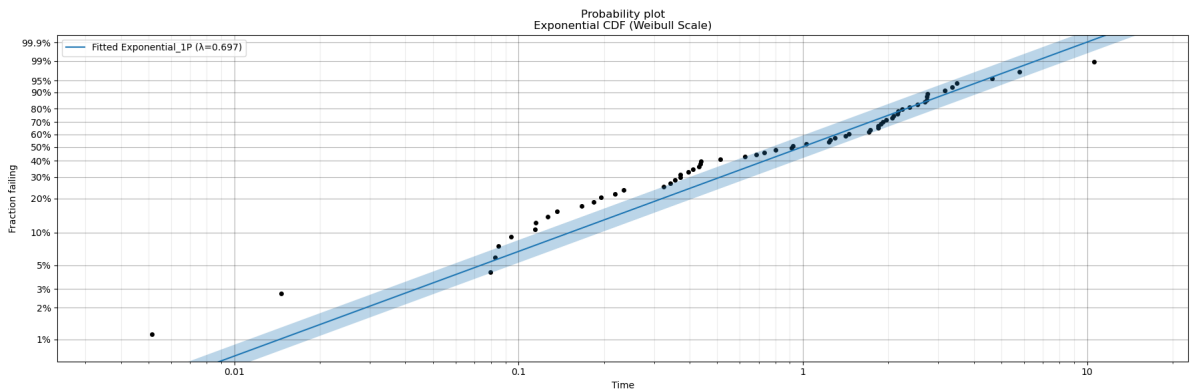


Figure B.31: Exponential Distribution fitted to the Extracted Extreme Wind Events

Table B.6: Wind Speed Characteristics

Wind State	U_{wind} (m/s)
Moderate winds: 1-Year Return Period	10.228
Extreme winds: 30-Year Return Period	15.860

Regular Wind Conditions

Following the approach in Appendix B.5.3, the wind record is split up into three percentile bands to capture day-to-day forcing: calm (20th–30th), median (45th–55th), and energetic (80th–90th). For each band the representative wind speed, U_{wind}^{rep} , is taken as the median within that band. The wind speed values are presented in Table B.7.

Table B.7: Representative Regular Wind States for Wind Modelling

Wind State	Percentile Band	Rep. Wind Speed, U_{wind}^{rep} (m/s)
Calm	20th – 30th	3.87
Median	45th – 55th	5.60
Energetic	80th – 90th	8.04

C | Interviews

In this appendix, the prepared questions for the semi-structured interviews are projected, as well as the actual interview.

C.1. Prepared Questions Beforehand

Questions were prepared beforehand for the interviews. These were prepared for researchers in general, the local authority and Dr. Tri to gain specific insights on Dike 4.

C.1.1. Questions Researchers

The questions for researchers were focussed on the whole coastal system of Kim Đông. Depending on the expertise of the researcher, additional questions were asked during the interview.

Questions regarding the ecosystem and land-use trade-offs:

1. What are important factors that influence the mangrove system in Kim Dong?
2. From your perspective, how does the mangrove system perform in Kim Dong compared to other areas?
3. What role do mangroves play in Kim Dong from an ecological and socio-economic perspective? Are there benefits for local communities? (economical, flood risk reduction).
4. What are the benefits in general of mangroves? Who wants them to be there?
5. Who or which organizations are planting new mangroves? Are these projects? Who funds those?
6. Are ricefields as important as aquaculture in Kim Dong? Are they the same kind of threat to mangrove forests?
7. What are the trade-offs when looking at land allocation between mangroves, rice-fields, aquaculture etc.?
8. Who wants to expand aquaculture? Big companies or the community?
9. Are mangroves also cut down for wood?

Questions regarding governance, institutions and policy:

1. How do you see the decision making of the local authority in relation to mangrove management? Does the government want mangroves? Why?
2. How would you describe the governance structure in Kim Dong?
3. Do you think policies from the province or central government align with mangrove conservation goals? Or are there contradictions?
4. From your perspective, what are the main governance challenges that hinder mangrove protection in Kim Dong?
5. What if mangroves are illegally cut down? Are there rules about that? Who is cutting down the mangroves mostly? Who is seeing to it that it does not happen? Are there fines?

Questions regarding data and monitoring:

1. What methods are currently being used to monitor mangrove health and growth in Kim Dong?
2. What is known about hydraulic factors in the Kim Dong area like sediment transportation etc.?
3. Are there knowledge or data gaps that make it harder to design effective mangrove management in Kim Dong?

Questions regarding challenges and coastal protection:

1. In your experience, what are the biggest threats to mangroves in Kim Dong (aquaculture, infrastructure, climate change)?
2. Are there strategies that have proven to be effective in balancing mangrove conservation, considering aquaculture development?
3. How do you assess the current coastal protection structures in place? How do you balance these with the needs of aquaculture?
4. Who decides that new dikes should be built? How much does it cost?

Questions regarding stakeholders:

1. How do you, in your project, collaborate with different authorities?
2. Who or what do you think are the most influential people or organizations when it comes to mangrove management in Kim Dong?
3. How would you assess the capacity of the commune to implement mangrove-related projects (staff, resources, training, knowledge)?
4. Do local communities play an active role in the mangrove projects you are involved in? In what way?
5. What about the law on land ownership, I read that people can only own a max. hectare of land. How does this work? Who allocated the land? Are there exceptions? Who owns the land with mangrove forests?
6. Who is paying for the research you guys are doing in Kim Dong?
7. Are there other international parties involved?
8. Does the church have influence in Kim Dong?
9. Is tourism important in the Kim Dong area?

Closing questions:

1. What do you think would help the Commune most to deal with its main challenges?
2. What would it take to make sure more mangroves will thrive in Kim Dong?
3. Is there anything else you would like to share, or is there something you think we have missed?

C.1.2. Local Authority

The questions for the local authority were focused on the whole coastal system of Kim Đông, but specifically on governance, stakeholders and funding.

Questions regarding the area in general:

1. How would you describe Kim Dong to someone who has never been here?
2. What are the main economic activities here in Kim Dong?
3. What are the biggest changes the commune has seen in the past years?
4. What are the biggest challenges you focus on for the Kim Dong commune?
5. Has something about that changed in the past years?
6. Are there other organizations or individuals that hold influence or decision-making power within the commune?

Questions regarding mangroves:

1. How important are mangroves for the commune, and in what way? (economical, environment, flood protection)?
2. How does aquaculture expansion affect mangroves here?
3. What role does the local government play in balancing mangrove protection and aquaculture development?
4. How is the collaboration with the department of forestry regarding mangrove protection?

5. Recently, we read that in collaboration with Korea, numerous new mangroves were planted. Have there been more of these projects?
6. Does the commune receive technical, financial or training support for mangrove management? From whom?
7. How does the local community participate in mangrove-related projects?
8. The fourth dike is only halfway finished. Do you want to finish it? Why? Where does the money for finishing the dike come from?

Questions regarding governance and stakeholders:

1. How would you describe the governance structure in Kim Dong?
2. How do different departments of the Kim Dong commune work together?
3. How are the members of the Commune People's Committee selected? Are they elected, appointed or assigned?
4. With which governing bodies, organizations or people do you cooperate most often?
5. How would you describe the collaboration with mass organizations such as the Women's Union or the Red Cross?
6. How often do you have to report back to the province, and in what form?
7. Do provincial officials visit regularly to check activities?
8. Have there been cases where you needed approval from higher levels (province, central government) before acting locally? How does such a process go?
9. Do you feel that provincial and central government policies on mangroves are clear and consistent?
10. Do you feel the local community is part of decision making processes in Kim Dong? How are they included?
11. Which projects or policies have been important for Kim Dong recently?
12. Are there examples where local initiatives or experiments were supported, or where they faced obstacles from higher authorities?

Closing questions:

1. What do you think would help the Commune most to deal with its main challenges?
2. What would it take for the local authority to make sure more mangroves are planted?
3. If you could change one thing in how policies are made or implemented, what would that be?
4. Is there anything else you would like to share, or is there something you think we have missed?

C.1.3. Dr. Tri

The questions for the Dr. Tri were focussed on Dike 4, since there were almost no resources to be found on that subject.

Questions regarding Dike 4:

1. What was your role in the development of the fourth dike?
2. Were you involved in the construction of the other dikes in Kim Dong?
3. Why was the fourth dike not finished in one take?
4. Why will the fourth dike be finished?
5. Who decided that the fourth dike would be finished?
6. Where does the funding for the dike come from?
7. Can we access the design plans for the rest of the fourth dike? Where will it be exactly?
8. How many gates will there be in the fourth dike and where will they be?
9. What company or companies design and build the dike?

10. When will the fourth dike be finished?
11. What do you think the effects of finishing the fourth dike will be?
12. Have you seen any change after the first section built of the fourth dike?
13. Is someone monitoring the area?
14. Do you have any relevant sources or documents for us to use?

C.2. Expert Interviews

In this section, the expert interviews are projected. The dark green text are main takeaways from the interviews.

C.2.1. Dutch Embassy

Date: 23-09-2025

September 23rd, this MDP group was invited to the Dutch Embassy together with another MDP group who were also working on a project regarding mangroves in Vietnam. Present at the lunch and meeting were three Dutch employees and three Vietnamese employees. All had an expertise relating to our project like environment, water management or communication. The insights gained during the lunch were used by the writing of this report.

C.2.2. Interview Ms. Trần Thị Lợi - MSc in Environmental Sciences, member of the Kim Đông mangrove project

Date: 12-09-2025

This interview was recorded by 'Voice Memos' and transcribed by Turboscriber

Thank you for taking the time for us. We will use this interview to gain more insights into how mangrove systems work and what improvements we can ultimately recommend. Could you give us a short introduction and tell us about your work here?

My name is Lợi, and I am a mangrove researcher. My research focusses on ecology and preservation of mangrove forests. I have been working at the institute of Civil Engineering at Thuyloi University for 1 year now. Before that, I have worked at the institute of ecology and forest protection, and I have worked in some NGO organizations where I focussed on marine conservation in Vietnam. I have worked in the Mekong Delta area and the Red River Delta.

How are you involved in the mangrove projects from Thuyloi and the Vietnamese government?

I joined this project in the beginning. Thuyloi University asked the government for funding of the project. This worked, because the project is funded by the department of science and technology of Ninh Binh province. The project lasts 48 months, so 4 years. My focus lies on mangrove preservation since I have a background in ecology. We are also looking into planting new mangrove forests.

Have you guys already decided where the new trees will be planted?

Yes we have identified the site of the model at gate 10 and gate 11, both sites will be 5000 hectares.

From your perspective, how do the mangrove forests in Kim Dong perform compared to other areas in Vietnam?

The mangroves in Kim Dong grow well, but have a lower biodiversity with fewer species. If you would go to the Mekong Delta, you would see that the mangroves have very high biodiversity with many species.

Do you think that a higher biodiversity is better for mangroves to thrive?

Yes of course, the more species the better.

And what about the planting of certain tree species? Mr. Trung told us that a certain mangrove tree is mostly planted in the Kim Dong area. Which kind is that and why?

We are planning to plant three kind of species. Some are native species which grow in nearby areas. We want to see how they perform in Kim Dong. We want the biodiversity to be higher, that is why we want to plant multiple species.

What do you think are the most important factors that influence the mangrove system in Kim Dong?

I think there are many important factors that influence the mangroves. For example, the aquaculture development. In some areas this developed very fast. Local people cut down the mangrove trees to be able to make aquaculture ponds. That is just one of the reasons why the mangrove area is decreasing. Another reason is the development of certain infrastructure, especially the dike constructions.

What would happen if the fourth dike would be finished?

The mangroves need water from the tidal and sediment to grow. When the dike would be finished, it would prevent sediment and water from the tide, from the sea, to go to the trees. There are a few gates in place, but most of the sediment that goes through the gates is very little compared to when there would be no dike. Also, after some years the mangroves inside the dike will die.

What role do mangroves play in Kim Do from an ecological and socio-economic perspective?

Many fish, shrimp and clams are living inside the mangroves. **The local people can get their economic benefits from the mangroves by collecting and catching these animals inside the mangroves.** Now, in Kim Dong, people develop extensive shrimp farming. They cut down mangroves and create aquaculture ponds.

Do you think the local government realizes that mangroves are a really efficient way of protecting the shore, or will they only believe a dike?

I think that most people from the local authority understand the role of mangroves in protecting the seas dike and to provide the benefits for them. Now, people are no longer cutting the mangrove trees.

Are all the shrimp farms from local people that live there? Or are they from bigger companies that pay them?

In Kim Dong, most of the shrimp farms belong to the local people because it's quite small scale. Most bigger companies are located in the Mekong Delta.

How do you see the decision making of the local authority in relation to mangrove management? And does the government want mangroves there?

Recently, the local authority has some policy to protect the mangroves. In Vietnam, the mangroves are managed by the Department of Forest Protection, and the land is managed by the local commune. Most policies regarding mangrove protection belong to the Department of Forestry.

Do you feel that those protection policies are well executed?

Yes, they are executed well. **Local people are no longer cutting the mangroves because of the policy.**

What is the main goal of the government in relation to mangrove coverage? Do they want to prevent erosion and offer coastal protection most of all, or is it a way for them to gain land in a more efficient way?

I think it is a mix of ecological, economical and other reasons.

Who has more influence with relation to the decision making of eventually planting mangroves? The local commune or the department of forestry?

I think the department of forestry, because they manage the mangroves. Both of them have to follow the plans of the province. So, the Ninh Binh province ultimately has a lot to say about where mangroves are going to be planted.

What are the main governance challenges that hinder mangrove protection in Kim Dong?

The main challenge is to balance the economic benefits and mangrove protection. When the fourth dike would be finished, that land will be meant for agriculture and aquaculture, which will affect the mangroves.

How do you collaborate with different authorities with your project?

The project is funded by the Department of Science and Technology of Ninh Binh province. They have introduced us to the local community. We ask the local community for help with the project. Also, we work with the department of forestry because they manage the mangroves. They provide a lot of information.

We ask local people to help us with planting mangroves. It both provides an income for them, but also helps increase awareness.

How can the local community contribute to a project?

They provide us with information about the area, the weather conditions, the land use, the policies in place... It helps us understand the area. Also, if we do not have permission from the local authorities (consisting of local people) we cannot work.

Are there any knowledge or data gaps that make it harder to design effective mangrove management?

Sometimes we have to face the difference in the knowledge sharing between the different agencies of different people. Many stakeholders are involved which makes it complex. **The local commune, department of forestry and department of dyke construction also have conflicted interests which makes it even harder.**

What data and monitoring techniques are used now?

We monitor the land by flying over the area every three months and comparing the maps. Also, we do several different measurements.

C.2.3. Interview Ms. Thao - Professor Sociology

Date: 15-09-2025

This interview was recorded by 'Voice Memos' and transcribed by Voice Memos. Also, a student from Thuyloi University translated English to Vietnamese and the other way around during the interview.

So, maybe to introduce ourselves: we're working on a project about the mangroves in Ninh Binh, in the Kim Đông area. We're looking at all the factors that influence the mangroves and how they can thrive here. That's what we'd like to talk about today. And we wanted to ask if Ms. Thao could introduce herself and tell us a little about her work or what she knows about the area.

She says she is a sociologist and psychologist, and in the past she used to visit the mangroves in Ninh Binh to study the forests and the human impacts on mangrove land. She also mentions that in a neighboring area called Quynh Cuu, there are mangroves too. She has interviewed local people there about the mangroves and their impact.

So, could you tell us what you think are the most important factors influencing the mangrove system?

She explains that human activity is the biggest factor. People have been exploiting the mangrove forests for their livelihoods, and this has caused degradation.

What kind of activities do people do? Why do they cut down the mangroves, and what do they want to use the land for?

She says people clear mangroves for aquaculture, especially shrimp farming.

And is aquaculture the only thing they do with the land, or are there other activities as well?

She explains that aquaculture is the main activity, but people's livelihoods have also changed. In the past, many depended on mangroves, but now people move to cities for jobs. As a result, they care less about the mangroves.

So the big problem is that people move away to cities?

Yes, but she adds that the bigger issue is not just out-migration. The main problem is that when mangroves are young, people can remove them for aquaculture. Once mangroves are mature, they can't easily be cleared, but people still find ways to bypass regulations.

Are there benefits of mangroves for the local community? Do people recognize them?

She says the benefits are not shared equally. Only a small group of people with aquaculture farms inside the mangroves gain, while most villagers don't benefit directly, so they don't care much.

So only the aquaculture farm owners benefit? Are they rich?

Yes, she says usually they are wealthier people, able to get contracts and long-term rights. Ordinary villagers see mangrove change slowly, so they don't view it as an immediate problem.

So the community is more interested in making money from farming or moving to the city than protecting mangroves?

Yes, that's correct.

But I don't fully understand. Aquaculture and fishing seem to reduce mangroves, but people moving away should reduce pressure on mangroves, right?

She explains it's more complicated. **Investment contracts allow companies to operate in mangrove areas, and local people often just work for them. So even if villagers leave, companies continue exploiting mangroves.**

So investment is the key issue?

Yes, because contracts require upfront capital. Local people often don't have the money, so only companies or wealthier investors get involved. They also must pay taxes, buy land, and meet environmental regulations, which is hard for poorer villagers.

And what about government policies? Does the government want mangroves?

She says yes, **the government wants mangrove expansion, partly because they can sell environmental certificates (carbon credits) to countries like China.** Industries there need to offset their environmental impact, so they buy credits from Vietnam.

So the government supports mangroves both for protection and for selling credits?

Yes. Local governments also plan mangrove planting, but the main planning comes from the provincial level.

How would you describe the governance structure?

She explains that policies come from the central government, then down to provinces and communes. For example, national policy now requires a buffer zone of about 1–2 km from the sea where houses and farms are restricted. But it's hard to implement because people already live there.

Do local communities influence policy?

She says ordinary people have little influence. **Only a small, wealthier group can sometimes affect local government decisions.**

Do people follow national policies?

She says most people do follow the laws, but not strictly.

Who are the most influential actors?

She explains it's mainly companies with aquaculture contracts. **They sometimes exploit loopholes, for example by reporting mangrove loss as caused by storms instead of human activity, so they can legally clear areas.**

So what does she think is the biggest threat to mangroves?

She believes the main factor is government policy. **While the government focuses on the environment and mangroves, in practice it is driven by economic goals and land expansion.** Mangroves help stabilize land and protect infrastructure, but the tension between economic use and protection remains.

What could be the solution for healthier mangroves?

She says it requires both policy change and greater awareness. Local people, especially youth and local authorities, need a better understanding of mangrove value. Scientific knowledge and technical expertise are crucial because without it, projects fail. For example, many mangrove planting projects fail after the first year due to poor conditions.

Can local people be motivated to care more?

She says it's difficult, because young people prefer moving to cities with better opportunities. Changing their mindset is not easy.

And what about policy?

She says policies are changing slowly. There are stricter rules in some sectors, like traffic laws, and people obey them because of high fines. But environmental enforcement is weaker, partly because local people are poor and sometimes related to officials, so fines are rarely applied.

C.2.4. Interview Dr. Tung Dao - PhD. in Coastal Engineering and Lead member of the Kim Đông mangrove project

Date: 24-09-2025

This interview was recorded by 'Voice Memos' and transcribed by Voice Memos

First of all, thank you again for taking the time to meet with me. My goal here is to gain more background information about this specific area. We already have a lot of general information on mangroves, but not much on this particular region. So that's what I'd like to talk about today. Could you start by introducing yourself and explaining a bit about what you do here?

Thank you. My name is Tung Dao, and I am a project member in the Kim Đông project. Our project focuses on developing new methods to keep the mangroves healthy. We also conduct experiments on planting, growing, and evaluating the survival rates of mangroves. I've been involved since the beginning, and I've carried out several measurement campaigns. For example, in our first campaign in April, we measured wave and water levels as well as mangrove characteristics. I'm glad to share more about that today.

Great. You mentioned measurements. What are the most important factors that influence mangroves in this area?

Mangroves depend heavily on the tidal environment. The tidal flat is directly linked to the water level, and mangroves grow together with these tidal conditions. If I want to evaluate the health of mangroves, I first look at the water levels in the area.

Have you noticed major changes in recent years? For example, with climate change and sea-level rise?

Yes, there are several factors that affect how well mangroves survive. First, there are natural factors: **tidal forces often push the mangrove line backward.** The front line usually dies first, but mangroves are resilient. They can spread seeds and regrow, even under harsh seasonal conditions like the monsoon. Second, there are human factors: in the past 25 years, three layers of dikes have been built here. Each dike traps more sediment, but it also pushes the mangroves further inland. **This creates what we call the "mangrove squeeze": mangroves are trapped between rising water levels on one side and dikes on the other.** Eventually, they run out of space. Our project tries to understand this and to find ways to promote sedimentation so mangroves can expand again.

So would you say the dikes are the main human factor affecting mangroves? What about farmers or aquaculture activities?

The dikes are indeed very influential, but other human activities also matter. Historically, engineers didn't pay much attention to ecosystems. Nowadays, coastal engineering increasingly considers "building with nature," which is a positive change.

Farmers also play a role. In this area, they benefit from mangroves by harvesting crabs, fish, and other products. At the same time, mangroves protect them from storms and floods. So there is a mutual dependence. **However, farmers alone cannot protect mangroves. They need support from engineers, scientists, and policymakers.**

And how does this mangrove system compare with other regions in Vietnam?

Here, the mangroves are relatively healthy compared to some northern sites because the area is rich in sediments. But if you compare this region to the Mekong Delta, the difference is huge. Mangroves there can reach 5 meters on average, while here they are usually around 2.5 to 3 meters. Still, in recent years, the mangroves here have been recovering compared to a decade ago.

What are the main knowledge gaps in your research?

For me, as a coastal engineer, the biggest gap is identifying which mangrove species are best suited for this area. Some species thrive here, while others die quickly. **Another gap is understanding how to manage water and sediment flows more effectively to support mangrove growth.**

What about the economic side? How do local people benefit from mangroves?

