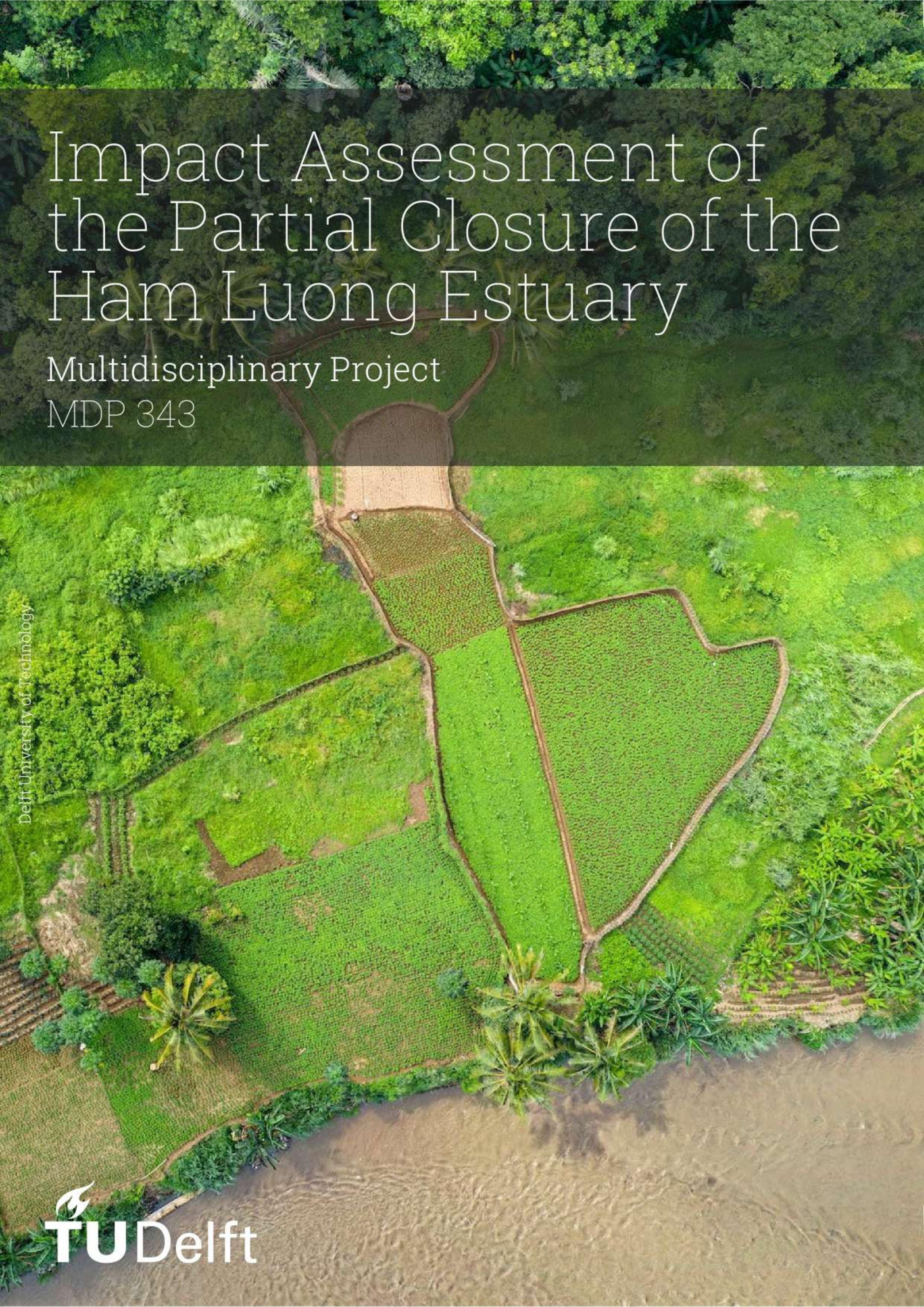
Impact Assessment of the Partial Closure of the Ham Luong Estuary

Multidisciplinary Project

MDP 343



Delft University of Technology

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Impact Assessment of the Partial Closure of the Ham Luong Estuary

by

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Cover: Bird’s Eye View of Green Farmland Landscape by Tom Fisk

Preface

This report is the result of a Multidisciplinary Project on the closure of the Ham Luong estuary in the Mekong Delta, Vietnam. The project came into being by the long-standing collaboration between Thuyloi University and Delft University of Technology. The Multidisciplinary Project is part of the curriculum of the Master Civil Engineering of the Delft University of Technology.

By means of different master track specialisations within the field of Civil Engineering (Structural Engineering, Hydraulic and Offshore Structures, River Engineering, and Coastal Engineering), the project aims to provide more insights into the ongoing discussion on the closure of the Ham Luong estuary. This document can be used by any party that is interested in the current situation of the Ham Luong estuary, the effect of the closure of the estuary on the hydro- and morphodynamic characteristics, the impact of the closure on the surroundings, and an optimal flood protection design. In reading this report, prerequisite knowledge in the fields of hydraulic modelling and hydraulic structures is recommended. When interpreting and/or reproducing the results presented in this report, the large number of assumptions, simplifications, and uncertainties which are inherent to this project and the scope should be taken into account accordingly.

We would like to thank Dr. Truong Hong Son, our supervisor at Thuyloi University in Hanoi, for his supervision in this project and his great advice. He helped us set up the project by providing us a lot of useful suggestions and valuable information. Furthermore, he also brought us into contact with different experts on the topic and he joined us during our field trip. Without him, this project would not have been possible. We would like to thank the Southern Institute for Water Resource Planning (SIWRP), the Institute of Coastal and Offshore Engineering (ICOE) and Royal HaskoningDHV for their professional insights which have been a great addition to our work. Additionally, we would like to thank Lindsey Schwidder from the Innovation & Impact Centre at TU Delft, who brought us in contact with our supervisors and was the first one to provide us with information about a possible research project in Vietnam. Last but not least, we want to thank our supervisors from TU Delft: Dr. Ir. Cong Mai Van and Ir. Hoessein Alkisaei. They provided us useful advice and guidance throughout the project.

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Abstract

The Mekong Delta in Vietnam is facing several challenges as a result of climate change. Among others, the effects include an increase in river discharge during the wet season, leading to river floods, and a decrease in river discharge during the dry season. The decrease in discharge results in a shortage of fresh water required for irrigation and drinking water. Besides that, the combination of sea-level rise, land subsidence, and decreased river discharge during the dry season results in saltwater intrusion. This threatens freshwater supply even more. Furthermore, there is an increasing risk of floods from the sea due to low land elevation and the rising sea level in combination with the occurrence of storm surges.

The scope of this research is the area around the Ham Luong estuary, which is a branch of the Mekong River. The partial closure of this river branch is considered by the Vietnamese government as a measure to reduce the effect of the above-mentioned effects of climate change. However, not enough research has been conducted yet on the impact of a partial closure on the Ham Luong estuary. This has lead to the following research question:

"What is the impact of various closure scenarios on the hydraulic characteristics and social activities in the Ham Luong estuary, considering a 75-year forecast?"

The region of the Ham Luong estuary is characterised by its intensive agri- and aquaculture. More than 60% of the inhabitants is directly active within the agri- or aquaculture. As these activities are strongly dependent on the salinity of the estuary, they are highly affected by the effects of climate change. The region is densely populated with more than 125,000 inhabitants living near the Ham Luong estuary. It is clear that the effects of climate change are threatening the region in hydraulic aspects, as well as socio-economic aspects. A partial closure could reduce these effects, but will influence the region in several ways. In order to estimate the impact, a combination of hydraulic and socio-economic aspects is assessed based on a criteria set. This criteria set contains the criteria of freshwater supply, agricultural and aquaculture adaptation, biodiversity, stable riverbanks, and navigability. These criteria will be tested on a total of four alternative interventions in the Ham Luong estuary. Three alternatives with a storm surge barrier and one alternative without a storm surge barrier. All alternatives include heightening of the existing dyke system, as this seems to be inevitable when aiming for long-term development in the region. The extend of dyke heightening is subject to the choice of alternative.

As a part of the impact analysis, a Delft3D model was built to analyse the hydrodynamic and morphodynamic processes in the Ham Luong estuary. The model was restricted to the chosen spatial scope, which only covers the Ham Luong estuary, without any upstream bifurcations. The model gave insights in processes like salt intrusion, sedimentation rates, and water levels. However, due to model simplifications and assumptions, the outcomes of the model where not useful for quantitative assessments. Still, the results are used to compare the impact of the different alternatives to each other. As expected, the alternatives that include a storm surge barrier will provide more possibilities to retain fresh water than the alternative without a barrier. From the results, it followed that the limited spatial scope excludes the redistribution of upstream discharge. It is recommended to look at a larger scale of the Mekong Delta when assessing hydro- and morphodynamic processes.

Forming a flood protection system, the structural design of such a storm surge barrier, together with a quick estimation of a dyke system. The dyke system is different for each alternative, depending on the presence and the location of a barrier. The barrier design includes a thorough analysis on feasibility of gate types, technical requirements, load combinations, design of dimensions, and the operation. The load combinations take hydrostatic, hydrodynamic, wind, and soil loads into account. The design of the dimensions is done for the gates, sill, lifting structure, pier, foundation, and the bed protection.

By assessing the above-mentioned criteria, a preferred solution is identified. This preference is based on a Multi-Criteria Analysis, which includes weighted scores for all alternatives. The outcome of the Multi-Criteria Analysis appears to be very sensitive to the rating and weights of the criteria, which makes it difficult to identify one of the alternatives as the preferred solution based on only the score on the different criteria. For this reason more research is needed. However, when including a cost estimation of the four alternatives, it can be stated that the alternative of no storm surge barrier and only the corresponding extensive dyke heightening could be considered as most cost-beneficial alternative and therefore as the preferred solution.

It is expected that with or without closure of the Ham Luong estuary the system will change. The availability of fresh water will be improved by the presence of a closure, although more research is needed to specify this further. The increasing salt intrusion, as a result of Relative Sea-Level Rise (RSLR) will lead to agricultural and aquaculture adaptation in all alternatives. Either due to the construction of the barrier, or due to the gradual RSLR. A closure also has effect on the biodiversity, stability of the river banks, and navigability in the river. When implementing a closure these effects should be further investigated to assess the effect quantitatively.

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List of Abbreviations

ADB	Asian Development Bank
AR	Assessment Report
BwN	Building with Nature
CPT	Cone Penetration Test
CRWES	Center of Rural Water and Environment Sanitation
DONRE	Department of Natural Resources and Environment
GRDP	Gross Regional Domestic Product
HAT	Highest Astronomical Tide
HCMC	Ho Chi Minh City
ICOE	Institute of Coastal and Offshore Engineering
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
JONSWAP	Joint North Sea Wave Project
KC	Keulegan–Carpenter
LAT	Lowest Astronomical Tide
LC	Load Combination
LMD	Lower Mekong Delta
MARD	Ministry of Agricultural and Rural Development
MCA	Multi-Criteria Analysis
MONRE	Ministry of Natural Resources and Environment
MRC	Mekong River Commission
MSL	Mean Sea Level
NE	North-East
RCP	Representative Concentration Pathway
RSLR	Relative Sea-Level Rise
SIWRP	Southern Institute for Water Resource Planning
SIWRR	Southern Institute of Water Resource Research
SLR	Sea-Level Rise
SW	South-West
SWAN	Simulating WAves Nearshore
UC	Unity Check
USAID	U.S. Agency for International Development
VND	Vietnamese Dong
WSC	Water Supply One-member Limited Liability Company
WWF	World Wildlife Fund

1 Introduction

The Mekong Delta is home to over 18 million people, adding up to 19% of the total population in Vietnam and it is also the area where the Mekong River meets the South China Sea. The delta consists of two major rivers: the Hau River (also known as Bassac) and the Tien River (also known as Mekong), and is made up of eight major estuary branches. These can be seen in Figure 1.1. The Mekong River is a crucial source for irrigation, freshwater supply, and sediment supply in the delta. Intensive rice production, aquaculture, and fruit production in the Mekong Delta contribute largely to food security in Vietnam (Woillez & Espagne, 2022).

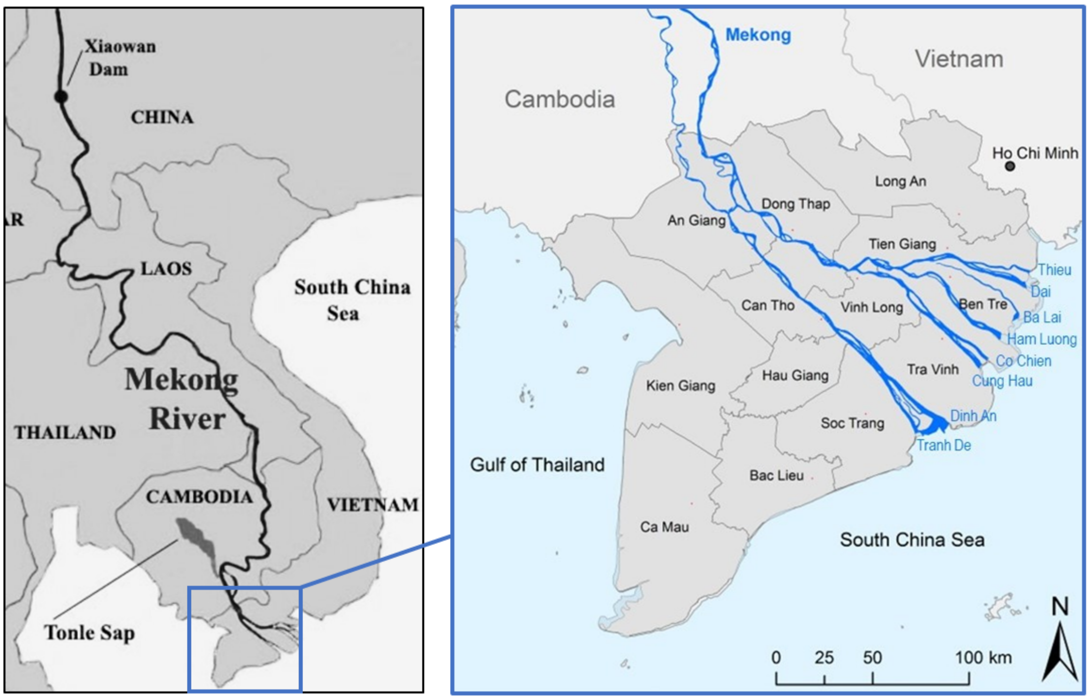


Figure 1.1: Overview Mekong Delta (The Asia-Pacific Journal, 2010), (Kuenzer et al., 2013)

1.1 Challenges

The devastating effects of climate change have started to become more and more evident over the last few decades, and unfortunately the Mekong Delta is no exception. In fact, the Mekong Delta is considered to be one of the most vulnerable deltas worldwide subject to the effects of climate change. Especially changes in river runoff, Sea-Level Rise (SLR) and land subsidence are expected to affect the delta in multiple ways:

1. The increase in river discharge during the wet season results in regular flooding of the rivers. Due to urbanisation, these river floods threaten the safety of inhabitants (Netherlands Advisory Team of the Mekong Delta Plan, 2013).
2. The decrease in river discharge during the dry season results in a shortage of fresh water required for irrigation and drinking water.
3. The combination of SLR, subsidence of the ground and decreased river discharge during the dry season results in saltwater intrusion, which influences freshwater supply and consequently increases groundwater salinity.
4. The rising sea level, in combination with the occurrence of storm surges as a result of typhoon storms will cause high inundation risks for the low-laying Mekong Delta. In the case of a SLR of 100 cm, 22% of the region of Ben Tre would be inundated (Tran Thuc et al., 2016).