The benefits are diverse. People collect crabs, fish, and oysters, and some practice aquaculture near mangroves. However, aquaculture can also create pollution and salinity issues, which harm the environment. **Ideally, aquaculture should work with nature rather than against it.**

Who wants mangroves in the Kim Đông area?

Everybody wants to have mangrove forests in their area. We, as researchers want to study the mangrove forests and the hydraulic structures. Farmers just see mangroves as a tree, from which they can harvest animals and stuff to provide for their families. The local authority wants mangroves to create extra land but also to protect the area from flooding.

And are there many projects planting mangroves in this area?

Yes, there are several projects. Some areas with dense mangroves grew naturally, while others were planted by projects. Unfortunately, many planted mangroves don't survive well. **There are also international collaborations—projects from Korea, Japan, and even private companies that fund planting as part of carbon offset programs.** Korea, Japan, America and mostly Europe pay for these projects, so companies can be net zero. Mangroves store up to five times more carbon than terrestrial trees, so they are valuable for climate commitments. **In the Kim Đông area, the project space is fully booked right now.** We want to have more land (10.000 m² right now for our project) to plant more mangroves but it is not possible.

Who funds your project specifically?

Our project is funded by the Vietnamese government.

Are there also big aquacultural companies with a lot of power in the Kim Đông area?

Not that I know of. In the Kim Đông area it is mostly private companies and families who have aquacultural farms.

How about land ownership and forestry management, who decides what happens with mangrove land?

Mangrove forests are managed by the Department of Forestry. **Local communes manage land for housing, roads, and daily life, but forests fall under forestry authorities.** Cutting down mangroves is illegal, especially in protected areas, and violators can face fines or even prison sentences. **However, in project-planted areas, limited use may be allowed with permission.**

One last thing: we read about eco-tourism in mangroves, but we didn't see much during our visit. Is tourism a factor here?

Not yet. There are long-term plans to develop eco-tourism in mangroves by 2030, but for now, aquaculture provides more direct income for local people. **Tourism might grow in the future, but currently it's not significant in this area.**

C.2.5. Anonymous interview - Local authority Commune

Date: 9-10-2025

This interview was conducted by Mr. Tung Dao in Vietnamese and later translated by him using the notes he made during the interview. Therefore the tekst was adjusted a lot and the key takeaways of the interview are written down.

Mangrove function and perception: The local government recognizes mangroves as essential for coastal protection and erosion prevention. They emphasize that mangroves help reduce wave energy during storms, protecting dikes and the land behind them. For local residents, however, mangroves are valued for their direct livelihood benefits, such as fisheries and aquaculture, rather than for their coastal protection role. They complain about the dike because the dike changes the mangrove forests.

Dike construction and land-use change: The local authority views the dike system as a necessary intervention for economic and border security, protecting inland areas from flooding and enabling new aquaculture and agricultural land. They acknowledge that mangroves inside the dike change ecologically, species composition and water levels shift, but see this transformation as a manageable trade-off for economic gain.

Governance and management challenges: Forest land is officially managed by the Department of Forestry, but local people are assigned small plots (1-2 hectares) for symbolic payments (around 20 euros/year). This policy is widely seen as ineffective and unfair, limiting local ownership and stewardship. Additionally, unclear legal frameworks and overlapping authority between departments hinder efficient mangrove management.

Tourism and long-term vision: The commune aims to diversify its economy through eco-tourism and education-based initiatives, but progress is slow due to restrictive policies, unclear procedures and concerns about security near the border zone.

Religion and community organization: Christianity plays a significant cultural role in Kim Đông. Churches and religious networks help foster social cohesion and could be valuable channels for future community-based mangrove initiatives.

C.2.6. Interview Dr. Tung Dao - PhD. in Coastal Engineering and Lead member of the Kim Đông mangrove project; part 2

Date: 14-10-2025

This interview was recorded by 'Voice Memos' and also transcribed by 'Voice Memos'.

In what ways are mangroves important or not important?

It's always the same answer, mangroves are very important and even crucial for people's lives. Locals always say that mangroves are essential for their livelihood. Scientists share the same view, but they also emphasize that mangroves protect the land, not just the dikes.

People build dikes to prevent flooding, which causes major financial losses. With the dike, floods can be reduced, and with the mangroves, the dike itself is protected. Mangroves help to reduce wave energy during storms and lessen the strength of water currents that could otherwise damage or break the dike. So, mangroves are vital for both the dike and the protection of the land behind it.

When we interviewed locals, many said that once the fourth dike is completed, the mangrove area and its ecosystem will change, and people fear they might become poorer again.

The local authorities, however, see it differently. They view the dike as essential to reclaim and secure land. **Every year, the coastline extends naturally, and by building more dikes, they can protect and utilize that land. From their perspective, mangroves mainly serve to protect the dike, while locals see them as a source of livelihood.**

But aren't there also aquaculture farmers who might actually support the construction of the dike? Since new land could be used for aquaculture?

Yes, that's exactly the point many locals overlook. With the dike, floods can be prevented. **During storms, when the tide is high, people who farm shrimp or fish need to close their gates; otherwise, their ponds would flood, and they could lose everything.** The dike provides them with protection and stability, which is ultimately good for the aquaculture economy — if everyone understands its function. Mangroves then play the role of protecting the dike itself. But, as you said, when the fourth dike is completed, mangrove forests inside the dike will likely decline.

So will the government finish building the fourth dike anyway?

Yes, they will. The construction is already planned and funded. You can imagine it like this: if you put an animal in a cage, its behaviour changes. The same will happen with the mangroves.

Inside the dike, the water level becomes stable, and the natural tidal rhythm disappears. **Over time, mangroves and the species that depend on them will adapt to this new environment. Some species can survive long-term submersion, while others will disappear.** The mangrove forest inside the dike will turn into a different kind of ecosystem.

From a scientific point of view, this is not necessarily bad, it's just different. Biologists and ecologists will be able to study how these systems evolve under stable water conditions.

Do you think aquaculture ponds will replace the mangroves that remain inside the dike?

Partly, yes. The same happened between the second and third dikes. **After a new dike was built, aquaculture expanded in the enclosed area. I think the same will happen after the fourth dike. The land inside will gradually be used for aquaculture.**

However, not all mangroves will be removed. In many places, integrated mangrove–aquaculture systems already exist. **Farmers build ponds with mangroves inside or around them. The mangroves improve water quality and provide shelter for fish and shrimp. Farmers can control the water level with small gates, letting it in and out depending on the tide.**

Some ponds have 30–50 percent water surface and 50–70 percent mangrove cover. The mangroves help maintain the ecosystem inside the ponds, making it more sustainable. Shrimp and crabs raised in such environments are of higher quality and taste better, which means they sell for a higher price.

So both intensive aquaculture and mixed mangrove-aquaculture exist?

Yes. **Intensive aquaculture, without mangroves, is becoming more dominant now because it produces faster results and higher short-term profit. But the mixed systems are more beneficial in the long run, both for the environment and for the economy.**

And what about tourism? We heard some plans about that

Yes, there are plans to develop tourism in the area, especially eco-tourism and educational tourism. People could visit to learn about mangroves, biodiversity, or local aquaculture. Some parts of the coast already have tours like this.

However, implementation is difficult. **Some areas are restricted by the border guards, who control access for security reasons.** Sometimes they don't allow people (especially foreigners) to go to the sea. It's not necessarily for safety but rather for border and economic security.

Locals are very protective of their economic activities. If they see strangers, they might become suspicious, thinking that someone could copy their aquaculture methods or compete with them. **So there's a mix of security and economic motives behind these restrictions.**

Do you know where the funding for the dike construction comes from?

The funding mainly comes from the provincial government, through the Department of Agriculture and Rural Development. It's a joint effort that also involves the Department of Forestry and local authorities.

And what are the biggest challenges for local mangrove management?

One big issue is the policy for mangrove management. Currently, the Department of Forestry assigns local people to take care of small mangrove plots, usually one or two hectares each. In return, they receive only about 20 euros per hectare per year. That is far too little to motivate anyone.

There is also no clear legal framework that allows locals to lease mangrove areas long-term, for example to develop eco-tourism or sustainable aquaculture. If there were such policies, they could invest, pay taxes, and benefit both themselves and the commune.

So right now, the Department of Forestry manages the mangroves, but not the local people?

Exactly. The Department of Forestry manages them officially, but local people only take care of them through small assignments. It would be much better if they could rent the land for 10 or 20 years and have a real stake in its management.

Is it difficult for foreigners to do research in the area?

Yes. The process for obtaining permission is unclear and restrictive, especially near the border. **The police and the border guards oversee access, and even local officials don't always understand the procedure.** It's very bureaucratic.

When the dike is finished, the land behind it will be new land. Who will decide what happens with it?

It hasn't been decided yet, but most likely it will fall under the management of the local authority and the Department of Forestry. Currently, that land belongs to no one. **After the dike is completed, it may be reclassified from "protected forest land" to "agricultural land", so that people can rent or buy it for farming or aquaculture.**

And what exactly is the role of the border guard?

The border guard belongs to the military. They manage boats, control population movement, and oversee who goes out to sea. Anyone who wants to go to the sea must get their permission. They work independently from the commune authority but cooperate when it comes to safety and security.

We also noticed there are many churches in the area. Does religion play a role in local governance or mangrove management?

Yes, most people here are Christian, almost 99 percent. This comes from the French colonial period. Religion is part of local culture. It makes people more united and caring toward each other and their surroundings. Churches could be useful for mobilizing communities, for example, in mangrove planting or awareness campaigns. Religion is not political here, but it helps strengthen community ties.

Are there any other projects or plans for Kim Đông's development?

There is a tourism development plan that runs until 2030. It focuses on creating eco-tourism and educational opportunities. **But in reality, implementation is slow and difficult. Plans often look good on paper, but turning them into action can take decades.**

What about carbon credit projects? Have there been any related to mangrove restoration?

I've heard about such projects in the Mekong Delta and with Korean investors, but in Kim Đông, it's unclear. **Maybe some areas are already involved, but no one shares information about it. As long as mangroves remain there is potential (both ecological and economic) but transparency and data are missing.**

That are all my questions. Is there anything else you would like to add?

Only that mangroves and aquaculture need to develop together. If we can balance protection and economic use, Kim Đông can have both sustainability and prosperity.

C.2.7. Interview Mr. Mai Cao Tri - PhD Coastal and Offshore Engineering

Date: 15-10-2025

This interview was conducted by a member of our group, and notes were taken simultaneously.

What was your role in the development of the first section of the fourth dike?

I designed the first section of the fourth dike. **The tender for the project was won by VINWATER (Vietnam Netherlands Center for Water and Environment).** We made different designs with numerical simulations to see what the effects on the coastal area would be. We simulated the flow and waves. We started in 2017 and also simulated flooding of the river. We needed to be sure that there would be enough space around the river to be flooded from upstream. River discharge flooding also determined how many gates were needed. Reports of the first section of the fourth dike belong to the project and are thus not published. **The width of the gates are 4 meters and the height 4.9 meters.**

Where you involved in the construction of the other dikes in Kim Dong?

A company from Ninh Binh province did the construction for those dikes.

Why was the fourth dike not finished in one take?

There wasn't enough funding.

Why will the fourth dike be finished?

For land reclamation. There can be aquaculture or farming there.

Who decided that the fourth dike would be finished?

The ministry of agriculture and environment.

Where does the funding for the dike come from?

The ministry of agriculture and environment.

Can we access the design plans for the rest of the fourth dike? Where will it be exactly?

Either from the end of the first section of dike four to gate 10 or from the end of the first section of dike four to just before the river connecting to dike 3. On the left side of that river, the boarder of the Ninh Binh province lies, which will not be crossed. They are currently still designing the second section of the fourth dike. **Since it is not allowed to destroy mangroves to built the dike, I think the end will be just before gate 10.**

How many gates will there be in the fourth dike and where will they be?

They have to have some gates, but where exactly is still to be designed. In the first section of Dike 4, there are three gates.

What company or companies design and build the second section of dike four?

That depends on the tender. I think it is a consultant company from the ministry of agriculture and environment.

When will the second section of the fourth dike be finished?

I think in five years or so. They are currently designing the dike.

What do you think the effects of finishing the fourth dike will be?

The commune and province want to gain the land and they want to develop mangroves, tourism and aquaculture for economic benefit, so a combined solution. They plan to have a sea harbour as well somewhere in the future, mainly for cargo. Because the water will change due to the dike, it may not be so good for the mangroves. There will be less water flow and tidal change. Aquaculture farms more inland can use solutions like pumps to get water even with the finishing of the fourth dike. This means the effects are more heavy for nature, and thus mangroves.

Have you seen any change after the first section of the fourth dike was built?

I haven't been to the field so much so I do not know. Outside of the dike, I know there are planting projects with other countries like Korea.

Is someone monitoring the area?

I think the ministry of agriculture and environment monitors the dikes, aquaculture and mangroves.

D | Field Research (8-13 October, 2025)

This appendix documents the planning, permissions, methods, and outcomes of the field research undertaken in the Kim Đông coastal area from 8 to 13 October 2025. The appendix outlines the objectives and original plan, the coordination with Thuyloi University and HUCE, the measurement protocols and instrumentation, and the campaign timeline. The aim is to present a transparent account of data sources, field procedures, and assumptions and to supply data for the model and the other chapters of the report.

D.1. Motivation for Field Trip

In addition to satellite data, previously acquired field measurements, photographs, and interviews, first-hand site inspection is essential to establish a sound understanding of the focus area. Additionally, the available data for the Kim Dong area is limited and inconclusive. A dedicated field expedition was planned to improve understanding and to obtain inputs for model refinement.

Within the MDP timeline, the Thuyloi and HUCE research team had already scheduled a field campaign, allowing the MDP expedition to coincide. This coordination provides the MDP team with practical experience in operating measurement equipment, translation support, and a broader understanding of procedures for conducting technical field measurements. Additionally, it offers the team valuable experience in conducting practical fieldwork in a foreign country.

D.2. Original Plan

Prior to the field campaign, a preparation plan was drafted. Supervisors coordinated logistics and supported the execution of measurements and interviews. The campaign was scheduled for up to five days, with accommodation in a homestay near the mangrove forests and the coast.

Primary objectives were bathymetry validation, interviews and surveys with local people. The plan incorporated flexibility to accommodate changing circumstances on site. This was the original plan:

- **Current Measurements:** Currents at selected locations to verify satellite-derived flow data.
- **Bathymetry Validation:** Onshore RTK (Real-Time Kinematic) measurements to validate the interpolated bathymetry.
- **Suspended Sediment Concentration (SSC):** Collection of water samples to provide inputs for sedimentation parametrisation and model calibration.
- **Propagule Collection for Dataset Contribution:** Contributions to the international database of PhD candidate Laura Bossaer to assess mangrove health by carrying out a small set of standard measurements (density, mass, and basic dimensions). The resulting observations can be compared with data from another MDP research group in the Mekong Delta to identify any differences.
- **Salinity Measurements:** Salinity measurements on both the landward and seaward sides of the dike to inform the assessment of local conditions affecting mangroves.
- **Interviews and Surveys:** The goal was to conduct a semi-structured interview with someone from the commune and someone from the department of forestry. Semi-structured means that there are pre-prepared questions but also room for open conversation. One of the supervisors would conduct the interview and take notes using the prepared interview beforehand. The answers to these interviews are qualitative and thus provide depth and context.

In addition to the expert interviews, a survey is constructed for the local residents of the Kim Đông Commune. The goal of this survey is to gain insights into the perspective of the local community towards mangroves and mangrove development. The survey consists of simple

closed questions in Vietnamese, since the local community generally does not speak English, and the goal is to make the survey as accessible as possible. This makes the data from the surveys conducted quantitative. It means the data can be used to compare results and even do some statistical analysis if there are enough respondents. Finally, insights can be generalised to a larger population of the Kim Đông Commune, which strengthens the validity of the conclusions. The surveys will also be conducted by the supervisors, since they speak Vietnamese and can talk to the local community.

D.3. Fieldwork Timeline

8 October 2025

The field campaign began on Wednesday, October 8th, at Gate 10 on the third dike ring (Bình Minh 3). On arrival, a site tour was provided, including an explanation of the bathymetric survey equipment and an overview of mangrove species present, as well as the first obtainment of propagules.



Figure D.1: Instruction of the Bathymetric Equipment (RTK) (Authors, 2025)

At 17:00 the team was informed that accommodation at the homestay near the coast and mangroves was not permitted due to regulatory constraints. The police and border guard did not approve the stay, despite the supervisors' continued efforts. Relocation was made to Phát Diệm, approximately 20 km from the Kim Đông mangrove area. That evening, a local authority representative travelled to Phát Diệm for a meeting and interview over dinner to make effective use of the changed circumstances.

9 October 2025

On Thursday, October 9th, the team remained in Phát Diệm while supervisors prepared the necessary documentation to avoid procedural issues during measurements and interviews. In the afternoon, the MDP Team received word that the field expedition in Kim Đông could not be approved at that time, and accommodation in Phát Diệm was also not permitted for this purpose. Despite the forced absence of the MDP team, supervisors indicated that community surveys and essential measurements would be pursued as far as possible (alongside their own campaign plans).

11 October 2025

On Saturday, October 11th, confirmation was received that the documentation had been finalised and that a return to Kim Đông was authorised.

12 October 2025

Travel back to Kim Đông took place on Sunday, October 12th, with arrival at 15:00. Supervisors briefed the measurement plan for Monday and reported that approximately eighteen community surveys had been completed as well as bathymetry measurements.

13 October 2025

On Monday, October 13th, arrival at Gate 10 occurred at 07:30. Multiple suspended sediment concentration (SSC) and salinity measurements were completed. The planned RTK bathymetry measurements could not be carried out due to elevated water levels and adverse weather conditions, as this could have posed safety risks. Police officers attended to observe the work. By lunchtime it was clear that the remaining planned measurements could not proceed, concluding the field campaign. The Thuyloi research team indicated that they would attempt to complete the outstanding measurements in the following days.

The figures below illustrate our participation during the field campaign, including the preparation for offshore measurements (Figure D.2), the suspended sediment concentration measurements (Figure D.3), and the salinity measurements (Figure D.4).



Figure D.2: Preparing for Offshore Measurements (Authors, 2025)



Figure D.3: Suspended Sediment Concentration Measurements (Authors, 2025)



Figure D.4: Salinity Measurements (Authors, 2025)

D.4. Results

Ultimately, only a limited number of measurements and interviews could be collected by the MDP team. Due to unexpected and unknown bureaucratic hurdles and adverse weather conditions, most of the fieldwork needed to be carried out by the supervisory team. Additionally, it was not possible to contribute to the propagule database as initially intended. The results of the field trip, primarily carried out by the supervisors, are documented below.

Bathymetry Validation

Using the RTK GNSS module (Figure D.6), several checkpoints were surveyed to verify the interpolated and extrapolated bathymetry. Adverse weather prevented the MDP team from completing the planned measurements themselves; however, the team obtained the necessary training and guidance for future deployments. A limited set of control points essential for model calibration was measured, indicating differences of up to 0.20 m between the RTK elevations and the interpolated bathymetric surface. These results will inform refinement of the bathymetric grid and subsequent calibration of the hydrodynamic model.

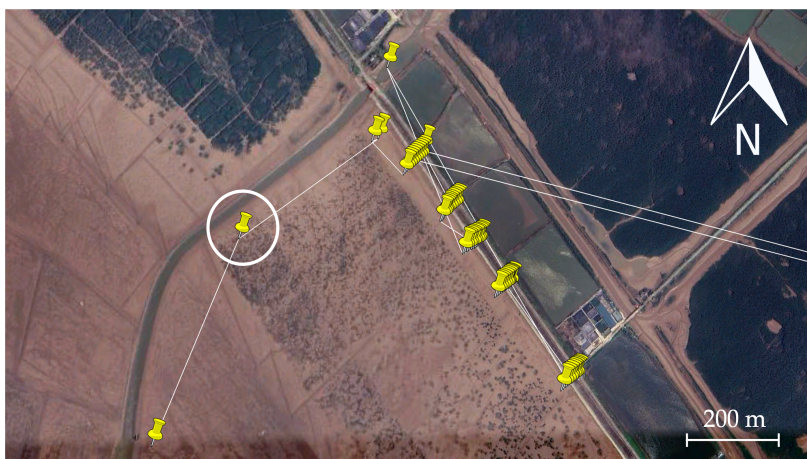


Figure D.5: Bathymetry Measurement Locations (Google LLC, 2024)



Figure D.6: Explanation of RTK Device (Authors, 2025)

Suspended Sediment Concentration (SSC)

On Monday, 13 October, the MDP team conducted multiple suspended sediment concentration (SSC) measurements at Location 1, near Gate 10, in Kim Đông (Figure 4.6). In addition, the supervisory team carried out SSC tests at various locations and times throughout the field campaign. The measurements were conducted using a simple sampling method.

A 1-litre bottle was submerged into the water. A rope attached to the bottle with a weight at the bottom to ensure that the bottle remained submerged allowed the team to control its movement. The procedure involved allowing the bottle to fill with water until the bubbling ceased, indicating that the bottle was full. Once filled, the bottle was pulled out of the water using the rope, and the bottle was then sealed for transport.

The MDP group was able to conduct this sampling procedure three times at Location 1. Meanwhile, the supervisors performed similar tests at other locations and different times during the campaign. In total, 76 samples were obtained.

After the samples were collected, they were transported to the Hydraulics Laboratory at Thuyloi University for processing. In the laboratory, the samples were filtered using a standard coffee filter. This set-up is shown in Figures D.7, D.8 and D.9.



Figure D.7: Preparing the SSC filters (Authors, 2025)



Figure D.8: Suspended Sediment Concentration Setup in progress (Authors, 2025)



Figure D.9: Pouring of the Sample (Authors, 2025)

The filtered sediments were then dried and weighed to calculate the SSC. For drying, the samples were placed in an oven with a temperature set at a 150° C until all moisture was removed. This can be seen

in Figures D.10, D.11 and D.12. Afterward, the filters with the dried sediment were carefully weighed and recorded.



Figure D.10: Putting the SSC Filters in the Oven (Authors, 2025)



Figure D.11: Putting the SSC Filters in the Oven (Authors, 2025)



Figure D.12: SSC Filters in the Oven (Authors, 2025)

The information from the samples of the MDP group is summarised in Table D.1 to provide an idea of the measured values and how they were calculated.

Table D.1: Suspended Sediment Concentration Measurements by the MDP team at Location 1 in Kim Đông (October 13th, 2025)

Date	Time	Weight Paper (g)	Wet (g)	Dried (g)	SSC (g/dm ³)
October 13th, 2025	08:12 AM	2.167	3.414	2.156	-0.011
October 13th, 2025	09:24 AM	2.174	3.336	2.113	-0.061
October 13th, 2025	10:24 AM	2.172	3.429	2.145	-0.027

Salinity Level

On the morning of October 13th, while the SSC measurements were being conducted, a few salinity level measurements were also taken. These measurements were performed using a handheld salinity meter, which was placed directly into the water. The meter recorded the salinity and temperature at the different times. The results of these measurements are displayed in Table D.2.

Table D.2: Salinity Level Measurements (October 13th, 2025)

Measurement Time	Salinity (ppm)	Temperature (°C)
08:12 AM	8000	-
09:24 AM	7640	28.3
10:24 AM	7850	27.9

Spatial Information

Besides the measurements conducted in the area, another site visit was carried out to gain a better understanding of the spatial characteristics of Kim Đông. New pictures were taken, and the site was observed regarding land use, water flows, vegetation patterns, mangrove forests and aquaculture zones. Although limited measurements could be performed, the site visit provided useful insights. Distinctions between inland and coastal aquaculture practices were observed, with sediment accumulation near sluice gates and mangrove forests around the dike. All these observations supported the complete understanding of different interactions in the area and in the system.

Interview Local Authority

On the first day of the field trip, an interview was conducted with someone from the local authority. The interview was conducted over dinner, as the MDP group had to relocate to Phát Diệm, and the local

authority official had to travel to our new location. The most important questions were written down in English. Someone from the Thuyloi research team could conduct the interview in Vietnamese and was able to make notes simultaneously. Approximately a week later, the answers were discussed. The main takeaways from the interview are written down in Appendix C.2.5.

Survey Local Community

Eighteen surveys have been conducted in the field. There is no data on who was exactly asked to participate and how the documenting on site went. Additionally, the last page of the four-page survey was filled in by none of the respondents. These were questions regarding the local government, which is a reason the questions may have been too sensitive. The main takeaway from the survey is that most people in Kim Đông are not highly educated and have relatively low wages. Most respondents have been living in Kim Đông for a long time. All respondents thought mangroves are important for the area, mainly for environmental reasons. Only four respondents also acknowledged the importance of mangroves for coastal protection. Most respondents said expanding aquaculture and expanding mangroves are equally important.

Governance Insights

The key new insight gained from the field trip was related to Vietnam's government system. The structure is highly organised and hierarchical, but it also relies on local interpretation of central policies and personal networks. This was noticeable due to the fact that a lot of different people and organisations were involved in the stay of the MDP team in Kim Đông, but also in how the communication between them took place (calls and visits back and forth). This combination resulted in a top-down system where decision-making was unclear and went slow and bureaucratic.

D.5. Takeaways

Although the field expedition conducted did not align with the original expectations, several lessons were derived that are highly relevant for future work in Vietnam.

- **Planning and Agility:** A detailed, Dutch-style schedule proved impractical for a measurement campaign in Vietnam. Plans should remain agile, with explicit buffer time for delays, resequencing of tasks, and rapid re-prioritisation when conditions change.
- **Administrative Hierarchy:** The hierarchical governmental structure of Vietnam can complicate approvals. Even when local counterparts are cooperative, certain activities require signatures from higher administrative levels, which may be difficult to obtain at short notice and can delay field operations.
- **Oversight of Foreign Research:** Activities undertaken by foreign researchers or people in general are closely regulated. Research permits, site access, and data collection protocols may be constrained by security considerations and local regulations. Early coordination with host institutions and authorities is essential.
- **External Constraints:** Multiple factors outside the control of the research team strongly influence the success of a field campaign, notably weather, tidal conditions, access to sites, and the reliability of transport and equipment. Contingency plans, alternative task lists, and adequate spare capacity are necessary to maintain progress under such constraints.
- **Comparison with the Mekong Delta:** The parallel MDP group investigating mangroves in the Mekong Delta returned from their own field research with similar results, encountering similar bureaucratic and planning constraints. As a result, cross-site propagule comparison could not be undertaken. These parallel outcomes underscore the systemic complexities of organising coastal fieldwork in Vietnam and the need for robust contingency planning.
- **Consistency in Measurement Techniques:** Because multiple teams collected and processed data without a written protocol, small inconsistencies in file formats, measurement methods and uneven calibration notes contributed to implausible SSC averages and a variability in RTK results. Going forward, especially when planning measurement campaigns at different time intervals, a clear manual should be written on how tasks should be performed, and a standard format for datasets should be determined. This way, extra work can be prevented, and good quality of data is assured.

E | Survey Information

In this appendix, the survey used is presented, and the results are showed. The survey is used to identify local people's perceptions about mangroves in Kim Đông, but also to understand certain demographics of the area.

E.1. Survey Used

The survey that was used in Kim Đông can be seen in Tables E.1, E.2, E.3 and E.4, but translated to Vietnamese. A Vietnamese survey was used since the local residents of Kim Đông can generally not speak any English. People had to choose one of the provided answers to the closed questions to make the survey even more efficient.

Table E.1: Demographics

Age	Gender	Education	Income	Job	Household size	How long have you lived here
0–25	Male	None	< 2,000,000 VND/month	Aquaculture	2	0–5 years
26–55	Female	Elementary	2,000,000 – 4,000,000 VND/month	Farmer/collector	3–4	6–15 years
56–90	Other/prefer not to say	High school	4,000,000 – 6,000,000 VND/month	Government	5–6	16–30 years
–	–	University	> 6,000,000 VND/month	Other	More	(Almost) whole life

Table E.2: Mangroves

Do you think mangroves are important for Kim Đông?	Why are mangroves important or why could they be important?	What have you noticed about the mangrove area over the last 10 years?	Did you participate in a project regarding mangroves?	Would you be willing to participate in mangrove planting if supported by the commune?
No	Economic benefit	Increasing	Yes	Yes
Yes	Environment	Decreasing	No	No
No opinion	Flood protection	Stayed the same	-	-
-	Other	-	-	-

Table E.3: Aquaculture

Does aquaculture influence you or your family?	In what way does it affect you?	Have you adopted any sustainable aquaculture practices (e.g., integrated mangrove–shrimp farming)?	What do you believe is more important?
Yes, positively	Economically	Yes	Expanding aquaculture farms
Yes, negatively	Environmentally	No	Expanding the mangrove forest
No influence	Socially	I am not an aquaculture farmer	-

Table E.4: Participation and Governance

Have you ever been asked to participate in local decision-making from the commune?	Are you satisfied with the government projects related to mangrove management?	Do you feel the local government takes your opinion into consideration in decision-making processes?	What kind of support do you need from the local authorities?
Yes	Always	Always	Financial
No	Often	Often	Technical training
-	Sometimes	Sometimes	Stricter law enforcement
-	Rarely	Rarely	New infrastructure
-	Never	Never	Better communication and information

E.2. Survey Results

The survey consists of four parts. The first part is about demographics, the second part about mangroves, the third part about aquaculture and the last part about participation and governance.

From the respondents, 50 percent is woman and 50 percent is men. Seven respondents are older than 56 years. None of the households are consisting of less than three people. Most of the respondents are farmers/collectors, which have an average income of 3.000.000 VND/month. Aquaculture farmers have an average income of more than 6.000.000 VND/month. However, only two respondents are aquaculture farmers and nine are farmers/collectors. Other respondents are daily wage workers and have an average income somewhere between the farmers and aquaculture farmers.

All respondents think that mangroves are important for the area, mostly for environmental reasons. Some respondents think they are also important for economic benefit. There is no correlation between these people. Four respondents think mangroves are also important for coastal protection. However, there is also no correlation between these respondents.

All respondents also think the area of mangrove forest has increased over the last years. Eight respondents have participated in projects regarding mangroves, which shows a part of the community does participate when it comes to mangrove related projects. The respondents that have participated in projects regarding mangroves are all farmers/collectors, which shows that people with this occupation most likely work within the mangroves or need the mangroves to do their work.

Only one respondent was negatively influenced by aquaculture due to the wastewater. This person's occupation was farmer/collector. Both aquaculture farmers that responded have adopted sustainable aquaculture practices such as mixed mangrove-aquaculture.

Six respondents think expanding the mangrove forest is more important. The rest of the respondents think expanding mangroves is equally important as expanding aquaculture. Only one respondent finds expanding aquaculture more important. This person is an aquaculture farmer.

F | Conceptual Numerical Model Elaboration

This appendix documents the setup and results of the numerical conceptual model used to assess the effects of completing the fourth sea dike (Binh Minh 4). It provides a transparent, reproducible description of the Delft3D configuration, including boundary conditions, parameters and settings for FLOW and WAVE.

F.1. Boundaries

In Delft3D, two types of boundary are defined: FLOW boundaries, which describe hydrodynamic conditions such as water levels or discharges, and WAVE boundaries, which define incoming wave characteristics like height, period, and direction; the former control the flow field, while the latter represent the external wave climate. This section elaborates on the determination of the Neumann boundaries applied in the FLOW module and the determination of the WAVE boundaries applied in the WAVE module.

F.1.1. FLOW Neumann boundaries

To define the FLOW Neumann boundaries in the model, several configurations were tested to achieve a realistic representation of the tidal propagation within the domain. Since the tidal wave is assumed to propagate from the south-east toward the north-west, the boundaries perpendicular to this direction, P4–P1 and P2–P3, are defined as FLOW Neumann boundaries, which is visualised in Figure F.1. Neumann boundaries in the FLOW module represent the water level gradient along the boundary, specifying how the water surface varies spatially instead of enforcing a fixed level. This approach allows the model to calculate the corresponding flow based on the imposed gradient, enabling a more natural representation of tidal propagation across these boundaries.

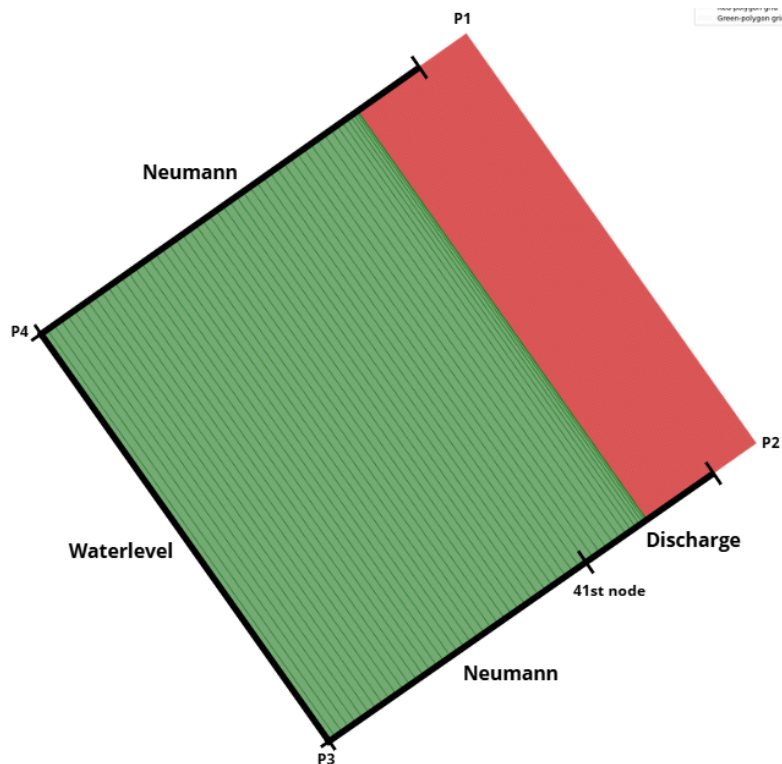


Figure F.1: The FLOW boundaries visualised in the model grid. Red = fine grid; Green = more coarser grid.

Initially, zero gradient Neumann conditions (no normal flow) are applied along boundary P3–P2 and P4–P1, but this produced unrealistic flow patterns in the model domain, mainly near the boundaries itself. In order to produce more realistic results, the water level gradient along these boundaries needed to be determined. Because the tide propagates from the south-east toward the north-west, perpendicular to the boundary P2–P3, a phase difference occurs between this boundary and the opposite boundary P4–P1, such that the tidal elevation along P2–P3 leads that along P4–P1.

Gradient Determination

The tide is assumed to propagate perpendicular to the Neumann boundaries. Therefore, the water level gradient between points P3 and P4 determined below is applied uniformly along the entire boundaries P2–P3 and P4–P1. This assumption implies that the tidal phase and amplitude vary consistently in the direction of propagation, while remaining constant along each Neumann boundary.

To determine the constant water level gradient along the Neumann boundaries, the tidal propagation between points P3 and P4 is analysed using the shallow-water wave approximation. The gradient is defined as the difference in water level over the distance between both points:

$$\frac{\partial \eta}{\partial x} = \frac{\eta_{P4}(t) - \eta_{P3}(t)}{a} \quad \text{F.1}$$

Where $\eta_{P3}(t)$ and $\eta_{P4}(t)$ are the instantaneous water levels at points P3 and P4, and a is the distance between the two points. Since direct measurements at P4 are unavailable, $\eta_{P4}(t)$ is estimated by introducing a phase lag to the measured tidal signal in April 2025 at P3, assuming one dimensional wave propagation in shallow water. The propagation speed of the tidal wave, or phase celerity, is determined using the shallow water approximation shown in Equation F.2.

$$c = \sqrt{g h_{\text{mean}}} \quad \text{F.2}$$

Where g is the gravitational acceleration and h_{mean} is the mean water depth between P3 and P4. The time lag τ between both points is then calculated as:

$$\tau = \frac{a}{c} \quad \text{F.3}$$

Using this lag, the water level at P4 can be approximated by a phase shifted version of the water level signal at P3 by using Equation F.4.

$$\eta_{P4}(t) = \eta_{P3}(t - \tau) \quad \text{F.4}$$

Substituting Equation F.4 into Equation F.1 results in the time varying water level gradient along the open boundaries:

$$\frac{\partial \eta}{\partial x} = \frac{\eta_{P3}(t - \tau) - \eta_{P3}(t)}{a} \quad \text{F.5}$$

In this study, the following parameters were used or determined by the equations, which resulted in a gradient for each time step:

$$h_{\text{mean}} = 3.300 \text{ m}, \quad c = 5.690 \text{ m s}^{-1}, \quad \tau = 19.19 \text{ min}$$

The resulting gradient from Equation F.5 was applied uniformly along the Neumann boundaries P2–P3 and P4–P1.

In reality, the tidal gradient along boundaries P2–P3 and P4–P1 differs slightly due to the phase shift of the propagating tidal wave. However, because only one tidal signal (at P3) is available, the same gradient derived from the P3–P4 section (Equation F.5) is applied uniformly to both Neumann boundaries. The resulting FLOW patterns computed by the model using these gradient in the Neumann boundaries are much more accurate than the previously mentioned zero gradient Neumann boundaries.

F.1.2. WAVE Boundary

To define the WAVE boundaries in the model, again several configurations were tested to achieve a realistic representation of wave propagation in the model domain. Since the dominant wave direction is from the south towards the north according to the wave analysis done in Chapter 4, the boundaries exposed to this incoming wave energy, P3 – P4 and partially P2 – P3, are defined as the two WAVE boundaries, visualised in Figure F.2.

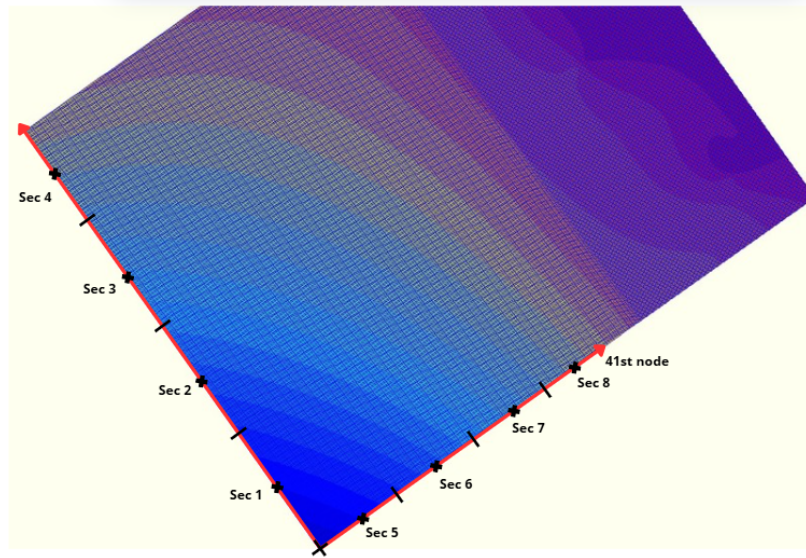


Figure F.2: WAVE boundaries visualised in red.

As can be observed in Figure F.2, each wave boundary spans multiple water depths. Since waves grow higher as they move into shallower water, the wave height along the boundary must be adjusted according to the principle of shoaling. At the same time, depth induced breaking limits the maximum possible wave height, represented by a breaking parameter of $\gamma = 0.73$.

Both boundaries P2 - P3 and P3 - P4 are divided into four sections. A new section is defined whenever the water depth decreases by one meter, resulting in a total of four sections per WAVE boundary. Dividing the WAVE boundaries into four sections provides a sufficient level of detail to capture the gradual transformation of waves along the boundaries. For each section, the average water depth of that section is used as the representative depth for the shoaling calculation, indicated as the black crosses in Figure F.2.

Shoaling Determination

The wave height for each boundary section is determined based on either the shoaling relation or the depth-induced breaking limit, as defined by Equation F.6.

$$H_s(h) = \min \left(H_{s,0} \sqrt{\frac{C_{g,0}}{C_g(h)}}, \gamma h \right) \quad \text{F.6}$$

where $H_{s,0}$ is the deep water significant wave height, $C_{g,0}$ and $C_g(h)$ are the group velocities in deep and local water depth, respectively, and γ is the depth-induced breaking parameter, taken as 0.73. The first term describes the increase in wave height due to shoaling, while the second term limits this increase based on the local water depth.

The shoaling process represents the transfer of wave energy from deeper to shallower water. As waves enter shallower regions, their celerity and wavelength decrease, leading to a concentration of energy and consequently to an increase in wave height. This effect is described by Equation F.7.

$$H_s(h) = H_{s,0} \sqrt{\frac{C_{g,0}}{C_g(h)}} \quad \text{F.7}$$

where C_g denotes the group velocity, representing the rate at which wave energy propagates through the water. It is defined as:

$$C_g = n c = n \frac{\omega}{k} \quad \text{F.8}$$

Here, c is the phase velocity, ω is the angular frequency, and k is the wave number. The factor n represents the ratio between the group and phase velocity and depends on the relative water depth, defined in Equation F.9

$$n = \frac{1}{2} \left(1 + \frac{2kh}{\sinh(2kh)} \right) \quad \text{F.9}$$

To compute $C_g(h)$, the wave number k must first be determined using the linear dispersion relation, defined as:

$$\omega^2 = gk \tanh(kh) \quad \text{F.10}$$

where g is the gravitational acceleration and h is the local water depth, which for each section is the average water depth at that section. For a given wave period T_p , the angular frequency is defined as $\omega = 2\pi/T_p$. Solving Equation F.10 for k results in the corresponding wavelength and, in turn, allows calculation of the local group velocity through Equation F.8.

While shoaling causes the wave height to increase as depth decreases, this growth is constrained by depth-induced breaking. Waves begin to break once their height reaches a certain fraction of the water depth, described by:

$$H_b = \gamma h \quad \text{F.11}$$

where $\gamma = 0.73$ is the empirical breaking index. If the shoaling-induced height exceeds this limit, the wave height is capped at H_b .

By applying these equations, the wave heights for each boundary section are calculated and presented in Table F.1. Because the bathymetry is linearly extrapolated, the corresponding sections along both boundaries have identical average depths, resulting in equal calculated wave heights for matching sections. Furthermore, it is important to note that under extreme storm conditions, the resulting wave heights are often limited by the depth-induced breaking limit, which explains why, in these sea-states, the calculated wave height decreases toward shallower depths instead of increasing.

Table F.1: Overview of Calculated Wave Height for Different Return Periods

Wave Height per Sea-state	Section 1 and 5	Section 2 and 6	Section 3 and 7	Value 4 and 8
Calm [m]	0.451	0.458	0.473	0.507
1 Year [m]	1.654	1.678	1.733	1.241
30 Years [m]	3.478	2.701	1.971	1.241

F.2. Model Parameters and Settings

This section provides an overview of the model parameters and settings used in Delft3D. It is included in the appendix to offer transparency and reproducibility of the modelling process. The tables and descriptions summarise the key input parameters applied in the simulations and briefly explain the iterative calibration process used to refine these settings during model setup.

F.2.1. Settings of Parameters in the FLOW Module

This subsection elaborates on all the parameters in the Delft3D FLOW module, which are used to calibrate the model.

Initial Conditions - Water level

The initial water level in the model has been set to the first value of the water level time series, derived from measurements in April 2025. This approach ensures consistency with the internal state of the model and the boundary forcing at the start of the simulation, meaning the water level in the domain at the first time step matches that of the boundary. For calibration, different initial values between -1 m and 1 m are tested, including both negative, zero, and positive values. The configurations in which the initial condition is equal to the first value of the water level time series reduce spin-up time and result in a more stable behaviour of the computed numerical results in the early stages of the simulation. In numerical models, spin-up time is the initial simulation period during which the model adjusts from simplified starting conditions to a stable, realistic state that aligns with the applied boundary conditions.