As a response to these changes, the Dutch Advisory Team for the Mekong Delta Plan has drafted a master plan for the Mekong Delta; The Mekong Delta Plan. This plan is to be used as a guideline by any party involved in the sustainable development of the Mekong Delta (Netherlands Advisory Team of the Mekong Delta Plan, 2013).

1.2 Research objective

The Mekong Delta Plan proposes a set of measures which could counteract the unwanted effects of climate change threatening the Mekong Delta. Amongst these measures is the closure of the Ham Luong estuary, one of the six branches of the Tien River. Additionally, the Ministry of Agricultural and Rural Development (MARD) of Vietnam also suggests to close off the Ham Luong estuary by means of a barrier to prevent salt-water intrusion (Ministry of Agriculture and Rural Development & Southern Institute for Water Resource Planning, 2021). The permanent or temporal closure of the estuary will prompt the system to adapt to the new hydrodynamics, which will greatly impact many facets of the estuary. These impacts have not yet been investigated thoroughly, and are therefore largely unknown. Moreover, there are many options for the location and the design of a closure. This has led to the formulation of the main research question of this report.

"What is the impact of various closure alternatives on the hydraulic characteristics and social activities in the Ham Luong estuary, considering a 75-year forecast?"

The main goal of this research question is to analyse the impact of proposed alternatives, which can support local authorities in their decision-making. The goal of this report is to build a basis for transparent and straight-forward decision-making of the preferred solution, based on prioritisation of the assessed impact on different aspects of the system. The spatial scope of this report is restricted to the area starting in the North at the bifurcation of the Ham Luong River from the Mekong River to the coastal zone in the South Chinese Sea. To address the main research question, it has been subdivided into multiple sub-questions:

1. What are the key characteristics of the Ham Luong estuary considering economic and social activities and hydro-morphodynamic properties?
2. What is the impact of the partial closure of the Ham Luong estuary on the hydro- and morphodynamics of the system?
3. What would be the optimal design for a flood protection system?
4. Considering the effect of the hydro-morphodynamic changes on the social and economic activities, what decision in terms of closure of the estuary can be regarded as the best fitting solution for the system?

1.3 Report structure

The report is structured as follows. In Section 2 the methodologies which were used in this report are presented. Next, a concise description of the system is provided in Section 3. This is followed by the selection of the scenarios that will be evaluated in Section 4. Following that, the conceptual model and the Delft3D model are introduced in Section 5. The results of the model in terms of water level, salinity and morphology are presented in Section 6. Additionally, this section refers to the results of a tool to assess additional morphodynamic changes. Subsequently, Section 7 dives into the design of the flood protection system which consists of the most optimal design of a river barrier and the design of the adjacent dyke system for each of the alternatives. In Section 8 the impacts of the different alternatives are compared with a Multi-Criteria Analysis (MCA). Additionally, a cost analysis is performed to assess the cost efficiency of the different alternatives. Finally, Section 9, Section 10 and Section 11 contain the conclusion, discussion and recommendations for this project.

2 Methodology

This section contains clarification on the approaches that were applied to eventually answer the research questions posed in Section 1. To begin with, an extensive analysis of the system was conducted. This was followed by the translation of the system of interest into a model. This model was in turn used to evaluate the effect of different closure scenarios on the hydraulic and morphodynamic characteristics of the estuary. Next, the the design of the flood protection system was elaborated. Finally, the changes in hydromorphodynamics and the design of the flood protection system were used as input for the MCA, which generated a best fitting solution.

2.1 Analysis of the system

In order to get a thorough understanding of the system of interest and to define the importance of different elements, a system analysis was conducted. This "System description" contains comprehensive area studies and a stakeholder analysis. By means of literature research, online research, visual research during the field trip, and a stakeholder survey, the information was collected for the chosen area of interest and other factors associated to that area. Here, a multidisciplinary approach was necessary to tackle the complexity of the system. The gathered information was used to map the different stakeholders, usage of land, and other important processes within the system.

2.2 Approach scenario selection

The knowledge gained through the system analysis was used to formulate criteria by which the impact on the system can be assessed. Having selected these criteria, the different modelling scenarios were identified, starting with the seasonal and weather conditions that are most crucial to the system in 2100. Next, the possible locations of the closure were selected. Finally, a decision was made on which Intergovernmental Panel on Climate Change (IPCC) climate change scenario was used throughout the report.

2.3 Modelling process

The effect of the closure on the hydro- and morphodynamics was studied using the modelling suite Delft3D. First, a conceptual model was created in which the system of interest was translated into key concepts and relationships. Next, numerical data was collected through various sources, of which Thuyloi University, SIWRP and ICOE were the main providers. These datasets were modified to useful data with Excel and Python.

From the conceptual model and the data collection the boundary conditions, initial conditions and bathymetry were derived. Then, the model was calibrated and verified using provided measurement data. This was followed by a sensitivity analysis, in which the effect of changing certain parameters was evaluated. Finally, the model was run for different weather and seasonal combinations and different closure alternatives, which were defined in the section on Scenario Selection.

2.4 Approach design of flood protection system

In this section, the design of the flood protection system is presented. First, a preliminary design was made for the adjacent river dyke system for each of the alternatives. The water level data from Delft3D and the data collection were used for this. Furthermore, a literature study on reference projects and barrier types for a storm surge barrier was performed. After that an MCA was conducted to find the best fitting gate type for the storm surge barrier. The different proposed barrier types were rated with weights on various evaluation criteria. For the resulting barrier type a preliminary design calculation was made. This was a modular design. This design consisted of gates, a sill, lifting structure, piers, foundation and bed protection. Furthermore, a short description of the operation of the gates was made for future commissioning.

2.5 MCA approach

To decide on the best fitting solution for the system, an MCA was used to compare the different alternatives. Each of the criteria, which were identified in the scenario selection, were given a weight of importance. Then, the alternative options and their relative rating for each criterion were displayed in an MCA-matrix. By multiplying the rating with the weight per criteria, the total ratings per alternative were calculated. After a comparison, the best option was defined.

3 System description

As mentioned in the Section 1, the spatial scope of this project is restricted to the area surrounding the Ham Luong estuary. The area which is affected by the river branch is outlined in Figure 3.1. It is located in the southern part of Vietnam, in the province of Ben Tre, where the Ham Luong estuary flows into the South China Sea as a branch of the Tien River. The largest city near the river is the city of Ben Tre with nearly 125,000 inhabitants and the overall area is sparsely populated. The coastal area connected to this estuary is also considered in this project. In this section the various characteristics of the area will be discussed. The aspects to be considered are divided into four main topics: local climate, hydraulic characteristics, land use, and stakeholders. Figure 3.1 shows a brief overview of the main activities in Ben Tre, which will be further explained in the remainder of this section.

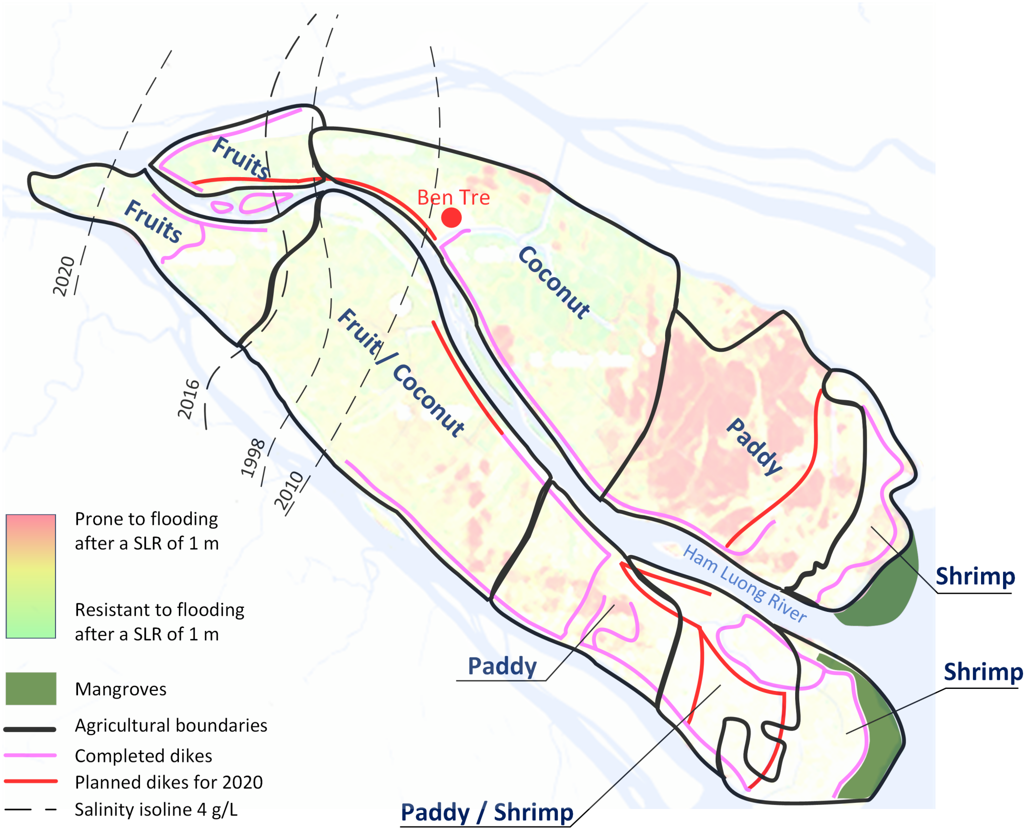


Figure 3.1: Overview of the main activities and processes in Ben Tre Province

3.1 Local Climate

Ben Tre Province has a tropical monsoon climate with a wet and a dry season. The average annual temperature in the Mekong Delta over the past two decades was 27°C (WorldData.info, n.d.). The wet season in Ben Tre extends from May through November, while the dry season lasts from December to April. During the wet season typically 80% to 85% of the annual precipitation rate is recorded. Over the past two decades, the average annual rainfall has amounted up to 1,733 mm (VESDEC, 2020). During the wet season, the prevailing monsoon is from the South-West (SW), whereas in the dry season, the North-East (NE) monsoon dominates. The NE monsoon winds are dominant over the SW winds in terms of magnitude and frequency. Besides monsoon winds, typhoons occur regularly in the South China Sea and have an impact on the Vietnamese mainland. Typically, the highest wind speeds occur during typhoons. In the period of 1952 to 2020, a total of 51 typhoons were observed along the Vietnamese coast (Thuyloi University, 2020).

Climate change projections indicate that by 2100, the average annual temperature and annual rainfall will have increased significantly compared to the reference period of 1986-2005 (Tran Thuc et al., 2016). Additionally, the Ministry of Natural Resources and Environment (MONRE) reports suggest that 5-day extreme rainfall events will intensify by 60% by 2100 in contrast to the 1986-2014 base period. Temperature is expected to increase the same amount as the global average, with a range between 1.0° and 3.4° (World Bank Group & Asian Development Bank, 2021). The forecasts from MONRE do not indicate significant changes in the frequency and intensity of typhoons (Tran Thuc et al., 2016).

3.2 Hydraulic characteristics

Hydraulic characteristics refer to physical properties and behaviour of water flow. These characteristics can differ depending on the location in the estuary. For this reason, a distinction is made between three areas; the estuary, the upstream part of the river, and the coastal area. Additionally, salt intrusion, which covers all three areas, is discussed.

3.2.1 Estuary characteristics

The Ham Luong estuary is approximately 70 km long. This is measured from the bifurcation at the most north-western part of the province of Ben Tre until the coast. The estuary is very wide; at some points the estuary width can be up to 2.7 km, measured in Google Maps. The depth of the bed of the Ham Luong estuary is considered shallow, but the exact depths may vary along the estuary. The Mekong Delta is an extremely flat and low delta area. The slope towards the sea has a gradient of 5 mm/km (Tromp, 2013). In the Ham Luong River eight small islands are present. The largest one is approximately 9 km in length and 1 km in width. The shapes of the islands change slightly over time due to erosion and sediment deposition in the river. These river islands are used mainly for aquacultural activities such as fishing ponds, but also contain resorts and living areas.

Within the estuary arm, several channels are connected to the Ham Luong River. Two main side channels can be identified. These channels are connecting the Ham Luong River to the Tien River in the North (Ben Tre Channel) and the Chien River in the South (Mo Cay Channel). Not much data is available about the discharge in these connecting channels. The connecting channels are water bodies with high sedimentation rates, as the flow velocities are much lower than the flow velocities in the main branches (Tromp, 2013). This implies that the discharge is significantly smaller than in the main branch.

The river naturally flushes sediment towards the sea, but also loses sediment in sand mining processes. Certain areas have been appointed for legal sand mining for limited volumes (Ministry of Agriculture and Rural Development, 2016). Throughout the whole Mekong Delta, there are illegal sand mining processes, which can have a significant impact on the riverbank erosion. Due to the incision of the riverbed by sand mining, an increase in tidal amplification can be observed (Loc et al., 2021).

The soil in the Mekong Delta is extremely acidic at many locations, caused by the deposition of pyritic sediments from the upstream river. When this sediment, which contains iron disulfide, is exposed to oxygen it acidifies the soil. The depth at which the acid soil is found, is often within 1 m of the surface. This is primarily a problem in the upper Mekong River Delta, but also in the lower delta where it is difficult to drain water. In Ben Tre, it is estimated that around 1.3% of the total land area is contaminated with acid soil, which is relatively small compared to other areas (Ministry of Agriculture and Rural Development, 2016).

3.2.2 Upstream river characteristics

To describe the upstream river characteristics, the whole catchment area of the Mekong River needs to be taken into account. Precipitation trends in the catchment area exert a significant influence on the flow regime. During the wet season, there is a high discharge peak, while in the dry season, the lowest discharge is observed. The high and low discharge seasons in the Ham Luong estuary demonstrate a time lag of a few months with respect to the wet and dry season (Nguyen Trug Viet et al., 2006). The highest upstream discharge can be observed in August and September, while the smallest discharge occurs in April and May (Kummu et al., 2008).

Upstream of the Ham Luong estuary, in Cambodia, Laos and China, multiple hydropower dams have the potential to withhold water and sediment that would originally direct flow towards the lower Mekong Basin (MRC, n.d.). Due to a lack of administration and available data, and the large size of the Mekong River system, it is very difficult to point out the effects of these dams (Adamson et al., 2009). The same can be said about upstream sand mining, which is difficult to monitor and prove. Currently, the effects of these interventions in the upstream river on the discharge and sediment flow cannot accurately be defined.

3.2.3 Coastal characteristics

The downstream boundary of the system of interest is formed by the coastal area at the mouth of the Ham Luong estuary. According to the Process Framework developed by Galloway (1975), the delta can be classified as a tide- and wave-dominated delta. This entails that the delta is subject to the influence of both tides and waves, which in turn influence how the delta develops in terms of morphology.

The wave climate near the Ham Luong estuary is strongly influenced by the behaviour of the winds that prevail there. As stated in Section 3.1, the most important winds that can be distinguished occur during the NE monsoon and the SW monsoon. Waves created by these monsoon winds are similar to swell waves (Hoan Van Huan & Nguyen Huu Nhan, 2006).