Bottom Roughness

The bottom roughness in the model is defined using the Manning–Strickler formulation, chosen for its simplicity, ease of calibration with field data, and widespread application in coastal hydrodynamic models under comparable conditions (Deltares, 2025a). For simplicity and time restriction reasons, the bottom roughness is assumed to be uniform in all directions. This simplification will slightly reduce the accuracy of local wave dissipation and current patterns, but is considered acceptable, as the model aims to analyse the overall hydrodynamic behaviour in the model domain, where local variations in bottom roughness have a limited influence on the results. The final value of the bottom roughness is assumed to be $0.02 \text{ s/m}^{1/3}$ in all directions (Chow, 2006), since this value suited the calibration data best.

Stress Formulation due to Wave Forces

The stress formulation resulting from the wave forces accounts for the combined wave-current interaction shear stress near the seabed. This is set to Fredsøe, which provides the most realistic representation of near-bed stresses in shallow and coastal environments as in the Kim Động area, leading to more accurate hydrodynamic behaviour under wave influence (Deltares, 2025a). The Fredsøe formulation is an empirical approach that estimates the increased seabed shear stress caused by the combined action of waves and currents in shallow water.

Eddy Viscosity and Diffusivity

In Delft3D, the horizontal eddy viscosity and diffusivity are not fixed physical constants but rather calibration parameters that depend on the model grid and flow characteristics. According to the Delft3D-FLOW User Manual (2025a), values between $1 - 10 \text{ m}^2/\text{s}$ are suitable for grid sizes of several tens of meters, while values between $10 - 100 \text{ m}^2/\text{s}$ are suitable for grids of several hundreds of meters. Furthermore, Duc Anh et al. (2020) applied a Delft3D model to the northern part of the Red River Delta in Vietnam with similar coastal characteristics as Kim Động, while using similar grid dimensions, and reported using a background horizontal eddy and diffusivity of $1 \text{ m}^2/\text{s}$, which produced good agreement with water level and velocity observations. Based on these findings, the model is using a background horizontal eddy viscosity and diffusivity of $1 \text{ m}^2/\text{s}$.

In order to determine the reliability of the model in the absence of site-specific calibration data, a sensitivity test is performed by halving and doubling the initial viscosity and diffusivity values. After evaluating the influence of these different values on the water level and flow velocities at multiple points of interest, the conclusion is drawn that the model is not significantly sensitive to changes in the eddy viscosity and diffusivity, and all simulations produced representative results. For this reason, the parameter for the final simulations is unchanged from its initial value and is set to $1 \text{ m}^2/\text{s}$.

Numerical Parameters

There are several numerical parameters in Delft3D that define threshold values used to ensure numerical stability and accuracy.

First, the option "grid cell centres and faces" is used for the drying and flooding check, since this option checks both the cell centre and cell faces for the wetting and drying process in Delft3D. Grid cell centres

refer to the middle points of each computational cell where main variables, such as water level and velocity, are calculated, while cell faces represent the boundaries between adjacent cells where fluxes and exchanges of water and momentum occur. Setting this option to "grid cell centres and faces" is more accurate than using only the grid cell faces. The depth at grid cell faces is set to "mor", which, according to the FLOW Manual 2025a, is the same as the setting "min", but more widely used in coastal areas, which applies to Kim Động.

The next numerical parameter that is defined in Delft3D is the threshold depth. The threshold depth is the minimum water depth required for flow to occur in a computational grid cell, preventing numerical instability in very shallow areas. The threshold depth is determined using Formula F.12 (Deltares, 2025a).

$$\delta \geq \left| \frac{\partial \zeta}{\partial t} \right| \Delta t \approx \frac{2\pi|a|}{T} \Delta t = \frac{2\pi|a|}{N} \quad \text{F.12}$$

Where:

- δ = threshold depth [m]
- ζ = water level [m]
- $\frac{\partial \zeta}{\partial t}$ = rate of change of water level [m/min]
- Δt = model time step [min]
- a = tidal amplitude [m]
- T = tidal period [min]
- $N = \frac{T}{\Delta t}$ = number of computational time steps per tidal cycle [–]

According to Chapter 4.6, the average interval between high and low water equal to 12.9 hours and a time step of 1 minute, the amount of steps N becomes 774. Combining this value with the mean tidal range amplitude of $1.86/2 = 0.93$ m, the following threshold can be determined.

$$\delta = \frac{2\pi|a|}{N} = \frac{2\pi \times 0.93}{774} = 7.55 \times 10^{-3} \text{ m} \quad \text{F.13}$$

However, during the first simulations, this value led to numerical errors in the model. Therefore, the value is increased. The value is doubled a total to two times, which increased the value to 0.003 m, in order to run stable numerical simulations.

The marginal depth is set to 0.01 m to ensure numerical stability in shallow areas by triggering a more robust advection scheme when flow conditions become supercritical (Deltares, 2025a). This value results in stable results for flow conditions near the dike and in the canals during the simulations with open gates.

The smoothing time defines the period over which boundary conditions are gradually introduced at the start of the simulation. This prevents sudden jumps between the initial conditions and the applied forcing, which could otherwise introduce artificial waves or numerical oscillations in the model (Deltares, 2025a). A value of 15 minutes is chosen because it provides a sufficient gradual transition during the spin-up phase of the model, while being short enough not to affect the overall simulation results.

Lastly, an advection scheme is specified. The advection scheme is the numerical method used in Delft3D to compute the transport of flow and scalars between grid cells. The cyclic advection scheme is selected for the model because, according to the Delft3D-FLOW User Manual 2025a, it provides a good balance between numerical stability and accuracy for oscillatory flow conditions, such as tides or wave driven currents. This setting is not changed during the iterative process of determining the settings, since it has always worked well.

Additional Parameters

The additional parameters ensure consistent data exchange and model stability. Setting $TpsCom = \#Y\#$ enables the communication between the FLOW and WAVE modules, allowing the exchange of hydrodynamic variables such as water levels and radiation stresses during coupled simulations. $AirOut = \#YES\#$ and $AirOut = \#euler\#$ activate and define the numerical scheme for storing intermediate results, making it possible to restart the simulation from saved states using a first order

Euler method. Finally, $CstBnd = \#YES\#$ ensures that boundary conditions remain constant in time when no time varying input is provided, preventing unwanted fluctuations or undefined behaviour at the model boundaries.

Output

To manage the model output efficiently while maintaining sufficient resolution, map results and the communication file are stored every 60 minutes. This interval ensures that large-scale hydrodynamic variations, such as tidal cycles and flow patterns, are well captured without generating unnecessary large output files. The history interval is set to 10 minutes, allowing for a higher resolution at the specified monitoring points in the model. The restart interval is set to 0 minutes, since no intermediate restart files are needed for short simulations.

F.2.2. Settings of Parameters in the WAVE Module

This subsection elaborates on all the parameters in the Delft3D WAVE module, which are used to calibrate the model.

Physical Parameters: Processes

Depth-induced breaking is taken into account by the Battjes and Janssen formulation, since it is commonly used in coastal areas with similar characteristics as in Kim Động. The theory assumes that waves break when their height exceeds a certain parameter multiplied by the water depth. This parameter is represented by $\gamma = 0.73$. The bottom friction is represented using JONSWAP formulation as recommended by the WAVE manual (Deltares, 2025b). This empirical approach expresses energy dissipation due to bottom friction with a constant coefficient. The coefficient is set to $0.038\text{m}^2\text{s}^{-3}$, as recommended by Van Vledder et al. 2011, because it provides the most accurate representation of wave energy dissipation over shallow muddy bottoms similar to the conditions in Kim Động. The other processes, non-linear triad interactions and diffraction, are turned off to simplify the conceptual model.

Physical Parameters Various: Whitecapping

Whitecapping is the loss of energy when steep waves break on the water surface. In Delft3D, different formulas are used to describe this process. The older Komen-type method links wave breaking to the average steepness of the waves, while the newer Van der Westhuysen method looks at how locally “saturated” or steep the waves are. The Van der Westhuysen works better in shallow and fetch-limited areas, like in Kim Động, so it is chosen for this model.

Numerical Parameters

In the WAVE module, the numerical parameters CDD (directional space discretisation) and CSS (frequency space discretisation) control the balance between central and upwind schemes. A central scheme is more accurate, as it computes the flux between grid points by averaging values from both sides. However, it can suffer from instabilities or false oscillations in steep gradients. In contrast, an upwind scheme is more stable because it uses only upstream information, but this comes at the cost of increased numerical diffusion and a loss of accuracy (Deltares, 2025b). Setting CDD and CSS to 0 induces a purely central scheme, while setting it to 1 induces a purely upwind scheme. To balance the trade-offs between accuracy and stability, both CDD and CSS are set to a value of 0.5. Additional sensitivity tests were performed with CDD and CSS values of 0.6 and 0.7, which showed negligible to no influence on the overall model results.

The accuracy criteria in the WAVE module, such as relative change in $H_s - T_{m01}$, percentage of wet grid points, relative change with relation to the mean values (H_s and T_{m01}) and the maximum number of iterations, are all set to the default values as recommended according to the manual (Deltares, 2025b).

Output Parameters

In this section it is specified which wave parameters are saved during the simulation. The stationary mode and test output level are kept at their default values, as they are suitable for the present model setup. The output for FLOW grid is enabled to make wave parameters such as significant wave height, mean period, and direction directly available to the hydrodynamic FLOW model for coupling. Additionally, the output for the computational grid is activated to export the full spatial distribution of wave parameters to external files for analysis. These outputs allow evaluation of nearshore wave transformation and provide essential input for further flow and morphological simulations.

F.2.3. Overview of Input Parameters

To provide a clear overview of the model configuration, Tables F.2 and F.3 present the input parameters used for the calm sea-state simulations of the FLOW and WAVE modules. These tables list the main model settings and their corresponding values as applied in the numerical setup. These Tables are displayed as example of how to set up the parameters in the model, while the main text in Chapter 5 explains which parameters are changed with each sea-state.

Table F.2: Delft3D–FLOW Model Settings - Scenario No Dike, Calm Sea-state

Category	Parameter	Value / Option	Notes
Time frame	Start date	01-04-2025 00:00:00	—
	End Time	04-04-2025 12:00:00	Variable
	Time step (DT)	1 <i>m</i>	—
Processes	Constituents	—	No options selected
	Physical	Waves Online Delft3D-WAVE	—
Initial Condition	Uniform values	—	—
	Water level	−0.657 <i>m</i>	—
Physical Parameters	Constants	$g = 9.81 \text{ m/s}^2$, $\rho = 1019 \text{ kg/m}^3$	ρ depends on sea state conditions
	Roughness	Manning, Uniform; $U = 0.02$, $V = 0.02$, Stress due to wave forces = Fredsoe, Wall roughness slip condition = Free	—
	Viscosity	Uniform horizontal eddy velocity = 1 m^2/s	No model for 2D turbulence selected
Numerical Parameters	Drying and flooding check at	Grid cell centres and faces	—
	Depth at grid cell faces	Mor	—
	Threshold depth	0.003 <i>m</i>	—
	Marginal depth	0.01 <i>m</i>	—
	Smoothing time	15 <i>min</i>	—
	Advection scheme for momentum	Cyclic	—
Operations	Discharges	—	No discharges added
Monitoring	Observations	54 points added	Added points of interest
	Drogues	—	No points added
	Cross-section	—	No cross-sections added
Additional Parameters	TpsCom	#Y#	—
	AirOut	#YES#	—
	AirOut	#euler#	—
	CstBnd	#YES#	—
Output	Store map & communication int	60 & 60 <i>min</i>	—
	History & Restart int	10 & 0 <i>min</i>	—
	Details	Deselected quantities	Derived In every category

Table F.3: Delft3D – WAVE Model Settings - Scenario No Dike, Calm Sea-state

Category	Parameter	Value / Option	Notes
Hydrodynamics	Run WAVE together with FLOW	Checked	—
Grids	Computational grid	Same grid as FLOW	—
	Bathymetry	Bathymetry without fourth dike	—
	Directional space	Circle, N of directions = 36	—
	Frequency space	$f_{\min} = 0.05 \text{ Hz}$, $f_{\max} = 1 \text{ Hz}$, $N_{\text{bins}} = 24$	—
	Hydrodynamics	Use but do not extent	All categories, except wind which is set to do not use
Time frame	Water level correction	0 m	—
Obstacles	Obstacles & obstacle segments	No obstacles defined	—
Physical parameters	Constants	$g = 9.81 \text{ m/s}^2$, $\rho = 1019 \text{ kg/m}^3$, North w.r.t. x-axis = 90° , Minimum depth = 0.05 m , Convection = nautical, Forces = wave energy dissipation rate	ρ depends on sea state conditions
	Wind	Speed = 3.427 m/s , Direction = 174°	—
	Processes	Generation mode = 3-rd generation, Depth induced breaking $\alpha = 1$, $\gamma = 0.73$, Bottom friction type JONSWAP $0.038 \text{ m}^2/\text{s}^3$	Non-linear and Diffraction disabled
	Various	Whitcapping = Van der Westhuysen	All categories checked except Frequency shift
Numerical parameters	Geographical space	First-order (SWAN 40.01) / Second-order (SWAN 40.11)	—
	Directional & Frequency space	0.5 & 0.5	—
	Hs-Tm01	= 0.02	—
	Percentage of wet grid points	= 98%	—
	Relative change w.r.t. mean value	Hs = 0.02 & Tm01 = 0.02	—
	Max number of iterations	15	—
Output curves	Output curves & segments	—	No output curves or segments selected
Output parameters	Level of test output	= 0	—
	Computational mode	Stationary	—
	Output variables	Output for FLOW grid	Other two not selected
	Output for computational grids	Interval = 0	Output for specific locations not enabled
Additional parameters	Domains, Constants, etc.	No options added or selected	—

F.3. Expanded Results of the Delft3D Model

This section provides an in-depth evaluation of the Delft3D conceptual model simulation results. The section starts with the general trends in the simulations, then expands on the modelled water depth in the Kim Động domain, followed by the flow, and finally the significant wave height.

The following points of interest have been identified within the Kim Động domain at which the modelled variables can be evaluated, as presented in Figure F.3.

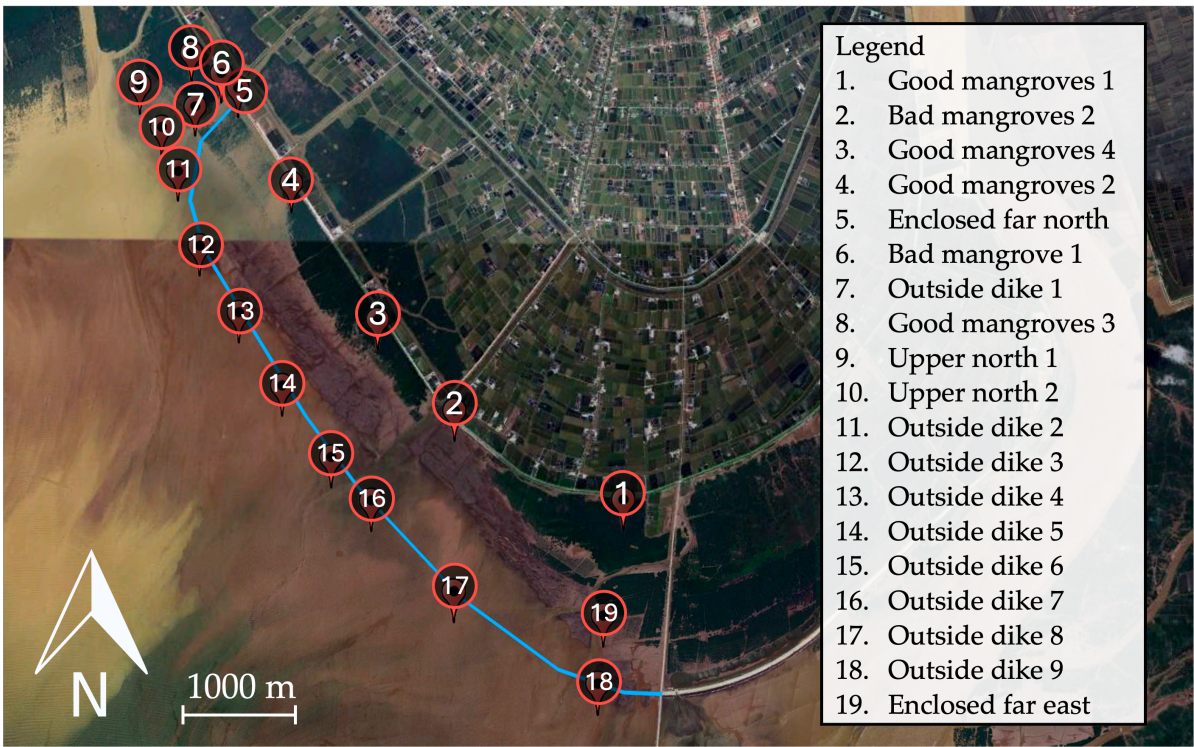


Figure F.3: Visualisation of the Different Locations of Interest in the Model Domain

F.3.1. General Trends of Main Variables

The following section expands on the percentages found in Table 5.6. First the general trends of the results with the dike with open gates configuration get evaluated, followed by the dike with closed gates configuration. The percentages were derived from multiple representative measurement points, for each variable, three illustrative plots are provided.

Dike with Open Gates

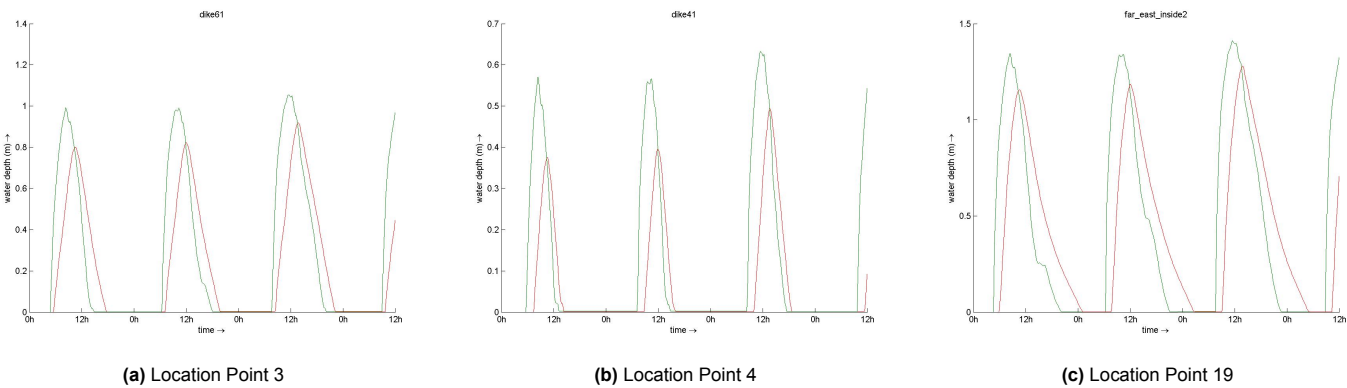


Figure F.4: Water Depth at Three Representative Measuring Points, Calm Conditions
Red: Dike Open Gates; Green: No Dike

Figure F.4 presents water depth at location points 3, 4, and 19. With gates open, water depth is lower by about 15% to 30% relative to the baseline, and inundation time changes between a range of approximately -10% until $+30\%$.

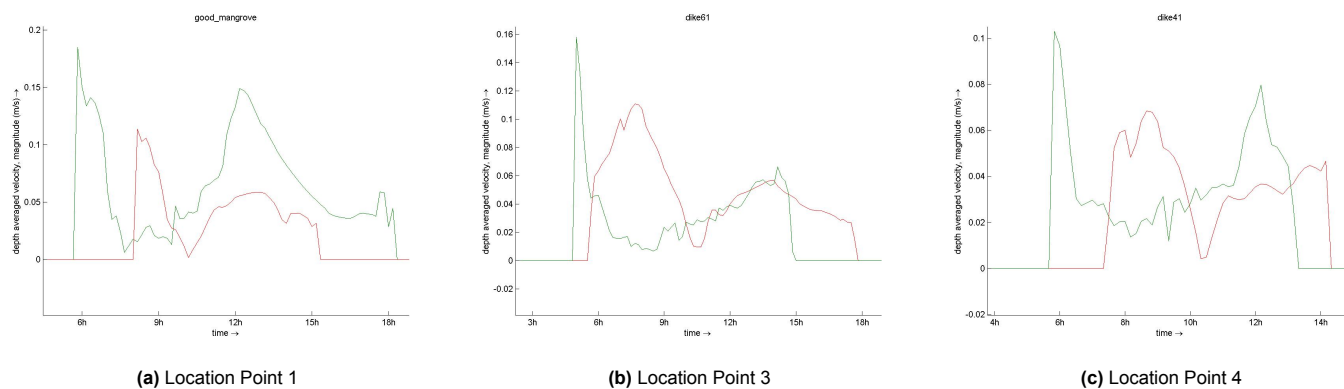


Figure F.5: Depth-Averaged Flow at Three Representative Measuring Points, Calm Conditions
Red: Dike Open Gates; Green: No Dike

Figure F.5 shows depth-averaged flow at location points 1, 3, and 4. With gates open, velocity changes range from about a 30% decrease to a 30% increase.

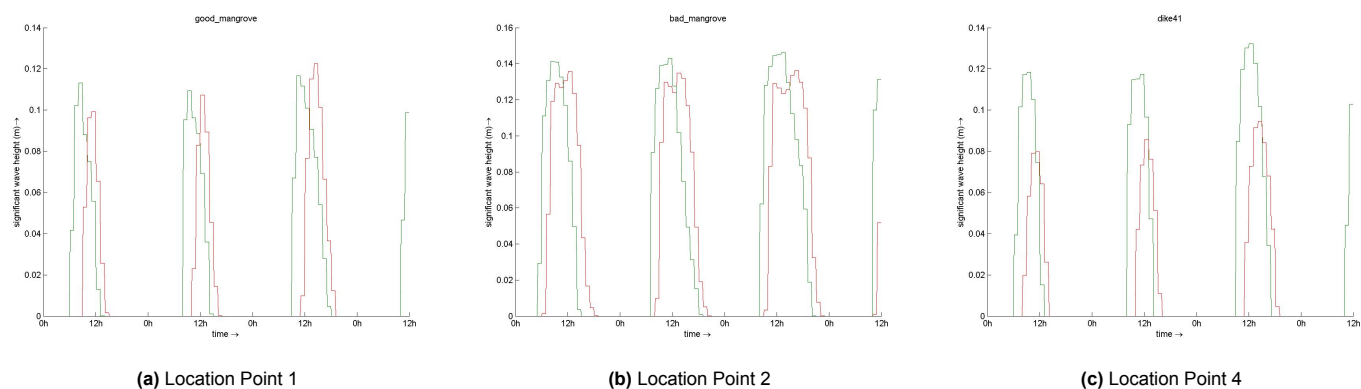


Figure F.6: Significant Wave Height at Three Representative Measuring Points, Calm Conditions
Red: Dike Open Gates; Green: No Dike

Figure F.6 shows significant wave height at location points 1, 2 and 4. With gates open, the significant wave height decreases by roughly 5% to 25% relative to the baseline.

Dike with Closed Gates

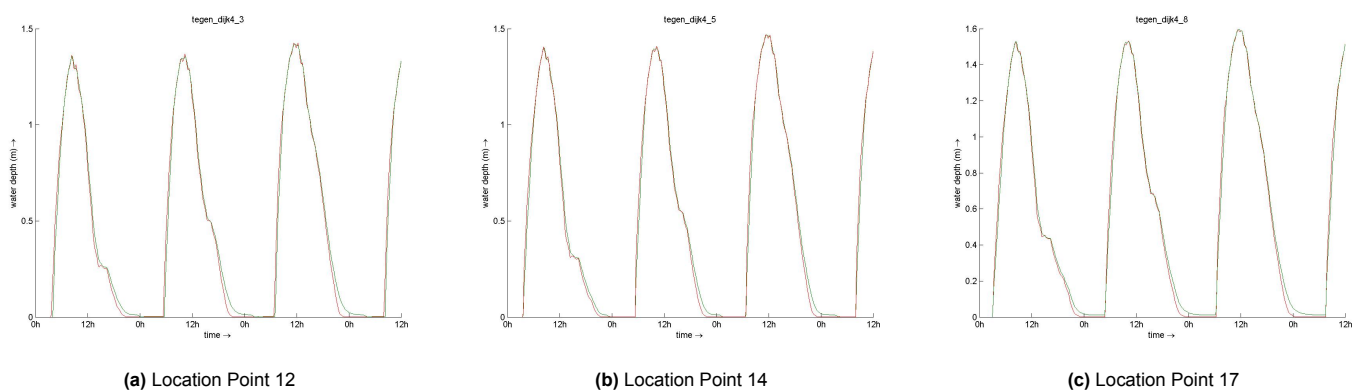


Figure F.7: Water Depth at Three Representative Measuring Points Outside the 4th Dike, Calm Conditions
Red: Dike Closed Gates; Green: No Dike

Figure F.7 shows that, with the gates closed, water depth at locations 12, 14, and 17 remains unchanged relative to the baseline, while the associated inundation time decreases by approximately 10% to 20%.

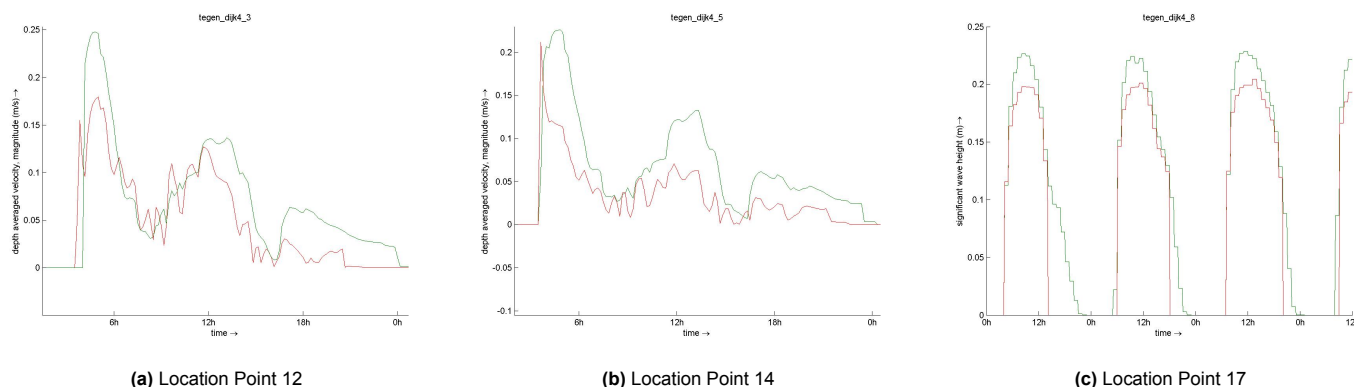


Figure F.8: Depth-Averaged Flow at Three Representative Measuring Points Outside the 4th Dike, Calm Conditions *Red: Dike Closed Gates; Green: No Dike*

Figure F.8 indicates that, with the gates closed, depth-averaged velocity at locations 12, 14, and 17 is decreased by roughly 10% to 40% compared with the baseline.

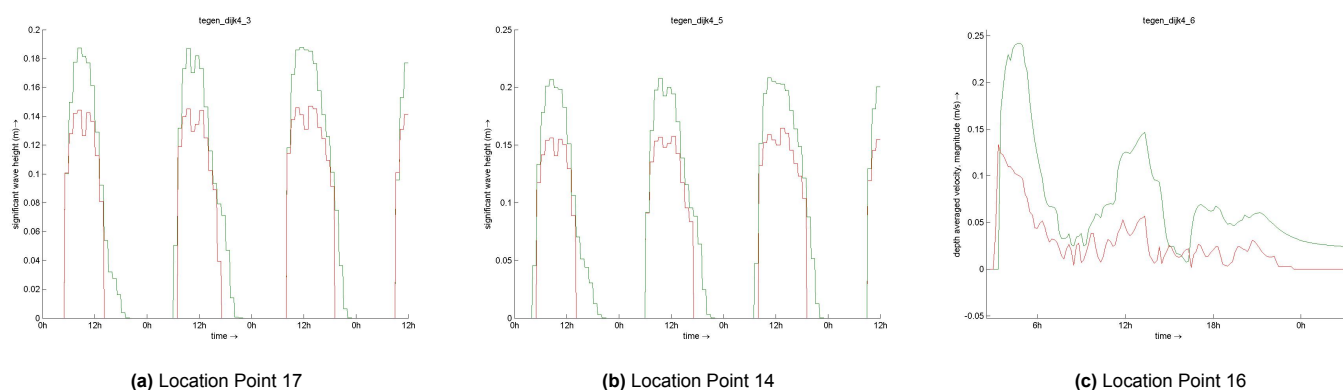


Figure F.9: Significant Wave Height at Three Representative Measuring Points Outside the 4th Dike, Calm Conditions *Red: Dike Closed Gates; Green: No Dike*

Figure F.9 shows that, with gates closed, at locations 12, 14, and 17, significant wave height decreases by approximately 15% to 25% relative to the baseline.

F.3.2. Modelled Water Depth

The water depth is evaluated across the domain for three configurations: (1) no dike, (2) a closed dike, and (3) a dike with open gates. Inundation time and the corresponding water depth are critical to mangrove health, as they govern submergence duration and water supply.

Patterns in Water Depth

First, results from modelling the water depth with the no-dike scenario are examined to provide insight into current mangrove conditions.

To characterise the tidal influences in the current situation without a dike, water depth is considered at five locations with differing levels of mangrove health, as shown in Figure F.10. The selected water-depth series represent calm and moderate weather. From the figures it can be concluded that healthy mangroves exhibit lower high-water peaks and shorter inundation duration than failing sites.

To evaluate the effect of the fourth dike on the mangrove sites, water depth is modelled for calm conditions using the open-gates configuration, as during these conditions gates are open. In Figures F.11 a,b,d

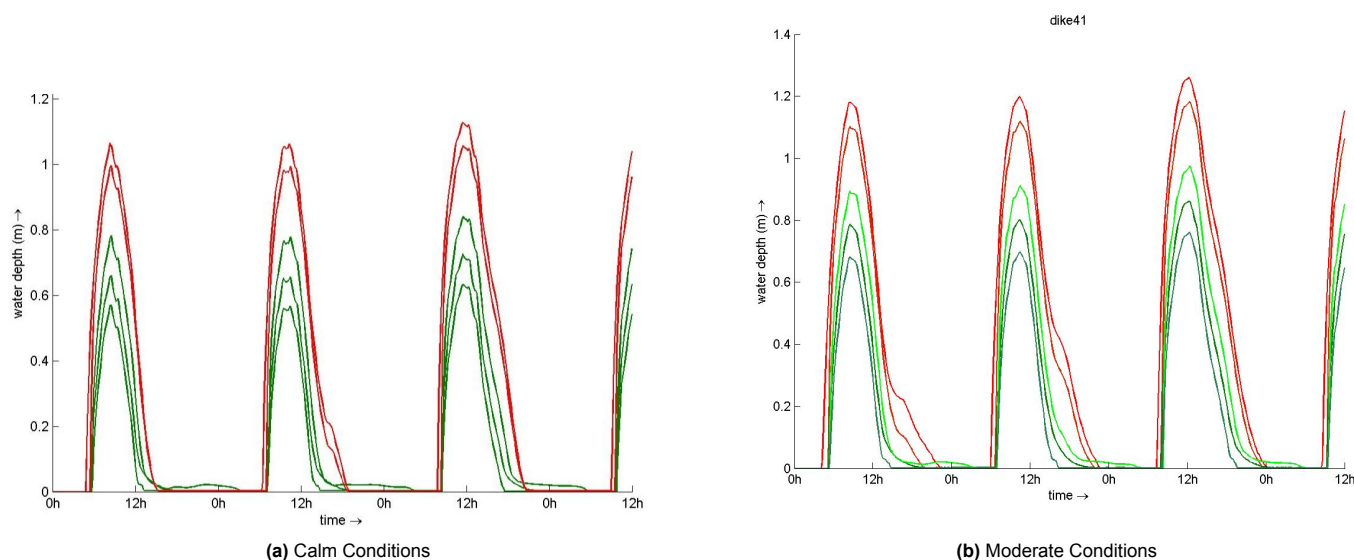


Figure F.10: Water Depth at Sites with Thriving and Failing Mangroves
Red: Failing Locations; Green: Thriving Locations

all enclosed mangrove locations show a reduction in peak water depth, and inundation time decreases after construction of the 4th dike. This brings the peak water depth at the failing mangrove locations closer to that of the thriving mangrove locations; however, the peak water depths of the thriving mangroves also decrease. Mangrove locations outside the enclosed area do not show significant change, as presented by Figure F.11 c.

Water Depth at Monitoring Points

To examine these lower peaks and shorter inundation times, the calm case with the dike with opened gates is considered to isolate the effect of restricted flow on water depth. Two measuring points along the northern canal are selected: one just outside the dike ring and one just inside.

Figure F.12 compares the water depth in the canal at the aforementioned observation points. The inside record lags the outside because flow must pass through a hydraulically resistive opening. By the time the external level reaches high water, the enclosed area has not fully filled, yielding a reduced high-water peak inside, while low water is almost unchanged. In short, the peaks show clear amplitude attenuation and a delayed response, whereas the troughs are nearly in phase and of similar amplitude.

Another informative measurement point is the Far East site inside the dike, as presented in Figure F.13. The modelled water depth is consistent with earlier results: installation of the fourth dike reduces the inflow peak and produces a slower, delayed response. Unlike the other sites, the increase in inundation time is markedly larger here, linked to the longer hydraulic pathway to the gate.

At the outer edge of the dike, interesting observations of water depth can be made. In the closed-dike model under calm conditions, the following pattern is recognised. Figure F.14 presents the water depth along a north-to-south transect. Here, the water depth along the seaward side of the dike gradually decreases northwards. At the peaks, the difference between the northern and southern points is about 20 cm, whereas at troughs the depth difference is significantly higher, at about 50 cm.

Another location that stands out in the water-depth analysis is Far North 1, situated at the top of the grid outside the dike. After completion of the fourth dike, water depth decreases by approximately 5% due to the dike's sheltering effect, as presented in Figure F.15.

By construction of the fourth dike, a new sea-facing boundary is created. Comparing the inundation times between P14 with the fourth dike, and P3 without it, it increases by 250%, as can be seen in Figure F.16.

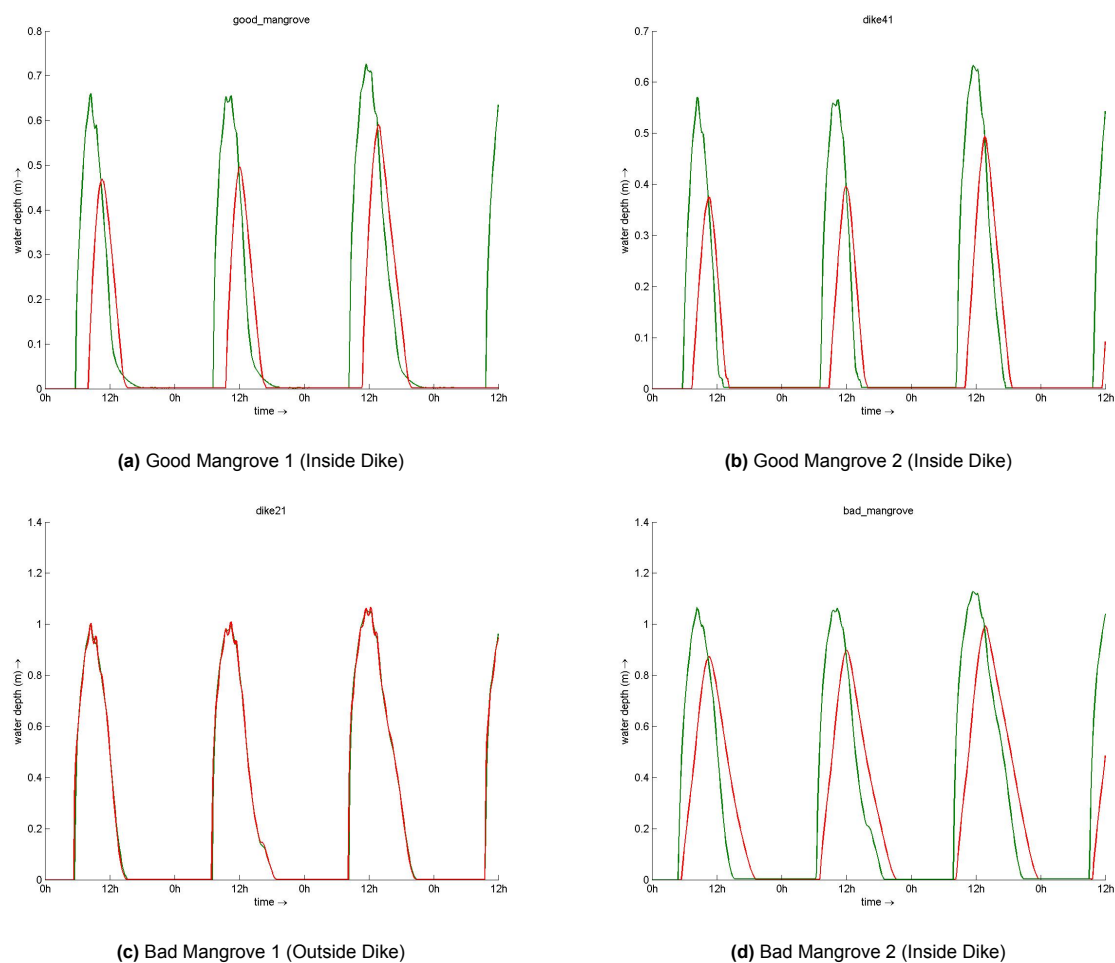


Figure F.11: Effect of the Fourth Dike at Four Mangrove Locations under Calm Conditions
Red: No Dike; Green: Dike with Open Gates.

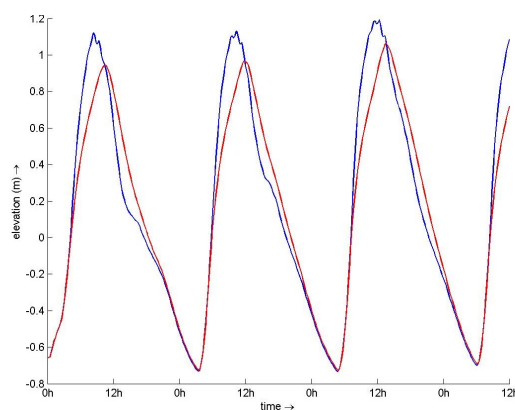


Figure F.12: Water Depth Inside and Outside Dike. Calm conditions
Red: Inside dike; Blue: Outside Dike

Sea-States Effects on Waterdepth

An observation between different sea-states can also be made; notably, the biggest difference can be expected between the calm and extreme cases.

Figures F.17 compare calm and extreme conditions at two locations: adjacent to Dike 4 and offshore. Under calm conditions, the records are comparatively symmetric. Under extreme forcing, the minimum

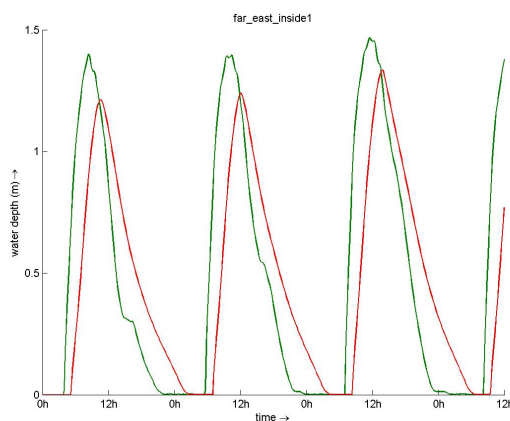


Figure F.13: Water Depth at Far East Location with and without Dike. Calm Conditions.
Red: Dike; Green: No Dike

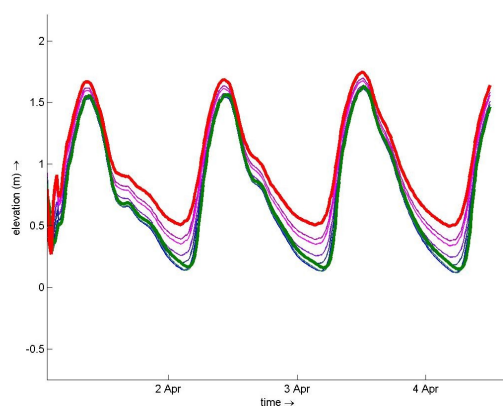


Figure F.14: Modelled Water Depth along a North-to-South Transect. Calm Conditions.
Purple: most Southern; Orange: most Northern

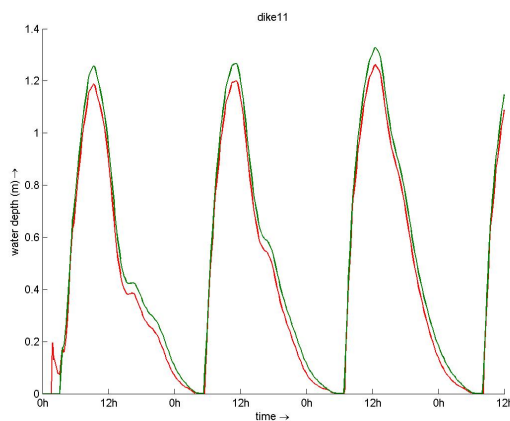


Figure F.15: Water Depth at the Far North 1 Location. Calm Conditions.
Green: No Dike; Red: With Dike

water depth gets disproportionately higher relative to the increase in the maxima. This asymmetry is consistent with wind and wave set-up.

It is also valuable to examine mangrove locations under extreme weather conditions. For both healthy and failing mangrove sites, three configurations are evaluated: no dike, dike open, and dike closed,

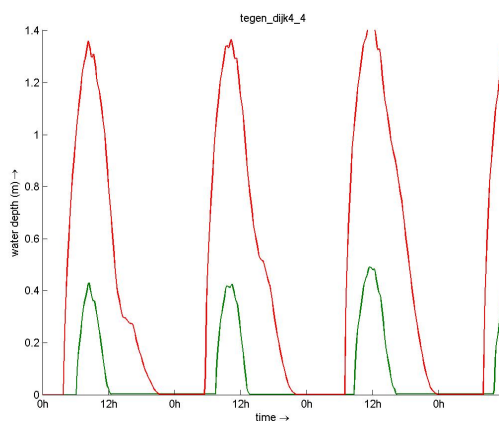


Figure F.16: Water Depth Comparison of Sea-Facing Boundary
Green: No Dike P3; Red: With Dike P14

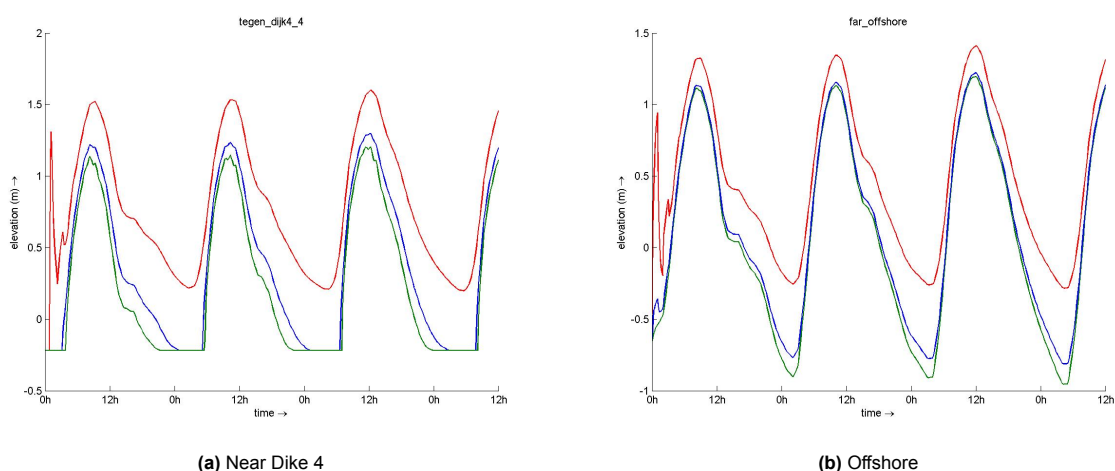


Figure F.17: Water Depth Response to Weather Conditions at Two Locations. Dike with Open Gates.
Green: Calm; Blue: Moderate; Red: Extreme

within the extreme states shown in Figure F.18. With the dike closed, the basin is hydraulically isolated and the tidal signal is effectively removed, resulting in no visible water-depth trace for the closed-dike configuration. With the dike open, inflow peaks are markedly lower than in the no-dike case, and the time the mangroves are submerged is reduced. Additionally, the restricted inflow can lead to periods when the mangroves are completely exposed (not inundated). Overall, the dike limits peak water depths during extreme conditions when opened at both mangrove locations.