The water level at the coast consists of three contributors: the tidal range, storm surge and RSLR, including absolute SLR and land subsidence. At the coastline of the Mekong Delta, the tidal regime is characterised as "mixed, more semi-diurnal". Storm surges are considered a dangerous phenomenon along the Vietnamese coastline. Storm surge is the piling up of the water surface as a result of friction between high wind speeds, during typhoons, and the water surface (Truong Hong Son, 2012).

3.2.4 Salt intrusion

As mentioned before, a large consequence of climate change is the saltwater intrusion in the Ham Luong River. This saltwater intrusion has an extensive impact on the area. Increased salinity levels influence the type of agri- and aquaculture that can be practised in the areas near the river and put pressure on the availability of fresh water for domestic use (Toan, 2014). The saltwater intrusion is caused by a combination of reduced river flow (due to droughts induced by climate change, and the construction of hydropower dams upstream) and absolute SLR. Additionally, the aforementioned increase in tidal amplification due to sand mining also gives rise to an increase in salt water in the Ham Luong estuary.

In previous research, the intrusion of salt was investigated in the dry years of 1998, 2010, 2016, and 2020. Figure 3.1, at the beginning of this Section 3, shows the areas affected by salt intrusion in these years. The figure shows that the salt intrusion has reached further inland into the Mekong Delta in recent years. It can be seen that the 4 g/L salinity isoline of 2020 touches the bifurcation of the Tien River and the Ham Luong River, 70 km inland. This shows that the whole area surrounding the Ham Luong River is affected by salt intrusion.

3.3 Land use

The province of Ben Tre has a wide variety of land use types. In assessing the impact of the closure of the Ham Luong estuary, it is crucial to be aware of these different types of land use and the various elements in the system. Therefore, this section focuses on the different aspects of land utilisation, including land coverage, current flood protection measures, shipping, ecology, and drinking water.

3.3.1 Land coverage

An overview of the land use in Ben Tre Province can be seen in Figure 3.1. The most common kinds of food produced in Ben Tre are fruits, coconut, rice and shrimps. Of these products, coconut and shrimps are the most cost-beneficial, while rice is the least cost-beneficial. The fruit plants are located more inland due to their low resistance to salt water. Coconut plants are more resistant to salt water than other fruit plants and are thus planted more seawards. The same goes for shrimp farms which use salt water. A rice field that is harvested one time a year is called a 1-rice paddy and a rice field that is harvested two or three times a year is 2/3-rice paddy. In the delta, 2/3-rice paddy is harder to harvest because therefore it should also grow in the dry season and rice is not very resistant to salt. An option is to alternate between rice and shrimp production using flood-based agri- and aquaculture. Rice can grow in the fields during the wet season, and during the dry season, when the water is saltier, shrimps can grow at the same location. Currently, most shrimps are produced in coastal areas with a high salinity level. Close to the coastline, mangrove forests thrive.

3.3.2 Flood protection measures

To protect the delta region from floods, different types of flood protection measures have been implemented in the area at the coast including mangroves. Mangroves are trees that grow in tidal waters and can trap sediment, preventing erosion, while they protect the low dykes from direct sea impact (Groenewold et al., 2018). The mangroves grow in the area naturally. Due to the decline of mangrove forests, the protections in front of the dykes are weakened. In the province of Ben Tre there are low sea dykes present. These are simple earth dykes which are mostly covered in grass (Cong San et al., 2017). To prevent the coastline from receding, several small-scale erosion measures have been taken along the coast. These handmade structures use materials such as wood and sandbags, which are also often used to repair sea dyke breaches.

Besides coastal protection, there are also protection measures present along the river banks of the Ham Luong River. An extensive protection system is present to prevent salinisation in the area (Käkönen, 2008). The dykes around the Ham Luong estuary are about 3.0 m in height and 5.0 m in width, with an inner slope of 1:2 and an outer slope of 1:3 (Institute of Coastal and Offshore Engineering, 2020). The dyke height is with respect to the Vietnam Datum 2000 reference system. This is almost the same as with respect to Mean Sea Level (MSL) but it can differ for various locations in Vietnam. For this project it is assumed that it is approximately the same as to MSL. Along the river banks, mangrove trees also grow. However, these are not large forests such as along the coast. The mangrove trees only grow a couple tens of metres inland. In Figure 3.1 the positions of the dykes and mangrove forest are shown.

There several are other river barriers built in the area. An example in Ben Tre Province is the Ba Lai River barrier. This is a relatively small barrier consisting of a dam and a gated section. Furthermore, in the Mekong Delta there is also a large barrier called the Cai Lon barrier. It is located in the west of the Mekong Delta in the province of Kien Giang and is a storm surge barrier with gates over the entire length of the river. Both barriers are built to prevent salt intrusion in the area. More information on them can be found in Section 7.2.

Along the Ham Luong River there are also numerous small sluice gates, such as shown in Figure 3.2. These can block off channels to prevent flooding and salt intrusion. There are plans to build more sluices and their locations are visible in Figure 3.3. The location of the dykes are also visible in this figure.

Figure 3.2: A small sluice in a side channel, located 35 km upstream of the Ham Luong River mouth. The photo was made from the Kinh Bridge during the field trip.

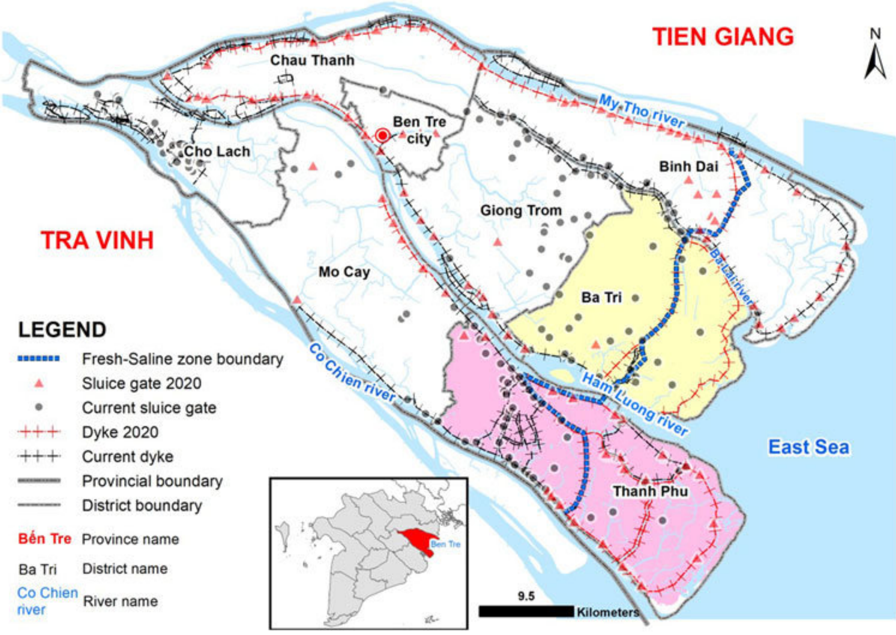
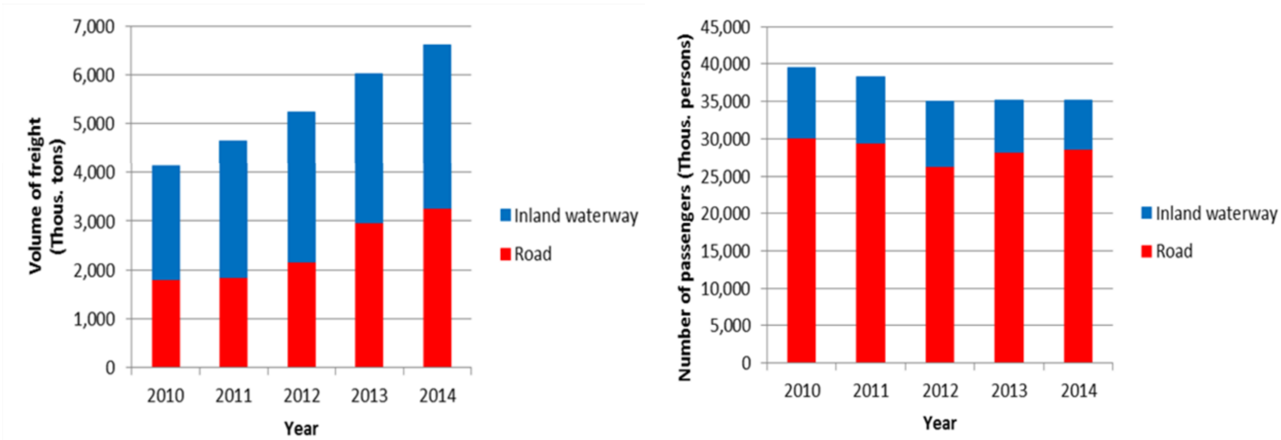


Figure 3.3: Ben Tre dyke protection and sluices (Korbee et al., 2019)

3.3.3 Shipping

While the primary shipping route from Phnom Phen to Ho Chi Minh City is not through the Ham Luong River (Shibasaki et al., 2021), there are several small boats making use of the river. The Mekong Delta has more transportation over water than the rest of Vietnam due to investments in channels during the French colonial rule (Ministry of Agriculture and Rural Development, 2016). In Ben Tre, more goods are transported by inland waterways than by road, but inland waterway transportation has been decreasing as a result of investments in roads and bridges. For public transport, more passengers are using the road instead of waterways. The numbers per transport mode are shown in Figure 3.4. Furthermore, it is important to note that tourism vessels are increasing in size due to the increase in popularity. These vessels also travel on the Ham Luong River (VietnamPlus, n.d.).



(a) Mode of freight transport in 1000 tonnes

(b) Mode of transport for passenger in 1000 persons

Figure 3.4: Mode of transport in Ben Tre from 2010 until 2014 (Ministry of Agriculture and Rural Development, 2016)

3.3.4 Ecology

Ecology describes relationships between the environment and living organisms, usually of a particular area. This is a very broad subject, hence only the main considered ecosystems will be described here. According to the Ministry of Agriculture and Rural Development (2016) the most important ecosystems are fish, birds and mangroves. In general in the Mekong Delta, the mammal fauna is not diverse, especially when compared to its fish fauna (McElwee & M Horowitz, 1999). The large diversity of fish is caused by the combination of fresh, brackish and salt water. Some rare species are even on the International Union for Conservation of Nature (IUCN) Red List, published in 2011. These fish migrate from the estuary into fresh water in higher areas (Ministry of Agriculture and Rural Development, 2016). Of the fish species with a known migration pattern, 165 out of 189 migratory fish species are long-distance migrants. Furthermore, it is expected that 90% of the fish species get migration cues when there is a variation in water level or discharge (Brian Eric, 2006).

There are a lot of birds in the Mekong Delta. A protected bird sanctuary in Ben Tre, called the Vam Ho Bird Sanctuary, is located next to the Ba Lai River. Another protected area is Than Phu Nature Reserve, which encloses the mangrove forests near the coast in the Than Phu district in Ben Tre.

Mangroves grow in saline and brackish water where the sea meets the coast in (sub)tropical environment. The specific conditions created by tidal fluctuations, with their interplay of salt and fresh water, reduces the competition among other plant species. This is a significant benefit for mangrove forests (University of Florida, 2023). There are sixteen mangrove species in Ben Tre; two of which grow along the Ham Luong estuary. These particular species are not protected by law or regulations.

The Department of Natural Resources and Environment (DONRE) regularly tests water quality by taking samples at different locations in Ben Tre Province. More than half of the water samples was heavily contaminated and classified as level 5 out of 5, indicating measures should be taken. Only 30% of the water samples were classified as level 1 and 2, which indicates water that can be used in daily activities (Ministry of Agriculture and Rural Development, 2016). This means that the living conditions of animals in the water are threatened by poor water conditions.

3.3.5 Drinking water

There are two organisations that provide the area with fresh water. The Water Supply One-member Limited Liability Company (WSC) provides the city of Ben Tre and its surrounding area with fresh water. They operate four water supply plants, which are Son Dong, Huu Dinh, Cho Lach, and Luong Quoi. The supply capacity of the pumps is 52,800 m^3/day in total (Ministry of Agriculture and Rural Development, 2016). The regions that are used for water supply and the locations of the plants of the WSC and the Center of Rural Water and Environment Sanitation (CRWES) can be seen in Figure 3.5. Besides these water supply plants, several rural water supply plants exist and they account for a total water supply of 1,583 m^3/day.

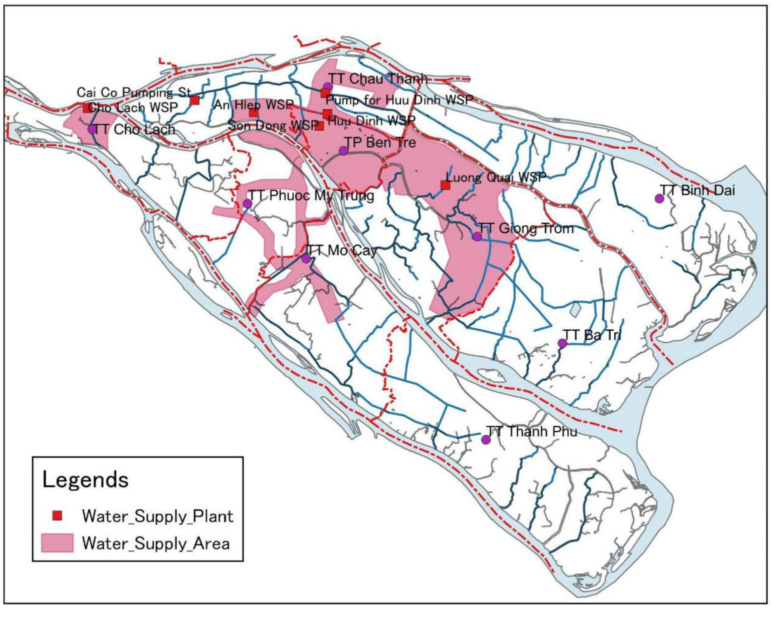


Figure 3.5: Drinking water supply areas and pumping stations (Ministry of Agriculture and Rural Development, 2016)

The saltwater intrusion in the river has led to difficulties in freshwater supply in Ben Tre. It affects the channels in the province as well as water pumps. At the Huu Dinh water supply plant the pumping has stopped because the borehole was too saline. Furthermore, salt water causes corrosion to pipes that contain fresh water, damaging the water supply system (Ministry of Agriculture and Rural Development, 2016). From the field trip it was also found that many people extract their fresh water from the river for domestic use, which is not an option if the water in the river is too saline. More information about the field trip can be found in Appendix A.

3.4 Stakeholder Analysis

Within this section, attention is paid to the most important stakeholders involved in this project. It provides insights into each stakeholder, including their concerns, needs, and the extent of their influence. It concludes with an overview table with each stakeholder and their interests, in addition to a Power Interest Matrix.

3.4.1 Agricultural and aquaculture sector

The agricultural and aquaculture sectors surrounding the Ham Luong estuary involves a variety of farmers. Figure 3.1 shows how the land is used in Ben Tre Province. Vietnam plays a significant role in global rice production, contributing approximately 8% of the world's total rice output, which is equal to 42 million tonnes. Within Vietnam, the Mekong Delta produces nearly 25 million tonnes and is therefore regarded as the heart of rice production in the country (Food and Agriculture Organization of the United Nations, 2018). One hectare of rice has an average yearly net income in 2015 of 16 million Vietnamese Dong (VND). Vietnam also produces 37% of the total world production of shrimp, with the production in the delta located near the coast. One hectare of shrimp has a yearly average net income in 2015 of 45 million VND. In addition to this is, it important to mention that shrimp cultivation comes with significantly higher costs than other farming practices. Approximately 30% of the total land area is used for fruit cultivation. Of the fruit production in the Ben Tre Province, the output is mostly distributed via middlemen, who distribute it to supermarkets in various provinces in Vietnam. Therefore, the exact quantities are uncertain. Ben Tre Province is seen as the most important area for coconut production and the share of coconut production has been increasing recently. One hectare with coconuts has a yearly average net income in 2015 of 70 million VND. Coconuts are also processed into higher value products, like coconut oil. In 2016, 526,000 tonnes of coconut were produced, of which 90% was exported (Ministry of Agriculture and Rural Development, 2016). Farmers change from producing rice to producing coconut due to their high resistance to salinity, smaller labour intensity, and high market price. Changes from rice production to shrimp farming are also observed.

In Ben Tre Province, 60% of the labour force is active in the agricultural or aquaculture sector. Their primary requirement is water supply. Depending on the product to be cultivated, brackish water or fresh water is preferred (Ministry of Agriculture and Rural Development, 2016). Fresh water availability in the future is their biggest concern. If the salinity levels increase, farmers would be forced to shift to different farming methods or other products. Their interest is to have ideal conditions to grow their products, to sell as many products as possible. Combining this with the high production rate, the agricultural sector is a very important stakeholder. While they do not have much influence on decision making, they are vital for the economy of Ben Tre.

3.4.2 Citizens

The province of Ben Tre is mainly inhabited by the Kinh people, although there are other minority groups including Chinese, Muong Tay, Khmer and Cham people. They all communicate in Vietnamese and there are little differences observed between the different groups (Ministry of Agriculture and Rural Development, 2016). The citizens work in different sectors, of which the agricultural and aquacultural economy is the largest. The service sector is also growing, taking up approximately 31% of the income of the province. The industry and construction sector are the smallest economy with only approximately 21% of the Gross Regional Domestic Product (GRDP). Currently with 15% of the workforce, the industry sector has grown vastly in recent years. Industries such as agricultural and aquatic product processing, paper production, wind energy, garments and mechanical engineering are the most developed industries (Ministry of Agriculture and Rural Development, 2016). These numbers are summarised in Table 3.1.

Table 3.1: Economic sector distribution in Ben Tre Province

Economic sector	Percentage of GRDP	Percentage of workforce
Agri- and aquaculture	44%	60%
Services	31%	22%
Industry and construction	21%	15%

The citizens are interested in the development and safety of their city. While their perspectives are more frequently being considered during stakeholder meetings (Ta Quynh Hoa et al., 2019), citizens still tend to think that these gatherings primarily serve as informative sessions to present the new plans, rather than an opportunity for them to exert influence. The reason for this is the lack of discussion with the stakeholders, which results in a low participation level. The local authorities sometimes attribute this to the low education level of the citizens (Andrew-Wells Dang et al., 2015). Therefore the influence of the citizens is relatively low compared to the other stakeholders, even though their interest is very high.

3.4.3 Vietnamese government

The Vietnamese government eventually decides which projects are carried out and is responsible for the safety and prosperity of Vietnamese citizens. The Mekong Delta is a region of economic importance due to its agricultural and aquaculture activity. Keeping this region safe and productive is the main goal of the Vietnamese government, while their concern is economic decline. There are a lot of different ministries that make decisions in the area. The Vietnamese government is a stakeholder with high power and high interest.

3.4.4 Local authorities

Local authorities in Vietnam are, in principle, local representatives of the state. Their responsibility is to carry out the plan of the state on a regional scale, because Ben Tre Province is under direct jurisdiction of the Vietnamese government. In the province, the organisation has the same structure as in the Vietnamese government, with a People's Council (local legislature), a People's Committee (local executive), and the same departments as the state (Finance, Transport, Health, and more). The departments correspond to their matching department at the national level (Albrecht et al., 2010).

The province and the Vietnamese government have corresponding goals, which are more specific for the province. For example, the Vietnamese government and the province both want to increase the productivity regarding rice cultivation. The province has knowledge about its region and knows that harvesting rice 2 or 3 times a year will be too intensive in Ben Tre due to the expected rise in salinity levels in the dry season, so it will adjust the goal to fit the local possibilities (Ministry of Agriculture and Rural Development, 2016). The province is also responsible for local public services, including the infrastructure, public transport and water supply. This gives the local authorities high power and also a high interest.

3.4.5 Environmental organisations

A big environmental organisation that is active in Ben Tre Province is World Wildlife Fund (WWF). Currently WWF is investing in sustainable shrimp-rice production. This project hopefully results in a reduction of pollution in the Ham Luong River (WWF, n.d.-a). WWF has the goal to sustain natural life for the benefit of people and wildlife. In the Mekong Delta this results in protecting the natural wildlife and morphology, addressing water risks, climate-smart food production and promoting nature based solutions (WWF, n.d.-b). Environmental organisations have less power than the development organisations, but their interest could be considered a little higher since the impact of any intervention in the river can be significant to them.

3.4.6 Development organisations

A few examples of development organisations are: The World Bank, U.S. Agency for International Development (USAID) and the Asian Development Bank (ADB) (ADB, 2020). The goal of these organisations is to improve the world by addressing various challenges and opportunities, such as poverty, climate change, health, education, governance, and energy. These organisations are also active in the Mekong Delta (USAID, n.d.). They cannot make any legal decisions in Vietnam, but they could stop funding projects if they disagree with certain projects or events. They should be kept informed and satisfied to retain financial contributions.

3.4.7 Maritime sector

Ben Tre Province has three seaports: Binh Thang Port, An Thuy Port and An Nhon Port. They form the connection between the Tien River and the South China Sea. In addition to that, there is one important river port in the Tien River, which is called the Giao Long River Port, with a capacity of 200,000 tonnes per year (Vietnam Briefing, 2020). All these ports are located outside the Ham Luong estuary, visible in Figure 3.6, due to the limited depth of 2.2 metres at certain locations. Some small harbours located in the Ham Luong River are primarily used for small industries. For example, the harbour at the An Hiep Industrial Zone can take ships of 2,000 - 3,000 tonnes (Vietnam Inland Waterways, n.d.), while the Ben Tre cruise port is used for tourists (CruiseMapper, n.d.). There have been plans for more industrial zones, but they have not been realised yet. Furthermore, it is important to note that 40% of the watercrafts are unregistered, which makes it difficult to get a clear picture of the maritime vessels in the Ham Luong River. During the field trip, it became evident that fishing vessels were using the river, as stated in Appendix A. The main concern for the maritime sector is reaching their destination via water. If there would be an obstacle in the Ham Luong River, it would have limited impact on these smaller vessels, as these small ships have the option to navigate through inland waterways. In conclusion, their interest and influence are relatively small.

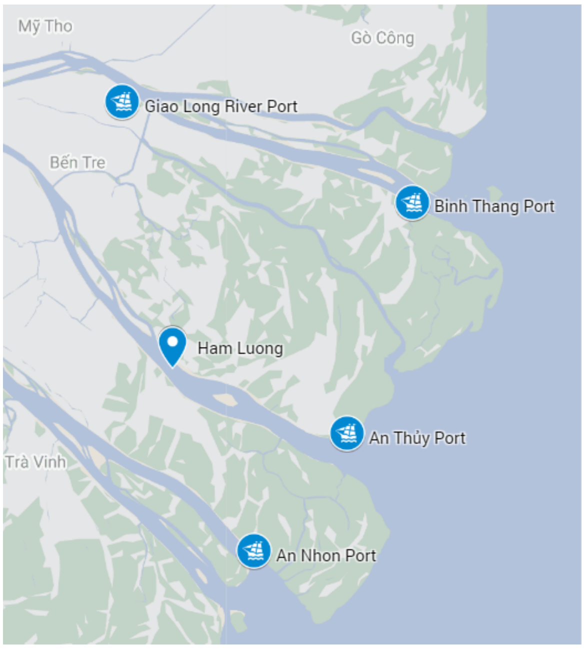


Figure 3.6: Different ports in Ben Tre Province, showing three sea ports and one river port, all outside the Ham Luong River.

3.4.8 Tourism

In 2018, the Mekong Delta welcomed approximately 1.8 million tourists out of a total of 7.8 million tourists in Vietnam. These visitors typically spend an average of two days exploring the Mekong Delta and spend relatively modest budgets for their trips. While there is a government initiative to boost both the number of tourists and their expenditures in the region, the current tourism figures indicate that tourism might not be the most significant stakeholder at present (Nguyen Hoang Phuong, 2019). Furthermore, it is important to note that small tourist boats could travel via side channels to another estuary. Therefore their power and interest are relatively low.

3.4.9 Overview stakeholders

In Table 3.2 each stakeholder is shown with a summarised description of its interest. In Figure 3.7 each stakeholder is placed on a Power Interest Matrix, based on the information provided above. The most important stakeholders are placed under 'key stakeholders'. It can be seen that the local authorities have more power than the Vietnamese government, on the area of Ben Tre. Due to the size of the Mekong River, many local authorities are actively involved in the decision making. Therefore, it is important that the local authorities actively work together to resolve the challenges in the Mekong Delta. Furthermore, it is important to also involve the agricultural sector in the decision making process.

Table 3.2: Overview of the stakeholders with their interests

Stakeholder	**Interest**
Agricultural and aquaculture sector	Functional (natural) conditions to produce products
Citizens	Safe and future-proof living area
Local authorities	Safe and productive province in the future for its citizens
Vietnamese government	Safe and productive area in the future for Vietnam
Environmental organisations	Protecting ecology in a sustainable way
Development organisations	Improving the overall prosperity of Ben Tre Province
Maritime sector	Accessibility to their destination
Tourism	Accessibility to their destination

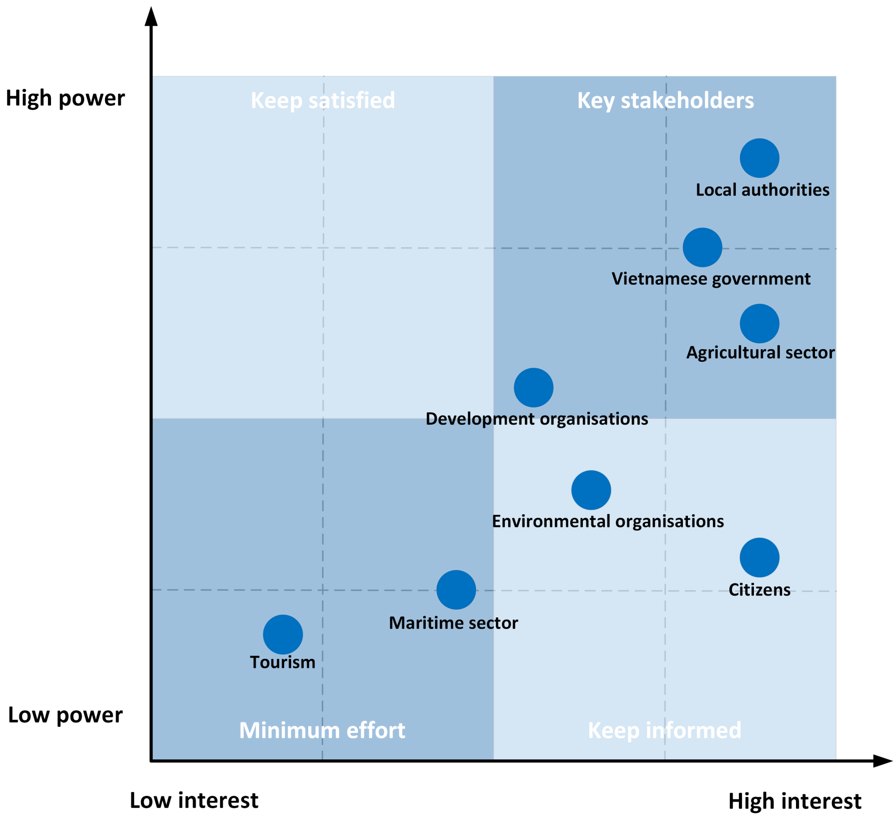


Figure 3.7: Stakeholder Power Interest Matrix

4 Scenario selection

This section elaborates on the selection of certain criteria and scenarios that are considered in this project. These are are based on the knowledge gained from the system description in Section 3. Firstly, the criteria that play a role in assessing the best fitting solution are mentioned. These criteria will eventually be used to compare the different closure alternatives. Next, a selection is made on the weather conditions that are considered in the simulations, taking the computational time into account. Moreover, three potential closure locations are determined. Which form the basis of the four different alternative closure scenarios that are considered in this project. Lastly, the relevant IPCC climate scenario is chosen.

4.1 Criteria

In order to evaluate the different alternatives, a criteria set is defined. These criteria are based on the different functions of the estuary that were identified in the system description in Section 3. For each criterion, an explanation is given to justify why it has been selected. The costs of the four alternatives are not considered as criteria, but will be used for the cost-benefit analysis, where the outcome of the four alternatives will be linked to the corresponding costs. In this criteria selection, it has been decided not to include the criteria of flood safety. Instead, this criteria is implemented as a structural design requirement of the flood defense systems.

Freshwater supply
The Ham Luong River functions as an important source of fresh water for domestic use. The extent to which salt water reaches into the river significantly impacts the freshwater supply. A closure of the Ham Luong River could change the salt intrusion lengths in the river.

Agricultural adaptation
From the system description and the stakeholder analysis, it was found that the agricultural sector plays a large role in the system of interest. Adding to this, the agricultural activities, including aquaculture, are highly dependent on the salinity of water. A possible closure could affect the locations that are suited for specific agricultural activities. It could cause a change in area division for the aqua- versus agriculture. Adaptation of current farmers is in this case inevitable, and should be considered carefully when opting for an alternative.

Biodiversity
Changes in the Ham Luong estuary will have impact on the species that define the biodiversity of the estuary. Not only climate change, but also a possible intervention in the estuary can have implications for their living environment. These effects and implications should be taken into account when assessing the various alternatives.

Stable riverbanks
Intervening in a morphodynamic system will eventually result in adaptation to a new morphodynamic equilibrium. This can lead to erosion or sedimentation of the riverbanks. The stability of the banks directly near the barriers will not be assessed, as the stability of these banks can be considered as technical requirements of the barrier. This criterion focuses on estuary-wide morphodynamic changes.

Navigability
The navigability is important for the transport on water on the Ham Luong River. Any intervention in the river can have significant consequences for its navigability, affecting factors such as the river's flow velocity and depth. The magnitude and impact of these consequences depend on the alternative.

4.2 Weather conditions

As mentioned in Section 3.1, the system of interest is characterised by a high and low discharge season. Different weather conditions can be attributed to these seasons. These weather conditions influence the hydraulic inputs of the system of interest in multiple ways. During the the high discharge season, for instance, large amounts of rainfall are expected, resulting in a larger upstream discharge into the system. These hydraulic boundary conditions can be divided into two categories; upstream discharge and downstream water level. The downstream water level is a combination of RSLR, the tide, waves, and storm surge.