Under extreme conditions, the gates are normally closed. Even if, for any reason, they are not operational, the dike still protects the area by reducing peak water depth and limiting inundation duration.

F.3.3. Modelled Depth-averaged Flow Velocities

This section analyses the magnitude of the depth-averaged flow velocities and the flow patterns inside the domain. The velocity magnitude is the most important aspect of the flow, since it directly influences the potential sedimentation deposition and erosion. Flow direction is only shown to give a general sense of the flow patterns within the domain, in order to see in which areas sedimentation and erosion might take place.

Flow Patterns

In order to observe the impact of the dike on the general flow patterns in the domain, the configuration of the dike without gates will be used, since the impact of the gates on the general flow patterns is

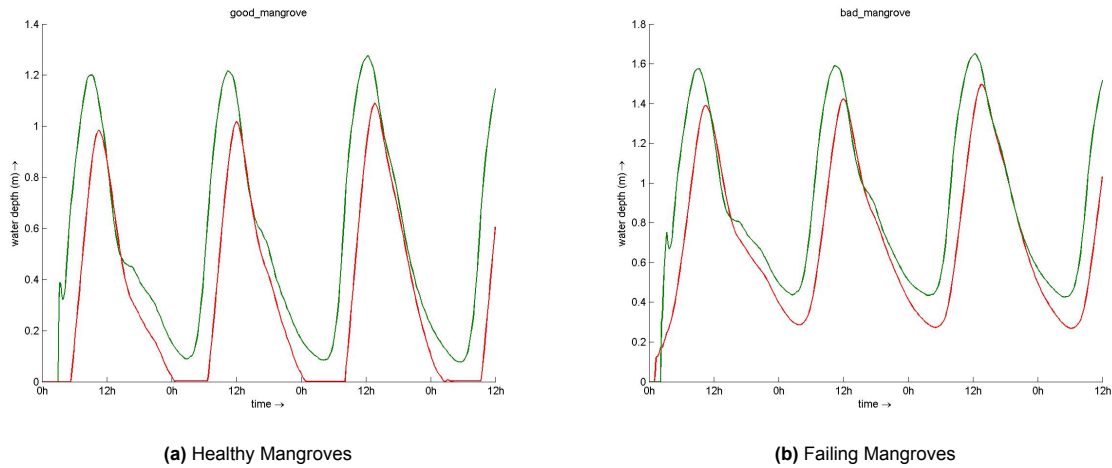


Figure F.18: Water Depth at Thriving and Failing Mangrove Sites during Extreme Conditions
Red: Dike Open Gates; Green: No Dike

insignificant on the larger scale. A visualisation of the flow patterns during high water with a calm sea state is shown in Figure F.19. From these figures, it can be observed that the dike does not have a significant impact on the flow patterns after a few kilometres offshore. However, the magnitude of flow velocities in front of the new dike segment are lower than the configuration in which the dike is not realised.

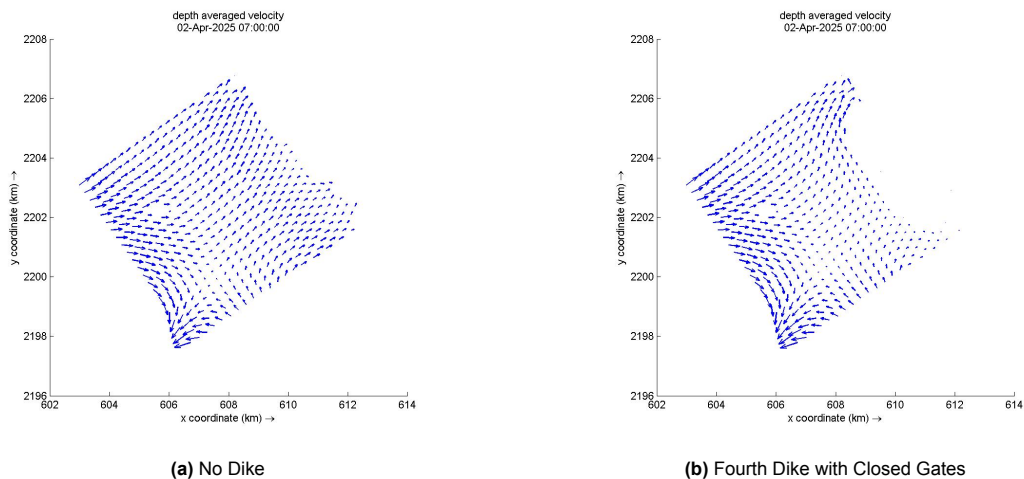


Figure F.19: Flow Patterns during High Water
Larger Arrow: Larger Magnitude of Depth-Averaged Flow Velocity

Both scenarios have also been analysed during low waters and are shown in Figure F.20. General flow velocities further offshore appear similar but ever so slightly higher in the configuration with the dike.

Lastly, the flow patterns inside Dike 4 have been analysed, both during high and during low water, as presented in Figure F.21. The flow patterns behave as expected: exchange occurs through the gates and currents spread gradually across the mudflat via the canals. In the high-water plot, velocities peak immediately landward of the gate and spread with distance. The restrictive opening is clearly visible, as limited inflow at high water and limited outflow at low water occur.

One interesting observation occurs during the intermediate environmental conditions in all configurations. At the P2 - P3 (south-western) boundary, there is a significant increase in the magnitude of the depth-averaged flow velocity, displayed in Figure F.22. This increase is visible during the entire simulation, which could be caused by the intersection point between the Neumann and discharge boundary.

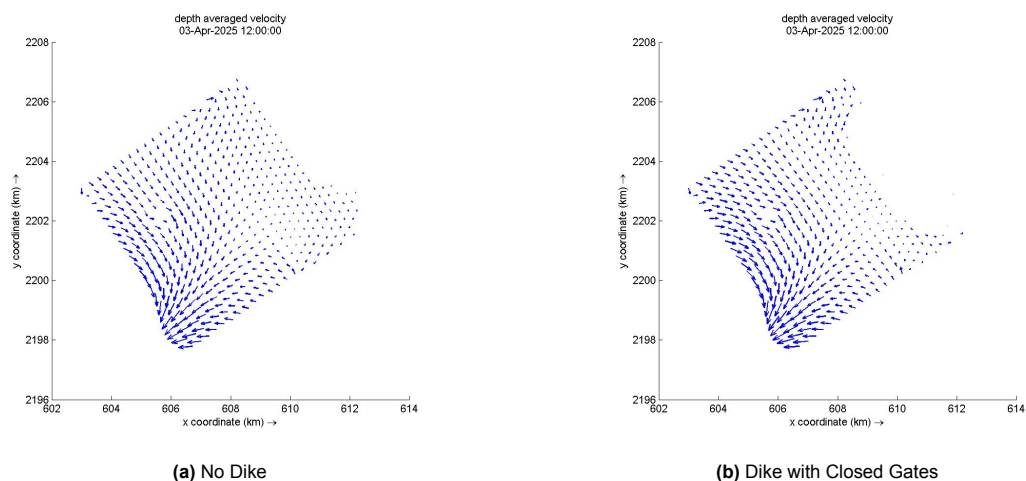


Figure F.20: Flow Patterns during Low Water
Larger Arrow: Larger Magnitude of Depth-averaged Flow Velocity

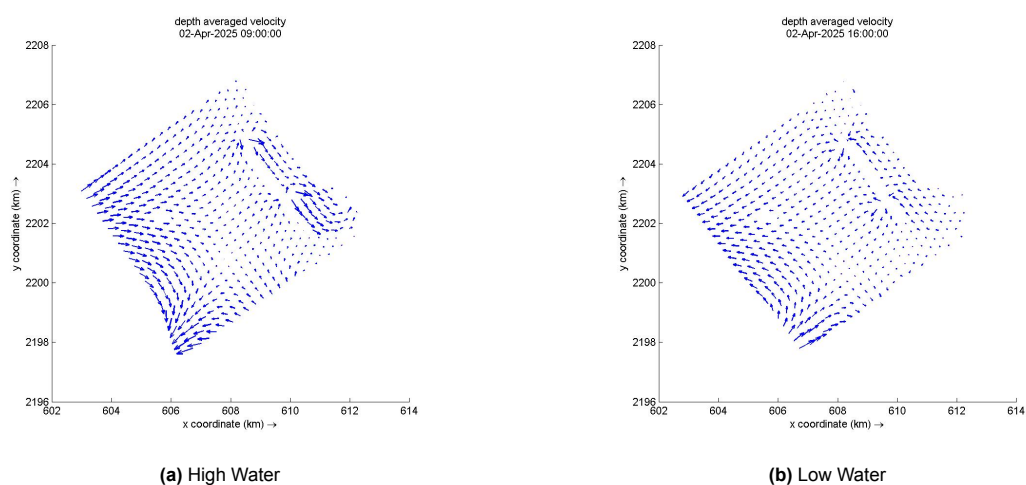


Figure F.21: Flow Patterns Inside the Fourth Dike
Larger Arrow: Larger Magnitude of Depth-averaged Flow Velocity

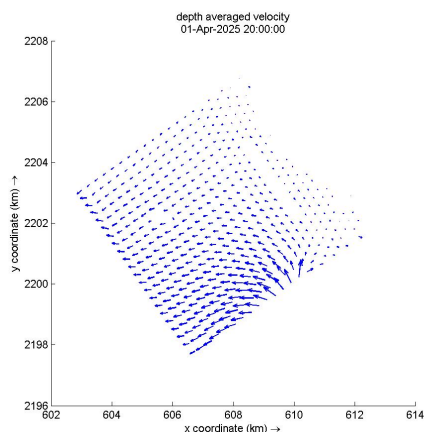


Figure F.22: High Flow Velocity near Discharge Boundary
Larger Arrow: Larger Magnitude of Depth-averaged Flow Velocity

Velocity Observations at Monitoring Points

To obtain a more detailed understanding of the local hydrodynamic behaviour within the model domain, depth-averaged flow velocities are examined at several monitoring point locations. First, the situation

without the fourth dike is analysed to assess how different sea-states influence flow velocities. These results are then compared with mangrove conditions, distinguishing areas where mangroves thrive from areas where they appear to be under stress, in order to explore possible links between hydrodynamic exposure and mangrove health. Subsequently, velocity profiles directly in front of the fourth dike are compared to those at the same locations in the no-dike scenario. Finally, the hydraulic conditions in the north-western corner for the different dike configurations are assessed to evaluate how they influence the local flow velocities in this area.

Flow velocities are evaluated at three monitoring locations representative of both healthy and failing mangrove zones, for calm and extreme hydrodynamic conditions. Depth-averaged velocity magnitudes under calm conditions are shown in Figure F.23a, while Figure F.23b illustrates the results for extreme conditions.

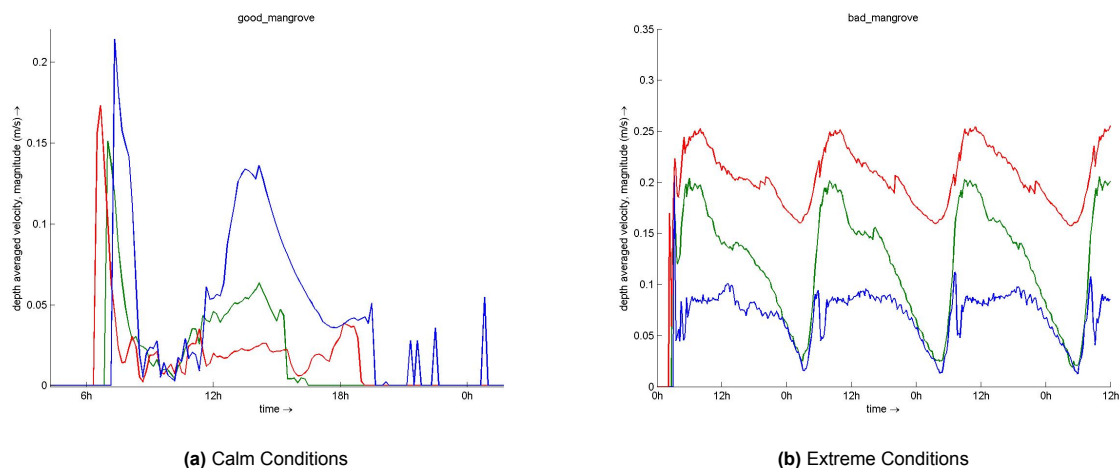


Figure F.23: Depth Averaged Flow Velocities at Three Locations Without Dike.
Blue: Good Mangroves 1; Green: Good Mangroves 4; Red: Bad Mangroves 2

Under calm conditions without the fourth dike, flow velocities remain relatively low across all locations, with the highest peaks coinciding with the incoming tidal wave. The area where mangroves are observed to be in poor condition exhibits the lowest velocities, which contrasts with the expectations from the literature review in Chapter 3.3.2. During extreme storm conditions, represented here by the extreme sea-state, flow velocities increase at all locations. The area with mangroves in poor conditions experiences the largest increase, ranging from 0.15 m/s to 0.25 m/s, whereas the other two areas generally remain below 0.15 m/s or even 0.10 m/s. This means that when conditions are calm, the mangroves in poor conditions are not stressed by strong currents. But under extreme events, this area becomes more exposed to high flow velocities than the healthier mangrove zones.

Now, the situation with the fourth dike in place is considered. The same three monitoring locations under calm and extreme sea-states are shown in Figure F.24. The green, blue, and red lines represent the same points as in Figure F.23, but this time the scenarios include the fourth dike. Here, the observation is made that the flow velocities under calm conditions do not differ to much. The area with bad mangroves experiences an increase in flow velocity in this configuration, which can be explained by the fact that this monitoring point is located closely to one of the main canals behind the gates. Furthermore, the area with failing mangroves continues to show the highest flow velocities under extreme conditions, likely again due to its location close to the canal. The last observation is that under storm conditions, the flow velocities in all three observation points are lower than in the case without a dike.

Velocities along the Fourth Dike

To further understand how the presence of the dike influences local flow dynamics, flow velocities are compared across six configurations: the situation without the dike under three sea-states (calm, moderate, and extreme), and the situation with the fourth dike and closed gates under the same three sea-states. The key observations are summarised in Figure F.25.

From the comparison between the two dike configurations, it can be concluded that the magnitude of

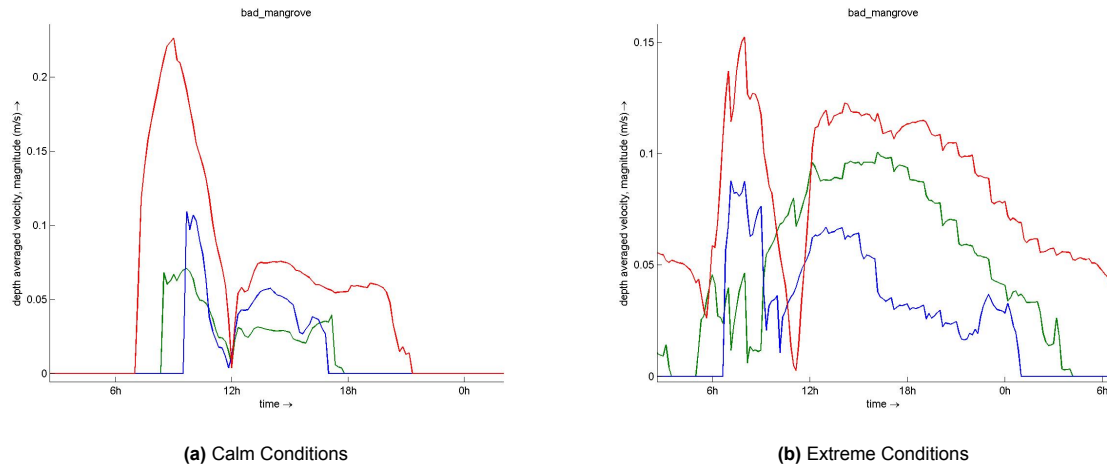


Figure F.24: Depth Averaged Flow Velocities at Three Locations after the Completion of the Fourth Dike.
Blue: Good Mangroves 1; Green: Good Mangroves 4; Red: Bad Mangroves 2

the depth-averaged flow velocity in calm conditions stays relatively the same. However, under extreme conditions, the presence of the fourth dike increases flow velocities by approximately 20%.

The fourth dike also changes how flow velocities respond to different sea-states. Without the dike, locations that have the highest velocities during calm conditions continue to experience the highest velocities under moderate and extreme conditions. In contrast, with the dike in place, locations that are sheltered and show the lowest velocities under calm conditions become the areas with the highest velocities during extreme events. This suggests that areas that appear sheltered during calm conditions may experience sudden and significantly stronger flows during storms once the dike is completed.

Depth-average Velocities in the Northwestern Corner

Another interesting region is the northwestern corner of the model domain. There, three key observations are made regarding the depth-averaged flow velocities. First, this region is generally not strongly affected by the construction of the fourth dike: four of the monitoring points show only minor differences between the dike and no-dike scenarios. However, two points experience noticeable changes under calm sea conditions, as shown in Figure F.26. Location 6 shows a reduction in flow velocity, indicating that this area becomes more sheltered once the fourth dike is constructed. In contrast, Location 10 experiences an increase in flow velocity, suggesting that the new dike redirects flow in this part of the domain.

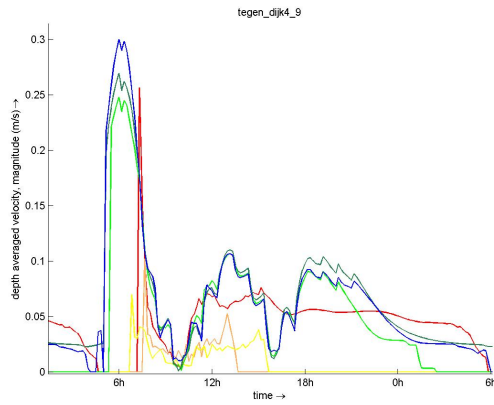
This pattern suggests that even in areas where the overall hydrodynamic impact is limited, local flow patterns are still altered by the dike, with implications for sediment transport and ecological conditions.

F.3.4. Significant Wave Height

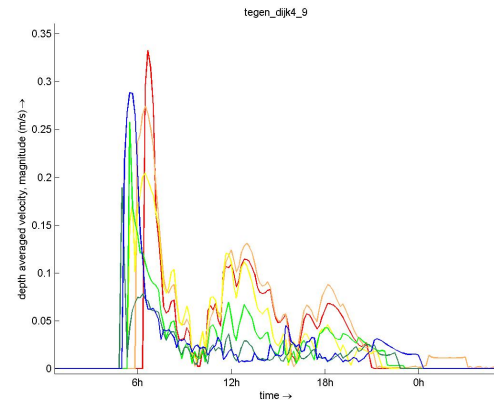
The following section analyses the significant wave height (H_s) across the model domain. This modelled variable is the primary wave metric and can give insight into the wave energy and wave-induced sediment transport. It is important to note that the results of the wave output are not the most accurate representation of reality. As the waves at the boundaries break immediately, followed by the significant wave height decreasing smoothly towards the coast. Shoaling is not visible in any output of the model, linked to the bottom friction, which has been minimised to reduce these effects.

Wave Patterns

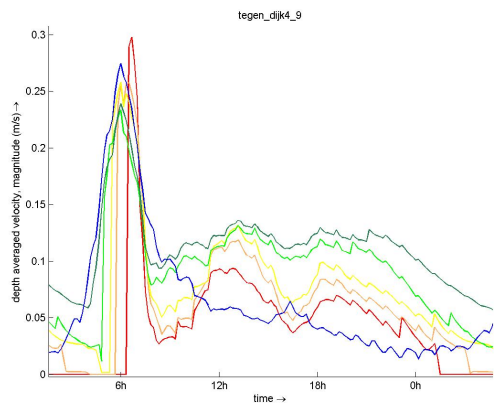
In Figure F.27 and Figure F.28, the significant wave height is plotted for calm conditions for ebb and high tide without Dike 4. The two wave boundaries are clearly visible, spanning the entire south-west boundary and part of the south-east boundary, as shown by the dark red edges. It stands out that there is no specific breaking point in Figure F.28, but rather a smooth decay of the significant wave height, which does not represent a realistic situation. The wave height difference along Dike 3 has also been displayed, including points of interest, in Figure F.29.



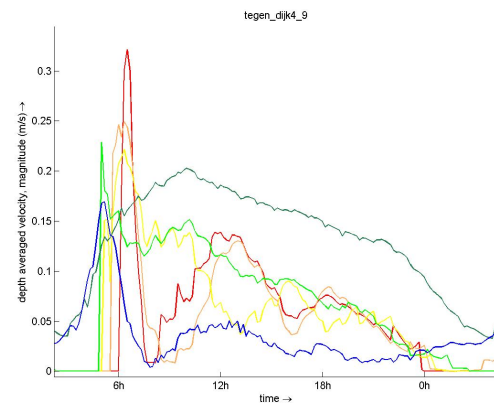
(a) Configuration without the Fourth Diagonal, Calm Sea-state.