Combining these different hydraulic boundary conditions ultimately leads to a large variety of model combinations that can be simulated. Unfortunately, due to a lack of (computational) time it is not possible to simulate every possible combination. This is also not necessary as the goal of this project is to focus only on the most critical situations for the system. For this reason the most likely combinations of upstream and downstream boundary conditions that threaten the aforementioned assessment criteria the most, are selected and are defined as the “critical situations”. In selecting the critical situations, both the present weather conditions and those in 2100 were considered. The different boundary conditions each have a different timescale in which they occur. For instance, storm surge occurs over the course of a few days, whereas larger discharges can be observed over multiple months during the wet season (Thuyloi University, 2020). For this reason a suitable timescales of the critical situations were also selected.

The combinations of hydraulic boundary conditions have led to the three most critical situations, which are listed in Table 4.1. A situation that was omitted is the combination of low discharge and a storm. Based on historical data of typhoons along the coast of Vietnam, it can be assumed that strong typhoons do not occur during dry season (Thuyloi University, 2020). For this reason, this situation is not considered.

Table 4.1: Critical situations

Scenario	Upstream	Downstream	Timescale
A: Low discharge season	Low discharge (2100)	RSLR (2100) + Tide + Waves	Months
B: High discharge season	High discharge (2100)	RSLR (2100) + Tide + Waves	Months
C: High discharge season + storm	High discharge (2100)	RSLR (2100) + Tide + Waves + Storm surge	Days

4.3 Alternatives

Throughout this report, four alternatives are considered. These four alternatives consist of three alternatives with a barrier and one alternative without a barrier. In all alternatives dyke heightening is included to prevent flooding. Within the three alternatives that include a barrier, the location of the barrier is different. In the preliminary selection of these locations, the aspects that have been taken into account are bathymetry, exposure to hydraulic loads, prevention of salt-water intrusion, and land use. Based on these four aspects, the following three locations have been determined as potential locations. The reasoning of these locations is explained in the section below.

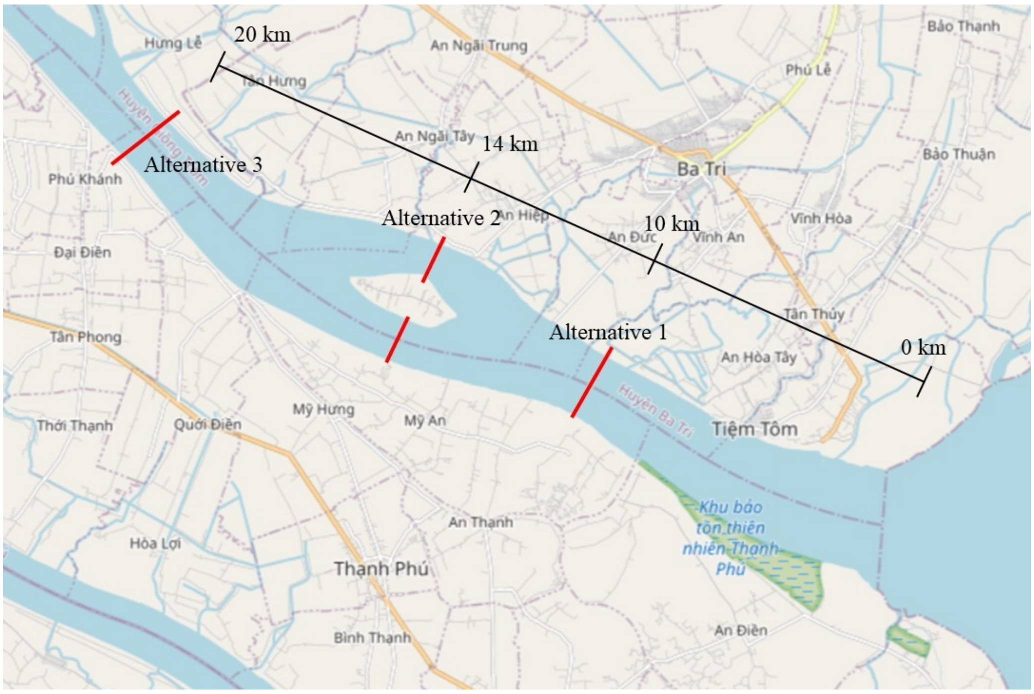


Figure 4.1: Selection of locations of the closure, retrieved from OpenStreetMap

Alternative 1
The location of Alternative 1 is the most seaward location of the selection. This makes it the location that is most exposed to hydraulic loads from the sea. The seaward location can significantly attribute to preventing salt intrusion. This also brings its downsides with respect to the possibility of aquacultural activities, which need salt water, in upstream areas. In the present situation, the aquacultural activities are only located along the first 10 km of the estuary and the location of the closure would not hinder these activities. However, a change in land-use is anticipated along the estuary as aquacultural activities expand farther inland due to the rising salinity levels.

Alternative 2
The location of Alternative 2 is based on the presence of an island, 14 km inland of the estuary mouth. This makes the individual spans of the barriers smaller. A reference project of a similar closure in the Mekong Delta is mentioned in Section 7.2. On Location 2 the depth of one of the two river branches is significant smaller than on the other locations. Location 2 is further inland than location 1, making it less exposed to hydraulic loads from the sea, but also reducing its prevention of salt intrusion. This location has some more space for aquacultural activities, but has a big impact on the land-use on the island.

Alternative 3
The location of Alternative 3 is the most landward location. The width of the river has reduced significantly compared to location 1. This could lead to high benefits in the construction costs. This location corresponds with proposed locations by Tromp (2013) and the Southern Institute of Water Resource Research (SIWRR). This location is the most sheltered location and is expected to experience the least hydraulic loads from sea. It gives room for the longest stretch of coastline for aquacultural activities, but is also expected to allow the highest salinity levels in surrounding areas.

The four alternatives will be further analysed in the upcoming sections. The effect on hydro- and morphodynamic processes in the system will be researched and modelled. In addition, the impact on social and economic activities will be evaluated.

4.4 IPCC Climate change scenario

As the devastating effects of climate change have become more and more evident in the last few decades, it is of huge importance to take climate change scenarios into account. In 2016, the Ministry of Natural Resources and Environment of Vietnam formulated the Vietnamese interpretation of the fifth assessment of the IPCC (AR5). In this assessment, the different climate change projections of IPCC are compared to climate models, predicting different aspects of climate change in Vietnam. The outcomes serve as a guideline to ministries, sectors and provinces which enable the development and implementation of effective plans to respond to climate change and SLR. The assessment's most important recommendation is as follows: "the Representative Concentration Pathway (RCP)8.5 scenarios should be applied to the permanent projects and long-term plans". Therefore, throughout this report, the RCP8.5 scenario will be the leading climate change projection. The corresponding values for relevant effects of climate change, like SLR or increased precipitation, are obtained from the assessment (Tran Thuc et al., 2016).

5 Model

This section presents the model which was used to assess the hydro- and morphodynamic response of the system to the partial closure of the Ham Luong estuary. To begin with, the simplifications, which have led to the formation of the conceptual model, are stated. Next, the conceptual model containing the different simulations, which were run in Delft3D, is presented. This is followed by a short intermezzo on Delft3D and its governing equations. Subsequently, the settings and input of Delft3D which were used in the simulations are shared. This is followed by the calibration and verification of the model, after which the sensitivity analysis is performed.

5.1 Model simplifications

As mentioned in Section 4.2, concessions have been made regarding the simulation of different weather conditions as it is not possible to simulate every potential weather condition. Similarly, there are other model simplifications which are required. To begin with, Section 3.2.1 refers to sand mining activities in the estuary and Section 3.2.2 touches upon the presence of hydropower dams in the upstream part of the Mekong River. Both processes influence sediment transport rates in the estuary. However, due to the little amount of information available, it is difficult to estimate these magnitudes. Thus, these processes have been neglected throughout this project. Moreover, as mentioned in Section 3.2.1, there are numerous small branches present within the Ham Luong estuary. It is difficult to include all these small branches in Delft3D, as a high level of detail is required to implement these, which will also consume extra computational time. For these reasons, it was decided not to include these branches in the model. It was also decided not to include water quality in the model. Although Section 3.2.1 and Section 3.3.4 address the implications of contaminated water and soil, a trade-off was made between the importance and the difficulty of modelling and it was chosen to be excluded in the model. Lastly, it has been decided to model in 2D, as a 3D model takes up too much computational time when applied to such a large region. As a consequence, the representation of salinity in this model is influenced.

5.2 Conceptual Model

In order to be able to accurately model the Ham Luong estuary, the area is translated into a conceptual model, which is a simplified version of the Ham Luong estuary and is shown in Figure 5.1. The figure provides an overview of the input necessary to run the model.

Figure 5.1: Conceptual Model; dark blue area indicates the part of the estuary in which the hydro- and morphodynamics are modelled, dark green area indicates the land that is part of the system of interest, orange contours mark the input boundaries of the hydraulic model.

Section 4.2 and Section 4.3 refer to the different weather conditions and the locations of the closures to be considered in this report. The combination of these weather conditions with the different locations leads to the formulation of the different model simulations. A barrier can be either open or closed, depending on operational instructions. An overview of the different model simulations can be found in Table 5.1. The runs which have 2025 in their names are simulations that are equivalent to the present time, so no effects of climate change were included in these simulations. The remainder of the simulations are set in 2100.

Table 5.1: Overview of the 24 simulations run with Delft3D

Run	Weather condition	Barrier location	Barrier type	Timescale	Processes
A_2025	A: Low discharge season	-	No barrier	Months	Salinity, sediment
A_2100	A: Low discharge season	-	No barrier	Months	Salinity, sediment
A_L1_closed	A: Low discharge season	L1	Closed	Months	Salinity, sediment
A_L1_open	A: Low discharge season	L1	Open	Months	Salinity, sediment
A_L2_closed	A: Low discharge season	L2	Closed	Months	Salinity, sediment
A_L2_open	A: Low discharge season	L2	Open	Months	Salinity, sediment
A_L3_closed	A: Low discharge season	L3	Closed	Months	Salinity, sediment
A_L3_open	A: Low discharge season	L3	Open	Months	Salinity, sediment
B_2025	B: High discharge season	-	No barrier	Months	Salinity, sediment
B_2100	B: High discharge season	-	No barrier	Months	Salinity, sediment
B_L1_closed	B: High discharge season	L1	Closed	Months	Salinity, sediment
B_L1_open	B: High discharge season	L1	Open	Months	Salinity, sediment
B_L2_closed	B: High discharge season	L2	Closed	Months	Salinity, sediment
B_L2_open	B: High discharge season	L2	Open	Months	Salinity, sediment
B_L3_closed	B: High discharge season	L3	Closed	Months	Salinity, sediment
B_L3_open	B: High discharge season	L3	Open	Months	Salinity, sediment
C_2025	C: High discharge + storm	-	No barrier	Days	Waves, wind
C_2100	C: High discharge + storm	-	No barrier	Days	Waves, wind
C_L1_closed	C: High discharge + storm	L1	Closed	Days	Waves, wind
C_L1_open	C: High discharge + storm	L1	Open	Days	Waves, wind
C_L2_closed	C: High discharge + storm	L2	Closed	Days	Waves, wind
C_L2_open	C: High discharge + storm	L2	Open	Days	Waves, wind
C_L3_closed	C: High discharge + storm	L3	Closed	Days	Waves, wind
C_L3_open	C: High discharge + storm	L3	Open	Days	Waves, wind

5.3 Delft3D

Delft3D is used to evaluate the conceptual model which is introduced in the previous section. Delft3D is a process-based numerical model that simulates hydrodynamics, sediment transport, water quality, morphodynamic processes and the interactions between these processes in coastal and estuarine environments. Delft3D makes use of the shallow water equations, a simplified form of the Navier-Stokes equations, to simulate water flow. In solving the governing hydraulic, sediment and other equations a time-step and spatial-steps need to be defined. These spatial-steps can be defined in the format of a grid.

Figure 5.2 depicts the schematic that Delft3D adheres to. Delft3D requires the boundary conditions, initial conditions, and bathymetry (bottom depth) as input. Based on these inputs the corresponding hydrodynamics are calculated in terms of waves and flow. These are in turn used to calculate the sediment transport. This influences the bathymetry, which is to be updated and then used again as input and all the aforementioned processes are repeated.

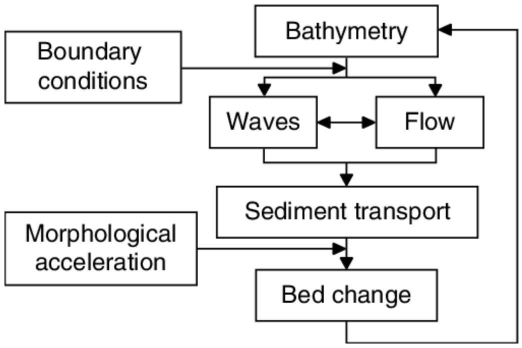


Figure 5.2: Delft3D processes within one time-step (Van Der Vegt et al., 2014)

5.4 Model settings

This subsection refers to the settings which were used as input for the Delft3D model. The grid, simulation time, boundary conditions, initial conditions, thin dams, and wave processes are considered here. For the remainder of the settings it can be assumed that default settings were used.

5.4.1 Grid and bathymetry

From Thuyloi University a dataset on the batymetry of the Ham Luong estuary was received, more information on this can be found in Appendix B.1. From this bathymetry a grid was made. In order to account for the influence of the tide on the upstream boundary of the model, it was decided to extend the grid 130 km beyond the upstream boundary. The calculations with simplified cross-sections are shown in Appendix C. Due to this extension, the grid has become quite large. This influenced the computational time significantly, and it was therefore decided to create a coarser grid. The smallest grid size is approximately 60 metres. As a consequence, the ratio of the grid cells in M-direction (the M-smoothness values) do not align with their recommended values at every grid cell in the model. Due to a lack of time, it was decided to accept that the processes at these locations are possibly underestimated and take this into consideration when interpreting the model results. Also on the seaside, an extended grid was used. This was done to compute waves.

5.4.2 Simulation time

As mentioned before, three different types of weather scenarios are considered in this project; low discharge season, high discharge season, and high discharge in combination with a storm. Each have different simulation times. The low discharge season occurs roughly from January to June, so these simulations were performed over a five month period starting at the first of January, to the first of June. For the high discharge season, also five months were modelled, now starting at the first of June, and ending at the first of November. The storm during the high discharge season was modelled for four days, from the 18th of August to the 22nd of August, as these dates align with the highest tidal water levels. A time step of one minute was used, to comply with the Courant number.

5.4.3 Boundary conditions

As can be seen in Figure 5.1, the model has four boundaries: one upstream and three downstream near the coast (North, East, and South). The upstream boundary is characterised by the discharge. During low discharge season a constant discharge of 256 m^3/s is used, while a simplified discharge time series is used during the high discharge season. This if further elaborated on in Appendix B.2. The downstream boundaries are characterised by the tide and the waves. Section 5.4.6 provides more information on waves. Using T-tide, the tidal constituents that are governing near the Ham Luong estuary were found (more on this appraoch can be found in Appendix B.3) and used as input for the East boundary. In order to account for RSLR (Appendix B.4) and storm surge (Appendix B.5) an extra tidal constituent (a_0) was introduced. For the North and South boundary a Neumann time series boundary condition was used. Moreover, salinity levels were also defined at the boundaries. For the upstream discharge, a value of 0 g/L, salinity is considered (Gugliotta et al., 2017). The salinity at the open coast is based on the default value within Delft3D for marine waters, and is defined as 31 g/L. Finally, the upstream boundary also includes sediment transport rates, more on this can be found in Appendix B.6.

5.4.4 Initial conditions

Initial conditions regarding water level, salinity, and sediment are needed. The initial conditions for water level, salinity and sediment concentrations are based on an initial value map. The processes of salt intrusion and sediment transport in an estuary are slow processes. When starting with one uniform initial value, the spin-up time that is needed to obtain realistic gradual gradients in salinity would be large. In order to avoid this long spin-up time in the different simulations, two separate simulations were run in advance. These two runs created an initial value maps for the low discharge season, as well as one initial value map for the high discharge season. These initial value maps contain water level, salinity and sediment concentration per grid cell and do therefore reduce the spin-up time significantly.

5.4.5 Thin dams

In order to be able to model the effect of the closure of the Ham Luong estuary, thin dams were used which represent a barrier. The barrier was modelled with open gates, and closed. The simulations in which the gates were closed, the barrier was represented by thin dams which span the entire width of the river. The 'open gate' simulations are represented by thin dams which span about 30% of the river width.

5.4.6 Waves

Due to the long computation time when including the wave module in Delft3D a decision was made about modelling with waves. For weather scenario A en B the wave impact is modelled for only a duration of 4 days, without processes like salinity and sediment, as there is no need to simulate wave action for the whole simulation period of 5 months. Scenario C has an duration of 4 days, which makes it possible to model waves for this scenario. The input values for the significant wave height, wave period and wind speed are visible in Appendix B.8 and Appendix B.7. For scenario C a return period of 100 year is chosen with the corresponding wave height.

5.5 Verification

The model has been verified using multiple datasets which were obtained from several Vietnamese institutes which were visited during the field trip. In doing so, the following different processes were considered; water level, discharge, and salinity. As too little data on sediment concentrations was available to verify the model, sedimentation rates could not be verified. This contributes largely to uncertainties in the interpretation of the sediment behaviour, which is elaborated further in the Sensitivity analysis (Section 5.6), and the Discussion (Section 10).

5.5.1 Water level

Three datasets are available with measurements on the water level at different locations in the Ham Luong River. The first two measurement sets were provided by the ICOE and contain the hourly water level at An Thuan and My Hoa over the course of 21 years (2000 to 2021). Bearing in mind that the dataset in An Thuan was also used to generate the tidal constituents in T-Tide, the water levels were compared to the output water levels of Delft3D and are shown in subgraphs A and C in Figure 5.3. For simplicity, only five months in the dry season are visualised. The other dataset which was available was provided by the SIWRP, and contains the hourly water level at Tren Song for 15 days in April 2023. Again this dataset was compared to the water level of the Delft3D simulation. This is shown in subgraph E of Figure 5.3. The simulations in Delft3D were performed over the same time periods, and an upstream discharge was used which is in accordance with the 15% fraction of the discharge in Kratie measured at that time (Mekong River Commission, 2023a).

At first glance, it looks as if the Delft3D water level is out of phase with the datasets of the institutes. When shifting the water level of Delft3D 3 days and 22 hours forward, the datasets seem to align better visually. Especially the peaks of the water levels are more in accordance. This phase shift can be explained by multiple factors; the spin-up time of the Delft3D model plays a role, as is the fact that not all tidal constituents (only the eleven largest) are taken into account in the Delft3D model. Additionally, the choice of initial conditions of the water level may also influence the shift. When bearing in mind the approximately four day shift of the Delft3D water level, the output of the Delft3D model does quite well resemble the water level of the datasets in terms of magnitude and tidal phase. An attempt was made to identify the cause of the tidal shift. By analysing the water level output from the Delft3D model, using the same tidal analysis tool (T-tide) as done in Appendix B.3, the tidal constituents of the modelled water level can be compared to the initial constituents of the input. By doing so, indeed significant difference in phase can be seen, while the amplitudes show a good fit. However, the specific cause of the phase shift was not identified. In view of time, no elaborate further quantitative methods were used to asses the model's performance.

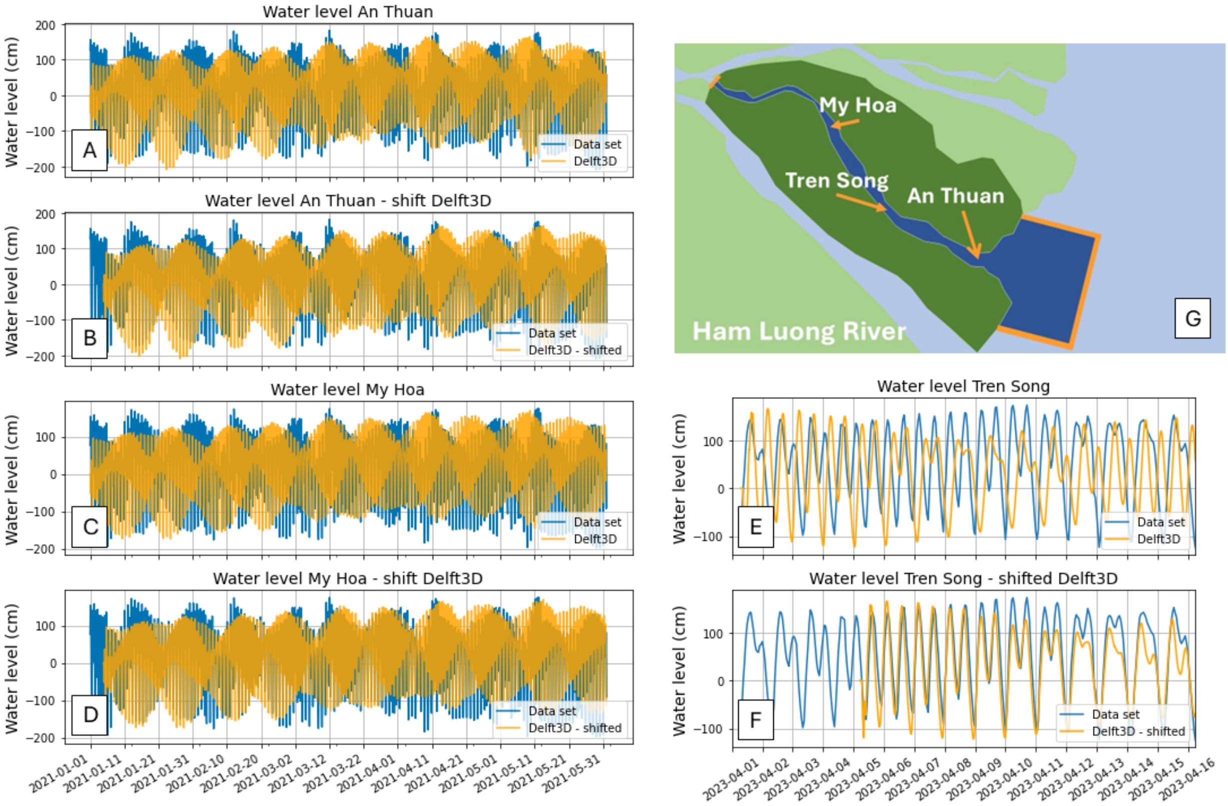


Figure 5.3: Comparision of water level from datasets to output of Delft3D. A: Water level in An Thuan, dataset provided by ICOE. B: Water level in An Thuan, same datasets as in subfigure A except the Delft3D data is shifted 3 days 22 hours forward. C: Water level in My Hoa, dataset provided by ICOE. D: Water level in My Hoa, same datasets as in figure C except the Delft3D data is shifted 3 days 22 hours forward. E: Water level in Tren Song, dataset provided by SIWRP. F: Water level in Treng Song, same datasets as in figure E except the Delft3D data is shifted 3 days 22 hours forward. G: Locations of the measurement stations in the Ham Luong estuary

5.5.2 Discharge

Besides water level, the dataset at Tren Song provided by the SIWRP also contains the discharge at that location for the same dates. Again these were compared to the outputs of Delft3D. Delft3D however, does not provide the discharge as an output. Only the water level and depth-averaged velocity are included in the output. In order to compute the discharge some assumptions were made. The depth-averaged velocity at the measurement station was assumed to be constant over the width of the river. Additionally, a time-dependent wet cross-section was calculated to resemble the tidal discharge. To do so, the wet cross section per timestep was computed by adding or subtracting the width of the water level at MSL multiplied with the water level to the cross section of the river below MSL. This wet cross section was in turn multiplied with the depth-averaged velocity. These discharges were compared, and are displayed in Figure 5.4. It can be observed from the figure that, when shifting the Delft3D outputs approximately four days, the discharge measured at the measuring station at Tren Song is in accordance with the discharge computed with Delft3D.

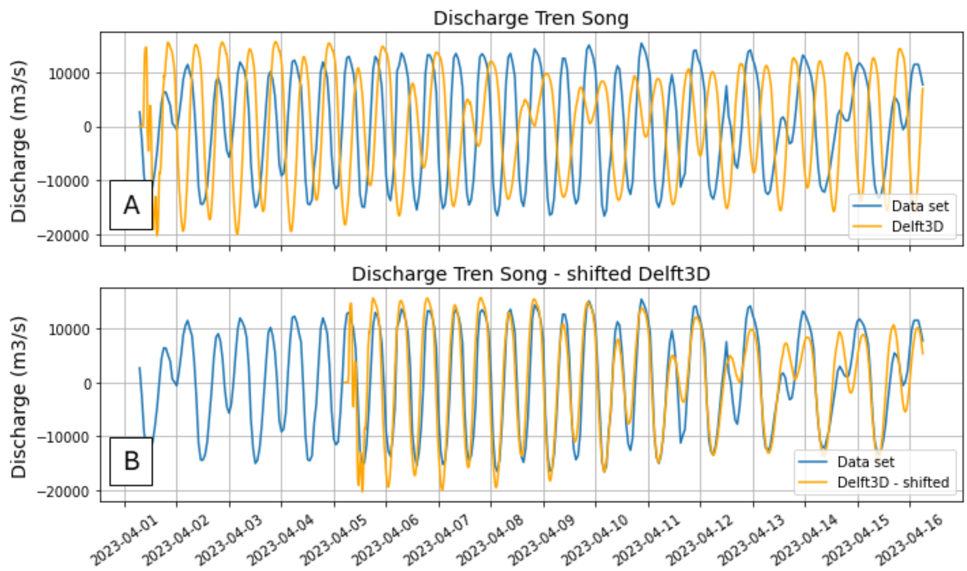


Figure 5.4: Comparison discharge from dataset to output of Delft3D. A: Discharge in Tren Song, dataset provided by SIWRP. B: Discharge in Tren Song, same datasets as in figure A except the Delft3D data is shifted 3 days 22 hours forward.

5.5.3 Salinity

Not much data is available to verify the modelling of salt intrusion. The most suited data was provided by ICOE. This data includes salinity values near the river mouth at An Thuan in 2015, 2016 and 2019. The data does not contain yearly measurements, but only series of 5-month measurements with regularly missing values. In order to verify the process of salinity in the Delft3D model, the same period of the year of the available data was modelled in Delft3D. The measurements and modelled values are shown in Figure 5.5. It can be seen that the model output is not matching the fluctuation of the measurements very well. Besides the daily fluctuations in salinity that might be the result of the daily varying discharge, a gradual decrease in salinity values can be seen in the measurements. The decrease in salinity around May and June is the result of the increasing discharge of the river towards the end of the low discharge season, which leads to lower salinity. As the verification runs did assume a constant discharge, this trend is not visible in the Delft3D output.

Furthermore, the modelled salinity shows significant lower minimum salinity values than the measurements. There can be several reasons for this difference. One of the possible causes of this mismatch is the fact that a 2D-model is used with a homogeneous density. In the model, the density of fresh water is assumed for both river discharge and seawater. In reality, the density difference between salt water and fresh water is causing a density-driven flow of seawater into the estuary, resulting in a salt wedge. This density-driven flow is not represented in the model, which could partially explain the lower salinity values in the model compared to measurements.

It becomes clear that the variable river discharge is strongly affecting the salinity in the river mouth. For the simulations, a simplified time series during high discharge season, or a fixed value during low discharge season was used. Reducing the discharge value increases the salt intrusion distance, but not as much as measurements have shown. The modelled salt intrusion is mainly driven by the tide and does not show significant variations, as for example a strongly fluctuating discharge would do.

Some more reasons for the underestimation of the salt intrusion might be found in other details of the model. For the viscosity and temperature, uniform default values have been used in the model. The viscosity values are connected to the grid concerning stability, but also to morphodynamic and hydrodynamic processes. An increase in salinity results in an increase of viscosity, which also depends on temperature (Sánchez-Juny et al., 2019). In reality these values are varying over along the estuary, which impacts connected salinity values. Additionally, the grid itself could also be a cause of the poor representation of salinity values. Especially at the interface between river mouth and sea, the used grid has too large grid cells. As this part of the system affects salt intrusion strongly, any inaccuracy related to the grid can cause discrepancies.

These discrepancies indicate that the model results are not quite as realistic as initially desired. For this reason, it should be carefully noted that outputs concerning the length of the salt intrusion, and the concentrations at these locations that follow from the model cannot be assumed to be true. Keeping in mind that salinity is underestimated in the model, it is however still possible to compare the salinity outputs of the different simulations amongst each other. As all simulations are subject to the same model settings, and thus display the same inaccuracies.

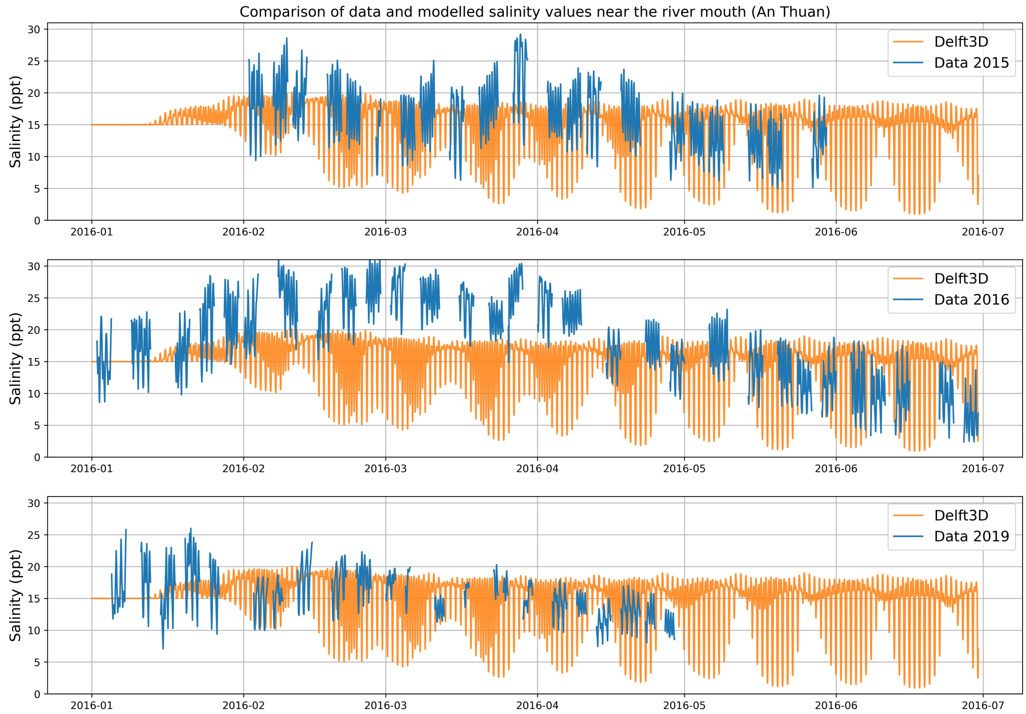


Figure 5.5: Verification salinity. Comparison between measured salinity values of three years and modelled salinity values.