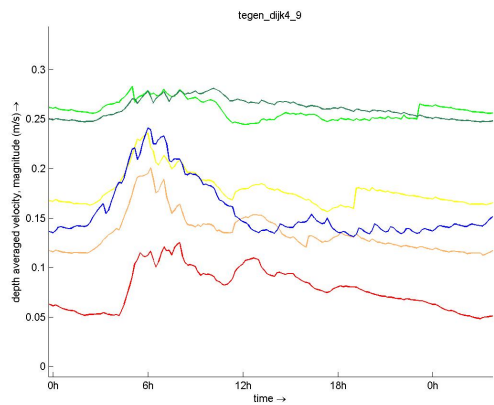
(b) Configuration with the Fourth Diagonal and Closed Gates, Calm Sea-state.



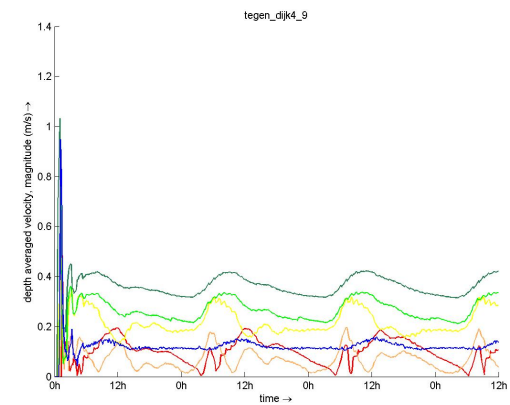
(c) Configuration without the Fourth Diagonal, Moderate Sea-state.



(d) Configuration with the Fourth Diagonal and Closed Gates, Moderate Sea-state.



(e) Configuration without the Fourth Diagonal, Extreme Sea-state.



(f) Configuration with the Fourth Diagonal and Closed Gates, Extreme Sea-state.

Figure F.25: Depth-Averaged Velocities at Six Monitoring Points along the Fourth Diagonal.
 From East to West: Locations 7, 11, 12, 14, 16, 18 respectively red, orange, yellow, light green, dark green, blue.

In Figure F.30, wave-induced forces are visualised (in N/mm^2). It is remarkable that at a specific dike section south of the lower gate in Diagonal 4, the wave force is higher than at other segments. This site is closest to the wave boundary and therefore experiences the highest wave-induced forcing. Figure F.33 shows that, under extreme conditions, the significant wave height decreases from the southern (lower) to the northern (upper) section of the dike.

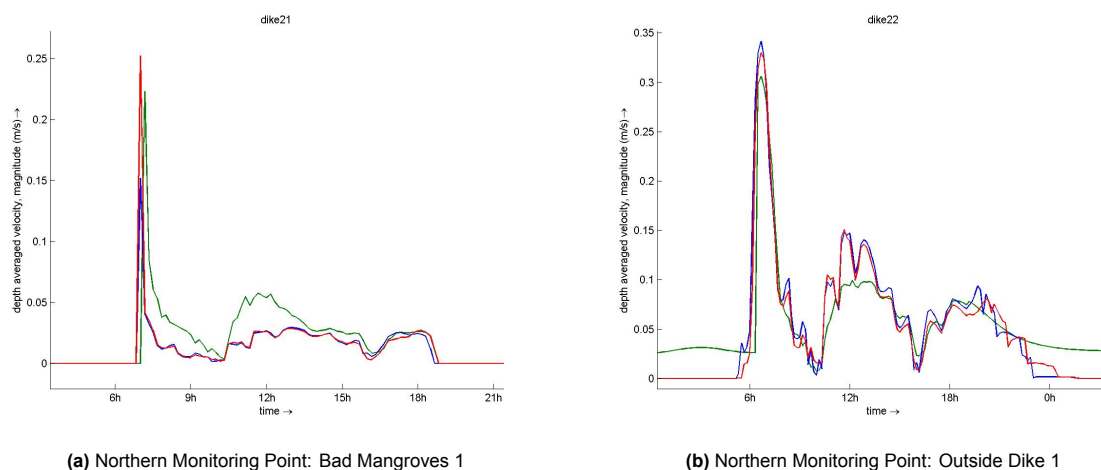


Figure F.26: Depth-Averaged Flow Velocities During Calm Conditions.
Green: No Dike; Blue: Dike Gates Closed; Red: Dike Open Gates

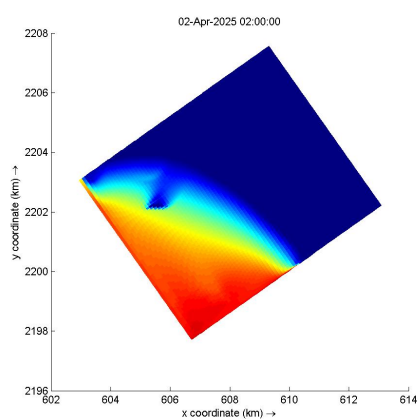


Figure F.27: Significant Wave Height (m) at Low Water without Fourth Dike (Calm Conditions)

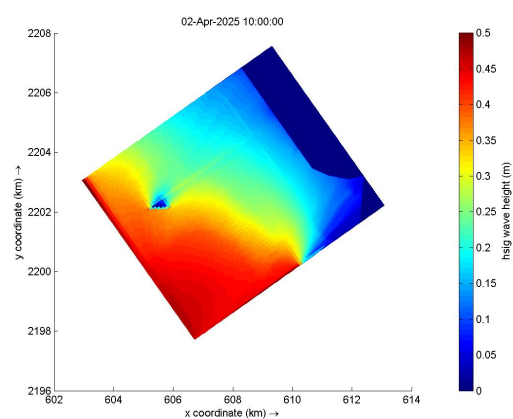


Figure F.28: Significant Wave Height (m) at High Water without Fourth Dike (Calm Conditions)

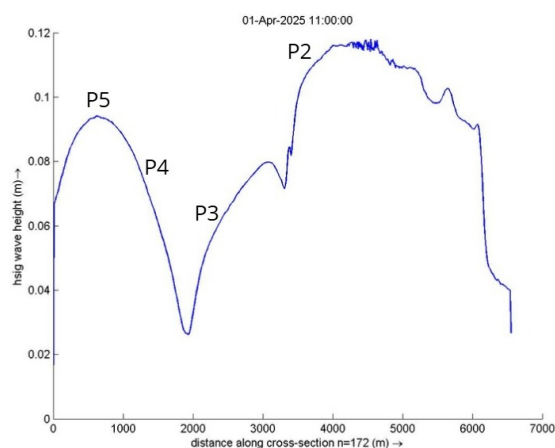


Figure F.29: Significant Wave Height of Transect Parallel to Dike 3 Before Construction of Dike 4. Calm Conditions

In Figure F.31, the significant wave height is shown for the configuration with Dike 4. Within the dike, particularly just behind the entrance to the lower (southern) gate, wave heights are noticeably higher than elsewhere inside. This likely reflects waves travelling through the canals with limited damping. A

further possibility is partial reflection from the third dike, which could locally increase wave height.

Another important observation to consider is that, at the southern part of the dike, exposed to the strongest wave forces, some waves appear to pass through the structure. This can be caused by Delft3D allowing unintentional wave transmission through the dike, as the dike is too high to be overtopped under calm sea conditions. This phenomenon may have influenced the wave height inside the dike area, so any conclusions drawn from it should be made with caution.

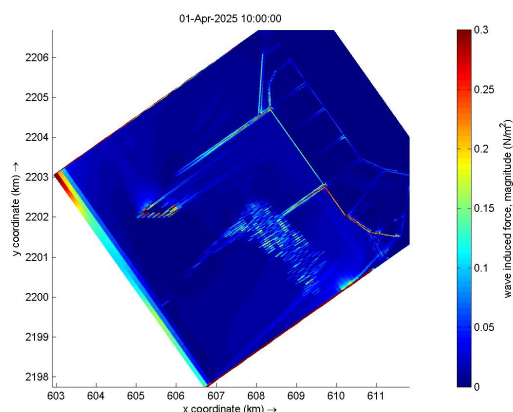


Figure F.30: Wave-Induced Force (N/mm^2) at High Water With Fourth Dike (Calm Conditions)

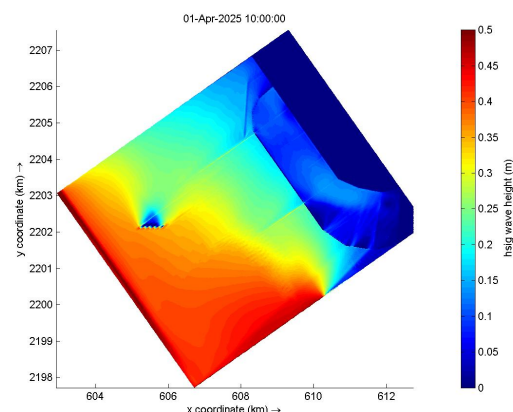


Figure F.31: Significant Wave Height (m) at High Water With Fourth Dike (Calm Conditions)

Waves in Monitoring Points and Transects

Figure F.32a shows the cross-shore evolution of significant wave height along a perpendicular transect midway between the two gates in Dike 4, for both the with-dike and without-dike cases. At $x = 0$ the ocean boundary is visible where the significant wave height is highest. The shoreline of the third dike lies at approximately $x = -6500$. Before construction, the wave height decreases smoothly towards the original shoreline of the third dike, where waves break. After construction, the significant wave height is already reduced in front of the 4th dike relative to the no-dike case, after which breaking occurs. Thus, the fourth dike reduces wave height seaward of the structure, a pattern seen in most of the domain.

Figure F.32b shows the cross-shore evolution of the significant wave height at the location just under the entrance of the lower (southern) gate, where the significant wave height reaches its maximum within the inner dike area, as seen in Figure F.31. The waves behind the dike reach similar heights to those observed without the dike, meaning in the model this area is exposed to nearly the same conditions as before the dike was added.

Another pattern observed is that the significant wave height decreases when moving from the lower (southern) part of the fourth dike toward the upper (northern) section. This is likely because the wave boundary is located closer to the southern part of the dike, causing the waves that penetrate further along the dike to be gradually damped over the distance they travel. As a result, the wave heights become lower toward the upper part of the dike, as illustrated in Figure F.33.

A noteworthy result for significant wave height is also observed along transect $n = 165$ m, which runs parallel to the original shoreline of the 3rd dike, as presented in Figure F.34. Here, $x = 0$ coincides with the north-western boundary, and $x = 6500$ with the south-eastern boundary. Under calm conditions, the significant wave height is nearly uniform along the transect up until the last kilometre. Under moderate and extreme conditions, however, the significant wave height exhibits peaks at locations where mangroves are failing and troughs at places where mangroves are thriving. Under extreme conditions, the difference in significant wave height between the trough and peak is roughly 40%. Additionally, the most eastward regions are more sheltered, with significant wave height dropping along this section of the shoreline. These patterns are the same for Calm conditions at a different transect, as displayed in Figure F.29. The figure below is more for an indication of the impact of Storm conditions.

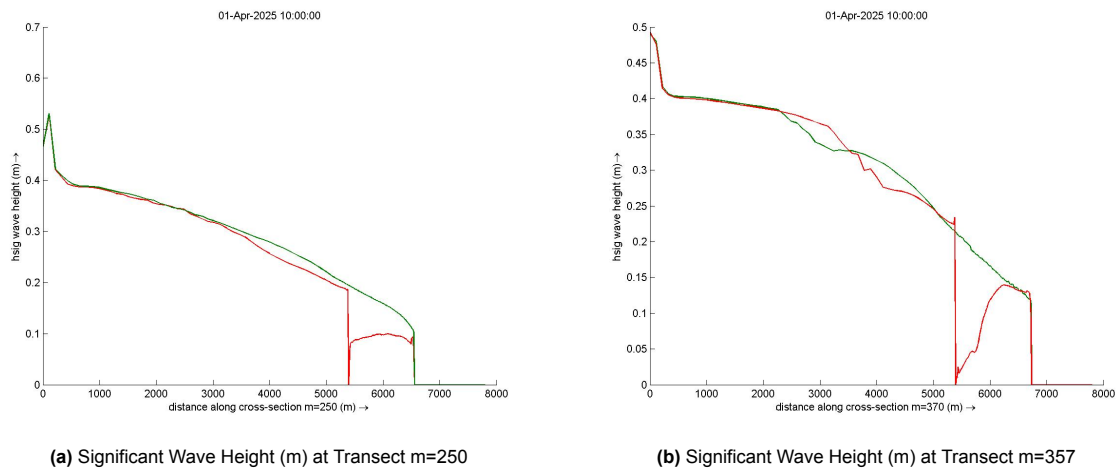


Figure F.32: Cross-Shore Evolutions of Significant Wave Height. Calm Conditions.
Red: With Fourth Dike; Green: Without Fourth Dike

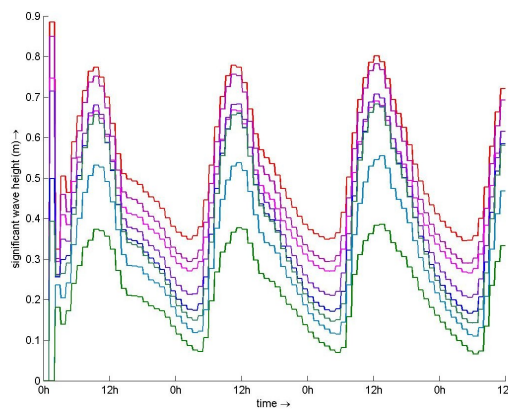


Figure F.33: Decrease of Wave Height under Extreme Conditions along North-to-South Transect Along 4th Closed Dike
Red: most Southern; Green: most Northern

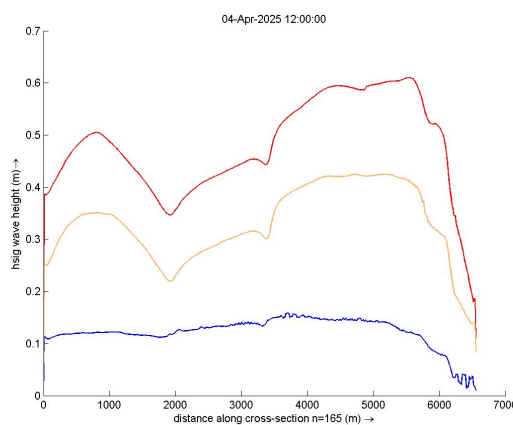


Figure F.34: Significant Wave Height along Original Shoreline (Transect n=165m) with No Dike
Blue: Calm; Yellow: Moderate; Red: Extreme

Sea-states Effects on the Significant Wave Height

When comparing the three sea-state conditions after completion of the 4th dike, the wave plots at a location in the dike's wave shadow (Bad Mangroves 1) show an interesting result. Figure F.35 presents

significant wave height at the most shadowed nearshore site outside Dike 4 in the northern part of the grid. The relative difference between the with-dike and no-dike curves decreases as forcing becomes more energetic. Under calm conditions, the difference between the significant wave heights between the two configurations is roughly 66%, whereas under extreme conditions this falls to roughly 50%.

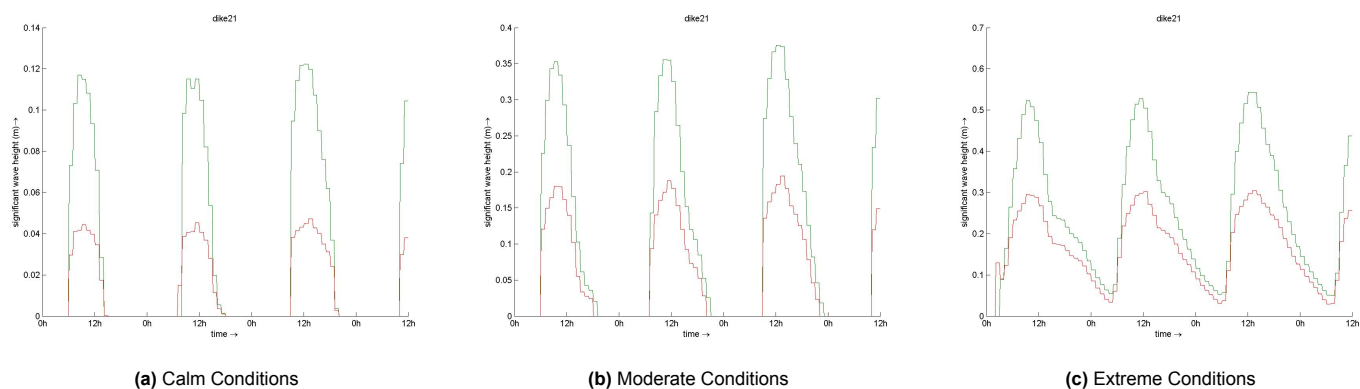


Figure F.35: Significant Wave Height at a Shadowed Nearshore Point.
Red: With Dike; Green: No Dike

G | Interventions Background

In this appendix, background information on the different alternatives to mitigate the negative effects of the fourth dike, the COCD box used and the Multi Criteria Analysis (MCA) is explained. This background information gives a detailed breakdown of what alternatives have been assessed and how and why they are feasible or not. Additionally, the scores in the MCA are explained.

G.1. COCD box

The COCD Box is a creativity tool used to categorise and evaluate ideas based on their originality and feasibility. It helps to identify which ideas are realistic to implement and which are more innovative or future-orientated.

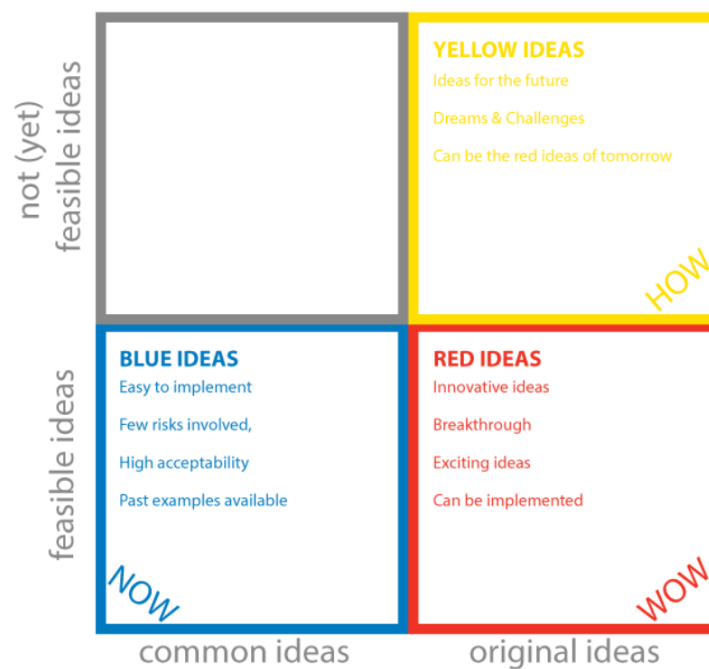


Figure G.1: COCD-Box (TUZZit, 2025)

The method divides ideas into three main colours:

- **Blue ideas:** represent safe and realistic alternatives that can be implemented directly within the current system or policy framework.
- **Yellow ideas:** are more original and creative. These ideas often require new thinking or approaches but may not yet be practical.
- **Red ideas:** combine both innovation and feasibility. These are challenging but achievable ideas that have high potential impact and are therefore most valuable for further development.

By organising ideas in this way, the COCD Box helps to structure brainstorming results and make strategic choices. In this research, it was used to identify which interventions for Kim Đông are both innovative and realistic, and therefore most suitable for further analysis in the Multi-Criteria Analysis (MCA).

G.2. Alternatives Morphological Chart

This section presents the different alternatives developed to address the key challenges within the Kim Đông coastal system and the completion of Dike 4. Each alternative represents a potential solution to a specific issue, with the colour classification described above used to indicate its feasibility and degree of innovation. These alternatives are used to construct the morphological chart shown in Chapter 6.

G.2.1. Reduced Tidal Connectivity and Water Quality

Because of the fourth dike, tidal connectivity between areas in and outside of the dike will be reduced, and water quality will worsen, which has a negative impact on the mangroves. To mitigate these effects, the following alternatives have been added to the morphological chart:

- **Controlled Tidal Exchange Systems (Adjustable Gates):** Installing adjustable sluice gates that allow tidal water to enter areas inside of the dike periodically, restoring salinity balance and sediment are essential for mangrove health. Since there are already sluices in all of the other dikes, it is likely that these will also be present in the fourth dike. This makes it a safe option, corresponding to the blue colour in the COCD box. Model results showed that tidal amplitude and salinity are significantly reduced inside the current dike system, indicating that controlled exchange is crucial to maintain ecological balance. Interviews with local engineers also confirmed that the technical design of such gates is already familiar in the region, which supports its feasibility.
- **Operation Plan for Gates:** Managing the operation of the gates could help to balance both economic and ecological needs. Gates can be opened during dry periods to maintain salinity and closed during floods to protect aquaculture ponds. This adaptive management balances ecological and economic needs and is rather a blue idea.
- **Sediment Nourishment in Front of Dike:** Adding sediment near the dike stimulates natural accretion and creates new substrate for mangrove growth. It also reduces coastal erosion by dissipating wave energy over a wider, shallower foreshore, thereby lowering the wave forces acting on the dike. In addition, by increasing sediment availability in front of the dike, the net sediment transport can become positive (i.e., sediment accumulation rather than erosion), which further stabilises the coastline (Smith, Zhang, Nguyen, & Morales, 2023). The Delft3D simulations indicated erosion hotspots near the foreshore of the fourth dike area. Sediment nourishment could reduce these effects, but such projects have not been applied locally, which makes feasibility and cost-effectiveness uncertain.
- **Floating Bioremediation Platforms:** Floating bioremediation platforms can clean water that stands still for a long time by absorbing nutrients and organic waste. These platforms function like floating wetlands, where aquatic plants and microorganisms naturally filter and break down pollutants. This improves the water quality in enclosed areas by the dike (Grosshans, Gunn, Stanley, & Lewtas, 2019). This is a fairly unrealistic alternative since it requires a lot of money and technical knowledge. This is an example of a yellow idea.
- **Digital Flow Monitoring System:** Real-time sensors could monitor hydraulic components like flow direction, water level or salinity to guide possible gate management and other interventions related to the hydraulic processes. This available data could also help with transparent decision-making. The lack of monitoring data was one of the main limitations of this research. Interviews with both Vietnamese and Dutch supervisors highlighted that a data-sharing system could fill that gap, but implementation remains complex due to limited digital infrastructure.

G.2.2. Mangrove Loss

Because of the fourth dike, mangrove loss could occur due to reduced tidal exchange and mangrove-squeeze. Model results and field observations show that the fourth dike reduces tidal exchange and sediment transport, leading to lower water quality and mangrove squeeze. This limits natural tidal exchange inside and outside the dike. Interviews confirmed that although authorities recognise this risk, no clear strategy exists to allow landward migration. Interventions should therefore restore sediment supply and create physical space for mangrove movement. To mitigate these effects, the following alternatives have been added to the morphological chart:

- **Formal Leasing Policy (Long-term Rights):** By assigning long-term leases for land with mangrove forests to local people or households, sustainable management will be encouraged. Ownership increases the feeling of responsibility and maintenance incentives. Also, it provides economic benefit for the local community. Clear regulations and management conditions would need to be established to ensure ecological protection and fair use. This complexity makes it a red idea.
- **Setback Zones for Future Landward Migration:** Setback zones are buffer strips between the dike and developed land. Creating these will enable mangroves to migrate inland. This will maintain long-term ecological resilience. Since this is a fairly easy-to-implement option in which there is no real evidence if it will work, it is considered a safe option (blue).
- **Replanting Native Mangroves in Degraded Zones:** Replanting mangroves will increase the mangrove forest. Especially using native species adapted to local hydraulic conditions. However, this is just a short-term solution for which there is no evidence if it will be resilient in the long term. The fact that it is also already implemented to some extent makes it a safe, blue option.
- **Mangrove Corridors Between Patches:** Creating connected mangrove corridors means connecting separate mangrove patches by restoring ecosystems or planting in the areas between them. These connected zones allow for species exchange, seed dispersal and natural migration of mangrove trees, especially under changing hydraulic conditions. The corridors will help to maintain sediment and water flow between the different patches, which supports stable growth. These corridors can be established in shallow, low-lying areas where tidal influence remains. This makes it a relatively safe and nature-based solution.
- **Blue Carbon Programmes:** By integrating mangroves into carbon credit systems, financial incentives for conservation are created. This links local restoration with global climate goals (red alternative).

G.2.3. Inefficient Governance

Inefficient governance is an issue that is at play either way, even if the fourth dike will not be constructed. However, when the fourth dike is constructed, governance becomes even more important because the land-allocation decisions have to be made. Governance in Kim Đông is highly hierarchical, with overlapping responsibilities and limited coordination between departments. This slows down decision-making and creates conflicting land-use outcomes. For the fourth dike, unclear responsibilities around mangrove protection and aquaculture expansion are a key issue. More transparent and coordinated governance is crucial for effective implementation. To mitigate the effects of inefficient governance, the following alternatives have been added to the morphological chart:

- **Clarify Institutional Procedures:** Several institutional procedures in Kim Đông are unclear. Responsibilities about land-allocation are not clearly defined, and there is still a lot of overlap, which causes delays. Simplifying and clearly defining responsibilities will ensure faster project approval and more coherent mangrove management. This is, however, a safe option since it is already being tried (blue).
- **Co-management Framework:** Co-management is a proven effective way in other areas which have implemented it to create stable and resilient coastal systems. Sharing management responsibilities with local communities improves accountability and policy acceptance. It can be somewhat tricky to implement since it is not common that local residents can co-decide, placing this alternative in the red category.
- **Integrate Mangrove Management into Provincial Plans:** Although mangrove forests are covered in national policies (Chapter 3), the integration within provincial coastal planning remains inconsistent. The mangrove-component is often weakly situated within the broader regulations and goals. For Kim Đông, this means that aligning mangrove management with provincial development plans remains critical. However, this alternative can be complex and bureaucratically challenging in Vietnam, making this a red idea.
- **Legal Pilot Area for Flexible Regulations:** In pilot areas, tests can be done to test innovative governance models or partnerships with other countries or researchers under relaxed regulations. Successful approaches can later be scaled up in the province. In the Mekong Delta, similar

projects have proved to be successful (Government of Viet Nam, 2021). Since it is still a challenging institutional intervention, it is red.

G.2.4. Weak Community Involvement:

Weak community involvement is a broad issue that is also at play either way, so even if the fourth dike will not be constructed. When the dike is constructed, community involvement is even more important, since they will be mostly affected by the effects of the dike. Local communities are essential in maintaining mangroves but have little say in official decisions. Surveys showed awareness of mangrove value but dependence on aquaculture income. To mitigate the effects of weak community involvement, the following alternatives have been added to the morphological chart:

- **Raise Payment for Mangrove Ground:** Similar to the alternative 'formal leasing policy (long-term rights)', raising payments for mangrove ground motivates locals to preserve rather than clear or not care for mangrove forests. It ties conservation directly to household income. However, establishing and maintaining a fair, sustainable payment scheme requires significant financial resources, clear governance rules, and administrative capacity, making this a red idea.
- **Eco-tourism Micro-projects:** Small-scale tourism offers alternative livelihoods for the local community linked to mangrove conservation. Examples include guided tours, homestays or local crafts. Since there are already plans to increase tourism (Appendix A) this is a safe alternative.
- **Mobile App for Monitoring:** An app could reward locals for reporting mangrove health or illegal activities. This increases awareness and data collection. The challenge lies in designing an effective system (e.g., clear reporting options, photo uploads, and follow-up actions) and ensuring active adoption and long-term use by the local community. Therefore, this is considered a red idea.
- **Technical Training and Awareness Programs:** Training and awareness programs create understanding of mangroves, the benefits and maintenance techniques. This empowers the local community to participate effectively in restoration. Such programmes are relatively straightforward to organise, and similar initiatives are already common in Vietnam (Vietnam Red Cross Society et al., 2016). Therefore, this is considered a blue idea.
- **Village-level Awards:** Rewarding active mangrove caretakers can promote pride and long-term engagement within the community. Small grants can also be a good incentive for the local community to be engaged. This type of collective recognition aligns well with Vietnam's socialist governance context, where community-based achievements are valued. This is considered a blue idea.

G.2.5. Economic Pressure from Aquaculture

In Kim Đông, aquaculture is very important for the economy and people's income. This is why there is big pressure to use additional land for aquaculture instead of mangrove projects, for example. By adding the fourth dike, new land has to be allocated, which raises the pressure. Aquaculture is vital for income in Kim Đông but drives land conversion and pressure on mangroves. Model results and interviews showed that ponds worsen water quality near mangrove areas. Balancing economic benefits with ecological stability will be key when allocating new land after dike completion. To mitigate the effects of economic pressure from aquaculture, the following alternatives have been added to the morphological chart.

- **Sustainable Aquaculture Certification:** By handing out eco-labels, farms can be certified to meet water quality and habitat protection standards. Certified producers often have access to higher market prices because of the increased quality, which also helps the local economy. It is, however, quite challenging for aquaculture farmers to change their business and for the local government to check and hand out certificates, which makes it a red idea.
- **Mixed Mangrove-Aquaculture:** This alternative focuses on expanding existing mixed mangrove aquaculture practices, which combine mangrove restoration with aquaculture production. Such systems support ecological functions while maintaining local livelihoods. As this approach is already implemented in Kim Đông, scaling it up is considered a realistic and low-risk option, making it a blue idea.

- **Payment for Ecosystem Services:** Similar to formal leasing policies and raising payment for mangrove grounds, local households will receive payments for maintaining mangrove areas next to their aquaculture farms or mixing the two. This diversifies income and reinforces conservation (red).
- **Water Treatment and Sediment Recycling:** Improving the water quality in aquaculture ponds through filtration and sediment reuse reduces pollution to mangroves. Also, it extends the lifespan and productivity of the pond, which is an economic benefit. However, implementing such systems requires advanced technology, technical expertise, and consistent maintenance. Therefore, this is considered a red idea.
- **AI-supported Farm Optimisation Tools:** AI can help farmers optimise feeding, water exchange and pond design for efficiency. However, this is a very expensive and complex alternative (yellow). Also, because there is limited data available.

G.2.6. Security and Research Restrictions

Security and research restrictions are a present problem in Kim Đông. (Foreign) researchers and tourists are closely monitored and need permits from several governing bodies to enter the area. This makes it hard to diversify livelihoods through tourism (which is a goal of the commune) and to gather data and knowledge crucial for further research and mitigating negative effects. Fieldwork required several permits and close coordination with local authorities. To mitigate the effects of security and research restrictions, the following alternatives have been added to the morphological chart.

- **Clarify Border Procedures for Research/Tourism:** As of now, the procedures researchers and tourists have to go through when they want to enter Kim Đông are very complicated and unclear. Establishing clear and documented protocols for access reduces administrative uncertainty. It enables safe and legal research near restricted coastal zones. It would also support controlled ecotourism, ensuring that visitors can access the area responsibly. However, changing administrative border procedures involves multiple governmental levels and security regulations, making this a complex and challenging process; therefore, this is considered a red idea.
- **Research Access Corridors:** Designated research zones can serve as zones where controlled scientific research can be carried out. This supports knowledge gathering without compromising security (red).
- **Remote Sensing Drones for Monitoring:** Drones can safely collect environmental data without entering restricted zones. They can even be checked by local authorities beforehand. Drones provide up-to-date information on mangrove conditions and coastal changes. Drones are, however, very expensive and can still be seen as a security threat by the border guard authorities. This is a plan for the future, making it a yellow alternative.
- **Defence-Environment Dialogue Platform:** A formal platform for discussion between military, authorities, and researchers fosters mutual understanding. Data and knowledge can be shared, as can rules, regulations and updates (yellow).

G.3. Multi-Criteria Analysis Background

This section explains how the values in the Multi-Criteria Analysis (MCA) are determined. First, the weights assigned to each criterion are described, and later for the sub-criteria. These weights reflect their relative importance to the province of Ninh Binh, the main stakeholder for whom the recommendations are intended. The total sum of all weights is equal to 1.

G.3.1. Criteria Weights

For the province of Ninh Binh, costs are the most important criterion. They need to allocate their budget across many different priorities, leaving limited funding available for the proposed interventions. Although they occasionally receive financial support from the national government or external donors, this is often uncertain. Therefore, costs are assigned a weight of 0.18.

Other key criteria for the local government include effectiveness, sustainability, and complexity. The extent to which an intervention produces tangible results and contributes to policy goals is crucial,

which is why effectiveness receives a weight of 0.15. Because the main objective of the interventions is to mitigate the negative effects of the fourth dike on mangroves, sustainability also carries significant importance, with a weight of 0.13. Lastly, complexity is essential to consider. If an intervention is too complicated, it may be difficult to implement within an already intricate governance and environmental system. Thus, complexity is weighted at 0.12.

As mentioned above, the system itself is quite complex, with many stakeholders with different interests, significant knowledge gaps, and limited data availability. Therefore, integration into the system is a highly relevant criterion, weighted at 0.10.

Adaptability, durability, and local economic benefit are also important but somewhat less critical. These criteria mainly assess how the interventions perform in the long term, which is why their weights are 0.09, 0.08, and 0.07, respectively.

Finally, scalability and disturbance are considered less important. Scalability evaluates whether interventions can be expanded or replicated in other coastal areas of Vietnam and is weighted at 0.04. Disturbance measures the potential negative impact of interventions on the local community. Although minimising disturbance is desirable, it is not the top priority for the province, so it is also weighted at 0.04.

G.3.2. Sub-criteria

Some criteria consist of sub-criteria, which also vary in importance. Their relative importance is expressed as percentages, and together they sum up to 100%.

The criterion costs consist of operation and maintenance costs and installation costs. Installation costs are more significant (60%) because they determine whether an intervention can be implemented in the first place. If the initial investment is too high, the intervention becomes less feasible for the local government, which already operates under a limited budget.

The criterion sustainability includes the sub-criteria ecological and social. Ecological sustainability is far more important, as the primary goal of this research is to preserve mangrove forests. Therefore, ecological sustainability has an importance of 80%. Social sustainability remains relevant, but is less critical in the context of this study.

Disturbance consists of three sub-criteria: noise, visual impact, and restrictions. Since noise and visual disturbance are already common in Vietnam, and citizens have limited influence over these due to the governance structure, both receive lower importance (20% each). Restrictions, however, are considered much more significant, as they directly affect all stakeholders involved. This sub-criterion is assigned an importance of 60%.

Finally, integration into the system includes three sub-criteria: integration into the spatial system, integration into the institutional system, and participation of the local community. Before an intervention can be effective, it must first be incorporated into both the spatial and institutional systems. These two sub-criteria are therefore each given an importance of 40%. Once this foundation is in place, integration with the local community becomes essential, as local participation can ultimately determine the success or failure of an intervention.

G.3.3. Intervention Scores

When giving scores to all the interventions, a scale of 1-2-3-4-5 is used. When an intervention scores 1, it scores bad on that criterion, and when it scores 5, it scores very good on that criterion. The interventions compared in the MCA are adaptive gate management, mangrove co-management with economic incentives, sustainable aquaculture (eco-certification) and digital monitoring and data sharing platforms. So, both innovative opportunities and realistically implementable alternatives are considered, ensuring a balanced assessment. The scores on different criteria for the various interventions are listed below.

Costs

In general, interventions that involve physical infrastructure have higher installation and maintenance costs than governance or software-based measures. The adaptive gate management system requires

hydraulic construction works, including sluices and control mechanisms, as well as regular maintenance. Therefore, this option receives a score of 2 for both installation and O&M cost. The digital monitoring platform involves development and research costs for data infrastructure and training but has low physical installation expenses, resulting in a score of 3 for O&M costs and a score of 2 for installation costs. The sustainable aquaculture intervention requires some investment for certification systems, awareness campaigns, and inspection mechanisms but remains relatively affordable overall, giving it a score of 4 for O&M costs and 3 for installation costs. The mangrove co-management approach mainly requires coordination, institutional collaboration, and capacity-building, leading to the lowest overall cost with a score of 4 for O&M costs and 5 for installation costs.

Effectiveness

Effectiveness measures how well an intervention mitigates the negative effects of the fourth dike. Adaptive gate management is highly effective (score 5) since it directly addresses reduced tidal connectivity and sediment exchange. Co-management and sustainable aquaculture are moderately effective (score 3 each), as their impact depends on stakeholder cooperation and enforcement. The digital platform indirectly supports all other measures through monitoring but does not by itself create physical or ecological change, resulting in a score of 2.

Sustainability

Ecological Sustainability Ecological sustainability considers the positive impact on mangroves and the broader coastal ecosystem. Adaptive gate management directly restores hydrological and sediment connectivity, earning a score of 5. Sustainable aquaculture practices and eco-certification promote lower pollution and encourage integrated mangrove–aquaculture systems, giving them a score of 4. Mangrove co-management supports conservation through local ownership and shared responsibility, earning a score of 3. The digital monitoring platform helps detect degradation early and supports ecological management but does not directly improve conditions, giving it a score of 2.

Social Sustainability Social sustainability reflects the involvement, benefits, and acceptance among local communities. Co-management with economic incentives ranks the highest (score 5), as it empowers communities, strengthens ownership, and provides income opportunities linked to conservation. Sustainable aquaculture also performs well (score 4) since it supports livelihoods and market access for local farmers. Adaptive gate management offers indirect benefits through flood control but limited community participation, giving it a score of 2. The digital monitoring platform contributes to awareness and transparency but involves limited direct community engagement (score 3).

Complexity

Complexity relates to the number of actors involved, institutional requirements, and technical difficulty. The mangrove co-management system is the most complex (score 1), as it depends on collaboration between local communities, authorities, and potentially donors, which is often challenging in hierarchical governance systems. The adaptive gate management intervention is technically complex because of its hydraulic operation and need for continuous coordination with upstream and downstream systems, resulting in a score of 3. The sustainable aquaculture certification process is relatively straightforward to implement once regulations and criteria are set, giving it a score of 4. The digital monitoring platform also has a certain degree of technical and organisational complexity, but since it builds upon existing digital initiatives, it scores 3.

Integration into System

Adaptive gate management integrates moderately well into the spatial system (score 4), since it can be added to the existing dike network but still changes local water dynamics. For the institutional system, it scores 3, as it fits within current water management responsibilities but requires improved coordination between provincial and local authorities. In terms of local participation, it scores 1, because decisions on gate operation are mainly top-down and technical. Mangrove co-management with economic incentives scores 4 for spatial integration, since it works with existing land-use structures and mangrove areas. It scores 3 for institutional integration, as it directly strengthens cooperation between government, communities, and local organisations but is somewhat difficult to implement in the current institutional environment. For local participation, it also scores 5, as it is built around shared responsibilities and local involvement. Sustainable aquaculture (eco-certification) scores 4 for spatial integration, as it can

easily be applied to existing ponds without major land changes. Institutional integration scores 3, since it requires new certification and enforcement mechanisms that are not yet fully in place. Participation scores 4, as farmers benefit directly from certification but still depend on external guidance. The digital monitoring and data-sharing platform scores 5 for institutional integration because it supports coordination and data exchange across governance levels. It scores 4 for spatial integration, since it operates within existing systems without physical change. For local participation, it scores 2, as it mainly provides access to information rather than direct involvement.

Adaptability

Adaptability reflects how easily an intervention can be adjusted to changing conditions or scaled to other areas. The digital monitoring platform scores the highest (5) because it can easily be scaled and updated. Co-management also performs well (4) since it can be adjusted to new governance or policy settings. Sustainable aquaculture has moderate adaptability (3), as it depends on certification systems and market demand. Adaptive gate management is the least flexible (2) due to its physical and hydraulic constraints.

Durability

Durability refers to the longevity and maintenance needs of each intervention. Once installed, adaptive gate systems are robust and can last for decades with proper maintenance, giving them a score of 4. Sustainable aquaculture is moderately durable (score 3) since it relies on continued compliance and market incentives to remain effective. Co-management is less durable (score 1) because it depends heavily on human participation and political stability. The digital monitoring platform is the most durable (score 5), as digital tools can be maintained and updated easily over time with minimal physical degradation.

Local Economic Benefit

The mangrove co-management intervention offers the strongest local economic benefits (score 5) through long-term ownership, payments for ecosystem services, and livelihood diversification. Sustainable aquaculture also provides stable income streams (score 4) through certified products and sustainable yields. Adaptive gate management indirectly supports local economies by improving environmental stability (score 3). The digital platform contributes mainly indirectly through improved data access and efficiency, giving it a score of 2.

Disturbance

Adaptive gate management scores 3 for visual impact, as the gates are clearly visible but integrated within the existing dike structure. Noise disturbance scores 2, due to temporary construction activities during installation. Restriction disturbance scores 4, since access near sluices may be limited for safety reasons, but that will not have such a big impact. Mangrove co-management with economic incentives scores 5 for visual and noise disturbance, as it requires no physical construction and does not generate sound. Restriction disturbance also scores 5, because participation is voluntary and restrictions are based on shared management agreements. Sustainable aquaculture (eco-certification) scores 4 for visual impact, as minor structural adjustments to ponds are required. Noise disturbance scores 4, since farming activities remain low-impact. Restriction disturbance scores 3, reflecting temporary limitations linked to certification requirements and compliance monitoring. The digital monitoring and data-sharing platform scores 5 across all three criteria, as it has no visible presence, produces no noise, and imposes only minor administrative restrictions related to data collection and reporting.

Scalability

Adaptive gate management scores 3, as it can technically be applied elsewhere but depends strongly on local hydrology, infrastructure, and available funding. It requires site-specific studies before implementation, which makes scaling up possible but not straightforward. Mangrove co-management with economic incentives scores 2, since it relies heavily on local relationships, governance capacity, and trust between communities and authorities. Although the concept is transferable, its success depends on social and institutional context, making large-scale replication challenging. Sustainable aquaculture (eco-certification) scores 4, as certification frameworks can be standardised and promoted nationwide with relative ease. Once the system is in place, it can be expanded to other provinces with similar aquaculture

practices. The digital monitoring and data-sharing platform scores 5, because digital tools are highly adaptable and can be scaled efficiently. Once developed, the same system can be rolled out across multiple coastal regions with limited additional cost or effort.

G.3.4. Multi-Criteria Analysis (MCA) Results

In Table G.1 the full Multi-Criteria Analysis is shown, based on the information provided in this section.

Table G.1: Multi-Criteria Analysis (MCA) Results

Criteria	Sub-criteria	Weighting	Adaptive Gate Management	Mangrove Co management	Sustainable Aquaculture	Digital Monitoring Platform
Costs	Installation costs	0.11	2	4	4	3
	O&M	0.07	2	4	4	3
Effectiveness	-	0.15	5	3	4	3
Sustainability	Ecological	0.10	5	3	4	5
	Social	0.03	2	5	4	2
Complexity	-	0.12	3	4	3	2
Integration into System	Spatial system	0.04	4	4	4	5
	Institutional system	0.04	3	3	3	5
	Participation of local community	0.03	1	5	4	2
Adaptability	-	0.09	2	5	3	5
Durability	-	0.08	4	1	4	5
Local Economic Benefit	-	0.07	3	5	4	2
Disturbance	Noise	0.01	2	3	4	5
	Visual	0.01	3	3	4	5
	Restrictions	0.02	4	5	5	5
Scalability	-	0.04	3	2	4	5
Total Weighted Score		1.00	3.41	3.49	3.67	3.25

H | Research Poster

In this appendix, the research poster is shown in figure H.1. The poster gives a visual summary of the main objectives, introduction, methods used, results and final recommendations. The poster highlights the key results from both the system analysis and the Delft 3D model, concluding in the expected effects of completing the fourth dike. The poster is a concise representation of the research, intended to serve as a tool for presentations and communication with different stakeholders and academic audiences.