5.6 Sensitivity analysis

To get a better understanding of the model and to quantify uncertainty, a sensitivity analysis is performed. By changing an input parameter, the range of outcomes can say something about the effect of that parameter on the results. This provides insight on the uncertainty range of the output considering assumptions and uncertainties in the input. For this model, the sensitivity analysis is performed for Manning's roughness coefficient and the median sediment diameter, D_{50}, of the sand. Due to lack of computational time, the simulation time is only one month, which can be enough to compare the initial differences, but will not give detailed information about further outcomes.

Manning's coefficient represents the roughness of the river bed, and is used to estimate the flow rate in a channel (Battjes & Labeur, 2017). In the model, the chosen value of 0.02 is taken to be uniform over the whole estuary, while there can be spatial variation due to vegetation or other obstructions. To analyse the sensitivity of the model to this coefficient, simulations were performed with a uniform value twice as high (0.04) and a value twice as low (0.01) as the assumed value, during one month with low discharge, without any intervention.

From these simulations it can be concluded that the change in Manning's coefficient has a significant effect on salinity values. Differences in salinity are in the order of a few ppt at the estuary mouth, where the lower Manning's coefficient results in higher salinity values. About 10 km upstream, the salinity values for a higher Manning's coefficient reach zero over time, while the salinity values for a Manning's coefficient of 0.01 reach values 5 times higher than for the default value of 0.02. The reduction of salinity was to be expected with a higher roughness, because the effect of tide has a smaller reach in a less smooth estuary. For a Manning's coefficient of 0.01, the tidal influence and the related salt intrusion reaches much further inward than for the default value.

The effect on depth averaged velocity is in the order of 0.1 m/s over the whole estuary. The lower the Manning's coefficient, the higher the depth averaged velocity. This can be related to morphodynamic processes such as sediment transport and erosion or sedimentation, which must be taken into account. So, a higher Manning's coefficient results in lower salinity levels and lower depth averaged velocities in the estuary and should be chosen carefully.

For the median sediment diameter (D_{50}) the default value of 200 µm is used throughout the simulations. To check the sensitivity of the model on the choice of this median sediment diameter, a value of 150 µm and a value of 300 µm were compared to the original value. The same default sediment transport formulas were used for each simulation. These simulations were done for one month during high discharge, which includes mud transport as well as sand.

The effect on the sediment sand amount is as expected: a lower D_{50} of the sand results in a higher amount of sand to be transported. This affects the cumulative erosion/sediment, which has different results over the length of the estuary, in the order of 0.0001 m to 0.01 m. In the river mouth, for example, a lower D_{50} results in more erosion, while the opposite occurs near the most downstream located island. These local changes result in small changes of the bed level, but there are no significant differences visible for water depth and water level. Same can be said about the salinity values, which shows that the choice of the median sediment diameter has little influence on the outcome of the model. These comparisons are done for a simulation that only covers one month, while morphodynamic changes can take much longer and reaching an equilibrium can take multiple decades, which is not taken into account in this sensitivity analysis. In the case of lack of data and information, choosing the default value, based on other research and data, seems to be the best option.

Small changes in parameters can often result in significant changes of the results. Those parameters have to be carefully considered and compared to other researches and experiments. In this case, it is more important to research and analyse the value of Manning's coefficient than the precise D_{50} of the sand. Knowledge about the uncertainties of the input is imperative for the interpretation of the results and its ranges of uncertainties.

6 Results

This section shows the findings of the Delft3D model presented in the previous section. Additionally, the results of an assisting sedimentation tool are shown. These results are to be used in the assessment of the different alternatives.

6.1 Model results

First the results on the water levels in Delft3D are presented, which is followed by the evaluation on the wave height and salinity. Finally, the sediment behaviour in the model is commented on. Before going into details about the model results, it must be noted that due to the scope of this project the processes upstream of the barrier in case of closure could not be analysed. This is due to the fact that no upstream bifurcations are included in this model, which has the consequence that the water piles up behind the barrier. This results in unrealistic water levels, and salinity and sediment processes. For this reason, the upstream parts of the simulations in which the barrier is closed were not interpreted. More comments on the scope can be found in Section 10. This applies to the results upstream of the barriers of the following runs mentioned in Table 5.1; “A_L1_closed”, “A_L2_closed”, “A_L3_closed”, “B_L1_closed”, “B_L2_closed”, “B_L3_closed”, “C_L1_closed”, “C_L2_closed”, and “C_L3_closed”.

6.1.1 Water levels

The water levels were investigated at multiple locations. This section only focuses on the water levels at two locations, as a clear distinction can be made between the water levels upstream, further away from the locations of the barriers and downstream near the mouth of the river. The two locations which were considered are shown in Figure 6.1 and Figure 6.2.

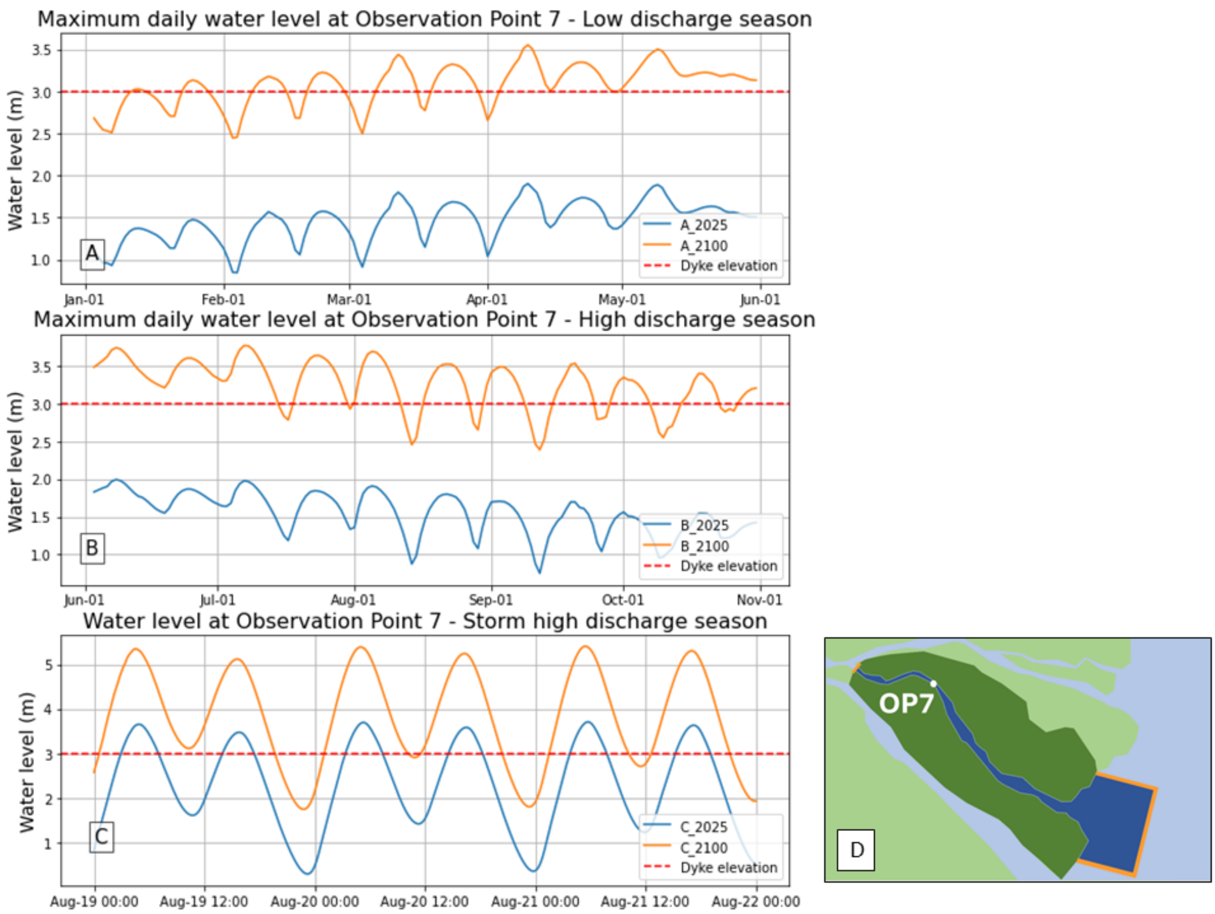


Figure 6.1: Water levels at observation point 7. A: The daily maximum water level at the observation point in the dry season. B: The daily maximum water level at the observation point in the wet season. C: The water levels during a storm at the observation point. D: Location of Observation Point 7.

The water levels upstream were analysed at the location of Observation Point 7 (OP7). The results are shown in Figure 6.1. Only the water levels of two runs are shown; the water level with no intervention in 2025 and 2100. The upstream water levels of the alternative barriers with open gates produced similar results to the water level at 2100 without interventions. The water levels in 2100 are significantly higher than the water level in 2025, which can be attributed to a larger discharge and RSLR. During the high and low discharge season, the water levels frequently rise above the elevation height of the dykes. Furthermore, it should be noted that a storm in the wet season will produce water levels above the dyke elevation, for both the 2025 and 2100 scenarios.

Figure 6.2 displays the downstream water level at the location of Observation Point 2 (OP2). Again no large differences can be observed between the water levels for runs in which the gates of the barriers are opened compared to the run with no intervention in 2100, and for this same reason these water levels were excluded from the graph. There is however a small difference in water level which can be observed when looking at the closed scenarios. Especially in the wet season, the water levels are lower when the barriers are closed. This can be attributed to the fact that the large discharge corresponding to the wet season is blocked by the barrier, thus reducing the water levels downstream. No water level difference can be observed during a storm in the wet season between the different closure cases. This can be attributed to the fact that the storm surge and waves are dominant over the discharge differences in affecting the water level.

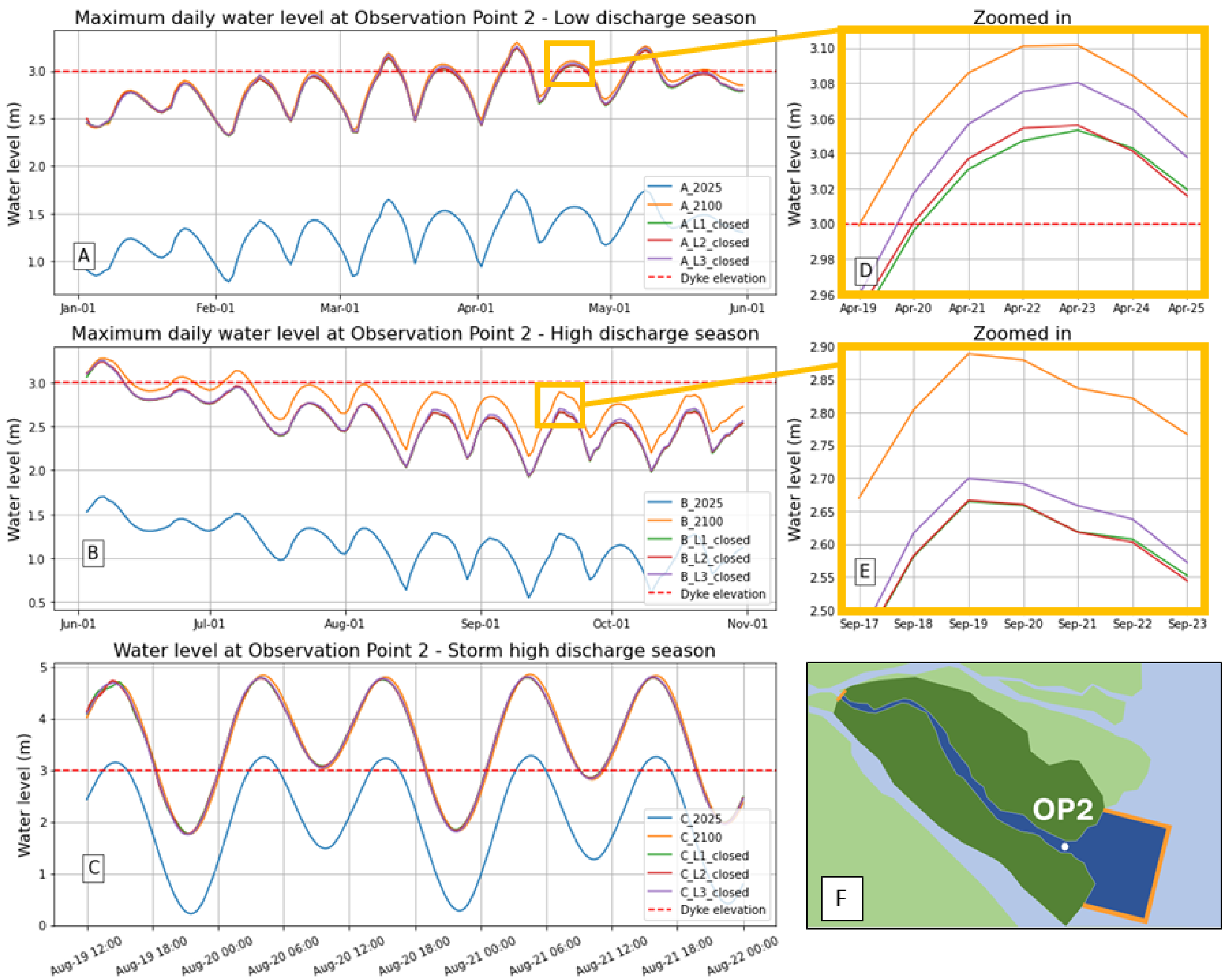


Figure 6.2: Water levels at Observation Point 2. A: The daily maximum water level at the observation point in the dry season. B: The daily maximum water level at the observation point in the wet season. C: The water levels during a storm at the observation point. D: The daily maximum water level at the observation point in the dry season, zoomed in on a period end of April. D: The daily maximum water level at the observation point in the wet season, zoomed in on a period end of September. F: Location of Observation Point 7.

6.1.2 Wave height

In Figure 6.3 the significant wave height is visible during storm conditions in 2100 in the high discharge season. The maximum significant wave height in the Ham Luong river during storm conditions is 3 metre. It can be seen that the waves that originate from the sea do not propagate far into the estuary. The reason for this is that the storm is approaching from the SW direction. The barriers at Alternative 1, 2 and 3 do not experience the influence of waves that originate from the sea. The Ham Luong estuary is a very wide estuary, which results in wind waves originating from inside the estuary. These waves are up to 1.5 metre, visible in Figure 6.3. For the normal weather conditions, the maximum significant wave height during the low discharge season is 1.1 metre and during the high discharge season is 0.5 metre. These waves originate from the sea and are only present near the river mouth. The difference in significant wave height between the high and low discharge season results from the different wind climates during the year. The significant wave height from the waves that are formed in the river during the both seasons are smaller 0.5 metre.

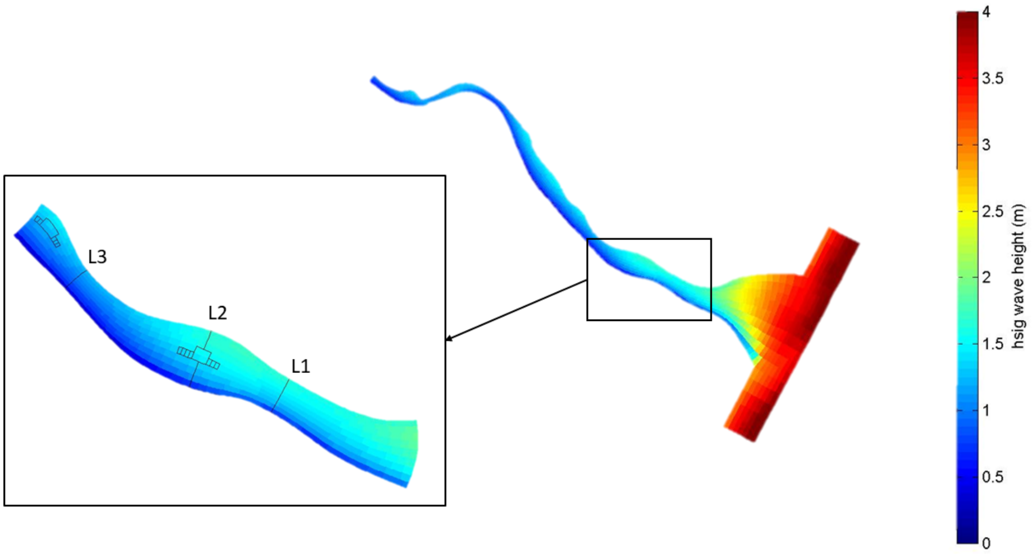


Figure 6.3: Significant wave height in the Ham Luong estuary during storm conditions in 2100

6.1.3 Salinity

The maximum salt intrusion in the Ham Luong estuary is visible in Figure 6.4. This result is obtained from run A_2100, as during low discharge season the salt intrusion is at is maximum. As stated in Section 5.5.3, the salinity levels in this model are underestimated, which means that it is expected that the salt intrusion will reach further into the estuary than is visible in Figure 6.4. When a barrier is closed for 2 months in 2100, the downstream side of the barrier behaves like a basin. This basin is slowly filled with salt water as visible in Figure 6.5. The 'basin' of the barrier at location 1 is closer to the sea and thus more saline than with a barrier at location 2 or 3 after two months of closure. However these two months should be interpreted carefully, as salinity is underestimated in the model, it is likely that this filling of the basin will occur faster than is shown in Figure 6.5. When looking at the salinity levels of A_2100, in Figure 6.5, it looks like the salinity at the location of the barrier in Alternative 3 is already 0 ppt. However, this is a result of the underestimation of salinity in the model.

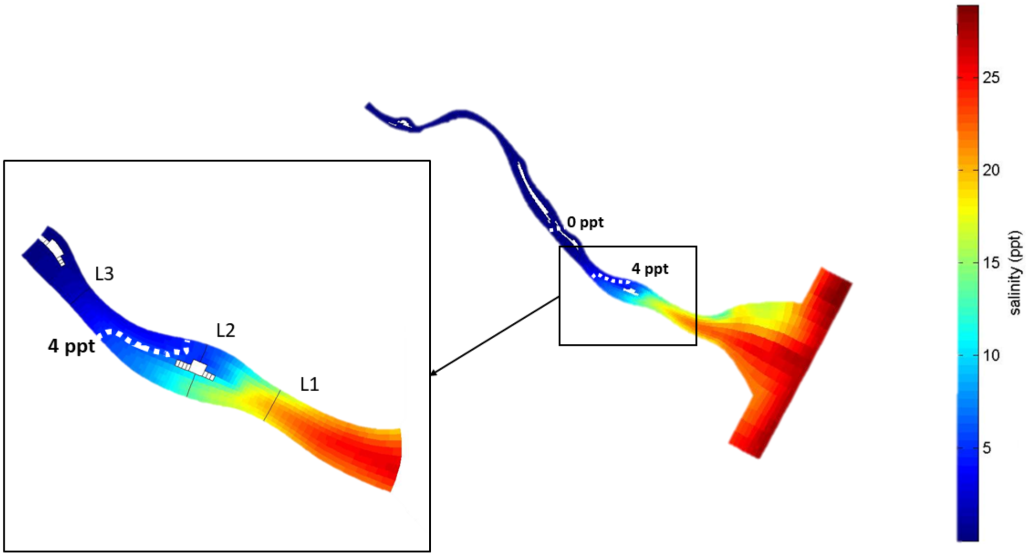


Figure 6.4: Maximum salt intrusion in 2100 during low discharge season in the Ham Luong River, with the 4pp and 0 ppt boundaries in white

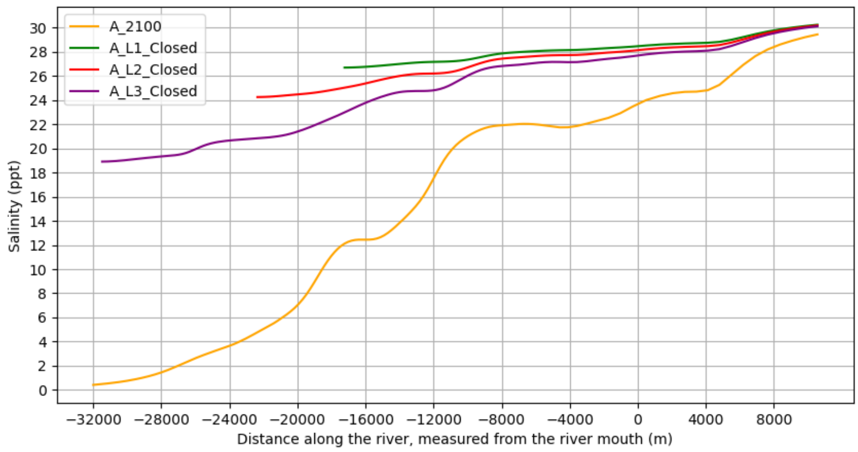


Figure 6.5: Salinity levels on the sea side at the barier along the river after 2 months closure in the low discharge season in 2100

6.1.4 Sediment

Any intervention in a system like the Ham Luong estuary will lead to changes in morphology until a new equilibrium is reached. In the upcoming analysis on sedimentation data, the year of 2025 is seen as the base year. The sedimentation will be described in terms of cumulative erosion/sedimentation rates in metres. Not every simulation from Table 5.1 will be discussed in these results. In terms of cumulative sedimentation, the simulations that include high river discharge lead to the most notable results. Therefore, only simulations with high river discharge are included in these results.

Before interpreting the results regarding sedimentation and erosion, it should be noted that the modelling of the riverbanks is not expected to match reality properly. The used bathymetry data, received from Thuyloi University, does not include water depths less than 2 metre, which results in unrealistic modelling of the riverbanks. However, it is assumed that erosion/sedimentation patterns that occur at the most outer grid cells can be used to interpret the rates at the riverbanks.

Three main drivers of sedimentation/erosion are expected in these simulations. RSLR and increased river discharge will change the morphodynamic equilibrium from 2025 into a new equilibrium in 2100. In Figure 6.6, the differences in sedimentation/erosion between the base year in 2025 and the simulation of 2100, with no barrier, is shown. This shows the effect of SLR and increased river discharge on the bed level. Only in the more upstream reach of the river, significant differences in bed level change can be seen. These differences are in the magnitude of maximum 1 metre for both erosion and sedimentation. In these upstream reaches, exactly the same differences can be seen, when looking at the three simulations with barriers in 2100.

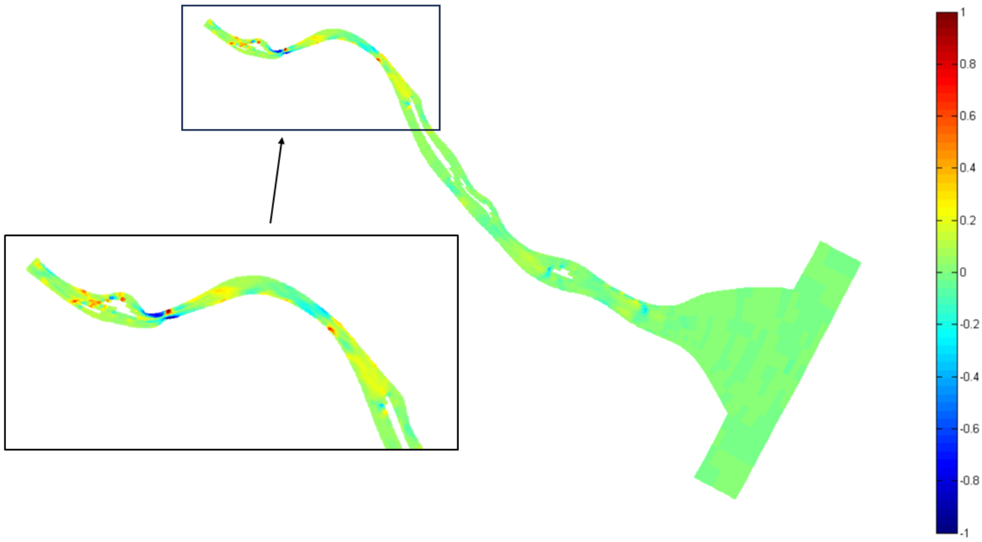


Figure 6.6: Difference in cumulative sedimentation/erosion between base year 2025 and 2100 without a barrier.

The third driver that is expected to induce changes in erosion and sedimentation rates, when comparing 2100 with 2025, is the implementation of a barrier. In Figure 6.7, the differences in sedimentation between the base year and the three runs with barriers on different locations in 2100 are shown. The results are as expected: near the barriers, high sedimentation and erosion rates can be seen. Erosion is mainly taking place just upstream of the barrier, as a result of the contraction of flow through the barriers. Sedimentation rates occur just downstream of the barriers when the flow rates are decreasing again. However, in Figure 6.7 only the local effects of the barrier are shown. When looking at sedimentation/erosion effects more upstream or downstream of the barrier locations, no differences between the four alternatives are observed.

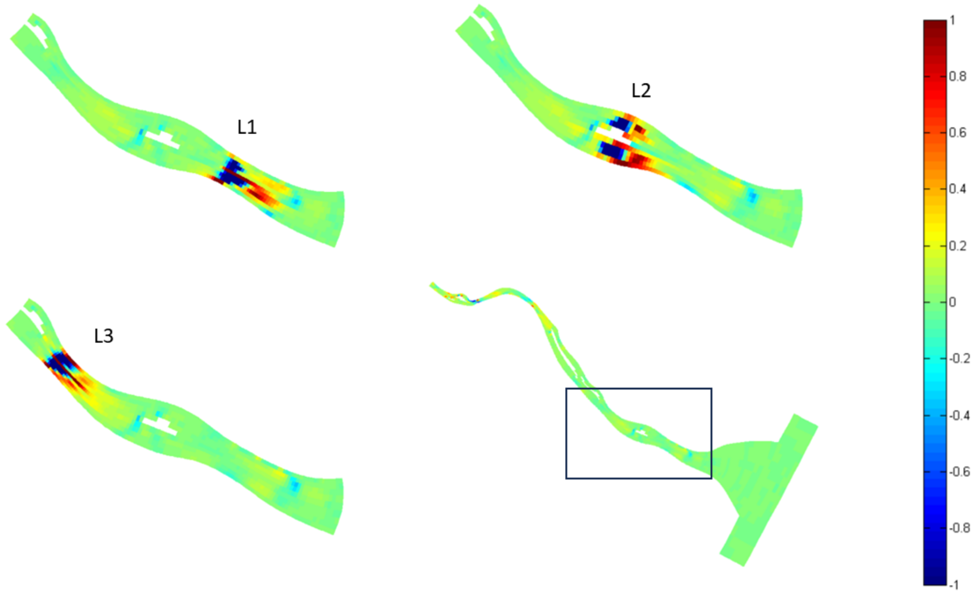


Figure 6.7: Differences in cumulative sedimentation/erosion between base year 2025 and three situations with barriers in 2100.

6.2 Sedimentation tool

As mentioned in Section 5.5, insufficient data is available to verify the sedimentation processes that are modelled in Delft3D. Therefore, an additional tool is used. This tool is based on the sedimentation formulas of Van Rijn (Van Rijn, n.d.). This tool is used to estimate the sedimentation rates and concentration in the case of closed barriers. As mentioned in Section 6, it is not possible to make well-based estimations about processes that are related to the upstream discharge while barriers are closed. Therefore, in this section the focus is only on sedimentation rates on the seaside of the barrier, while it is closed.

The used tool is a quick assessment on sedimentation rates and concentration of fine sediments in a basin that is influenced by a tidal regime via one entrance. In the case of the Ham Luong estuary, the part of the estuary between the closed barrier and the river mouth is considered as the basin. In Appendix D the input of the tool for the three different barrier locations is given in Table D.1. In Figure 6.8 the development of the concentration of mud during four tidal cycles is shown. A clear difference between the different locations can be seen.

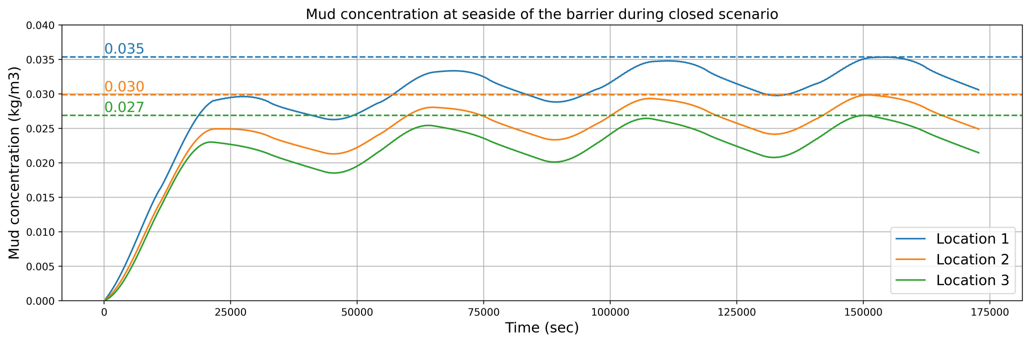


Figure 6.8: Mud concentration in case of closed barriers.

Besides the concentration, the tool also returns the total sedimentation layer. This sedimentation rate is initially calculated per tidal cycle. The extreme situation during dry season, where the barrier is closed for 5 months in order to prevent salt intrusion and store fresh water, is considered as a critical situation. This period would lead to a total sedimentation layer as stated in Table 6.1, depending on the location of the barrier.

Table 6.1: Total sedimentation layer after 5 months

Location	L1	L2	L3
Total sedimentation layer (m)	0.160	0.133	0.117

7 Design of flood protection system

In this section, the design of the flood protection system will be described. The flood protection system consists of dykes and a storm surge barrier. A storm surge barrier is a structure with a partial movable barrier that can be closed temporarily (Mooyaart et al., 2014). The function of the dykes is to withstand the water levels in the estuary to ensure flood safety, which is considered a strict requirement for all four alternatives. The storm surge barrier has the main function of closure in case of low discharge from the Ham Luong River or during storm surge, which can occur in combination with high discharge. Its goal is to prevent saltwater intrusion and flooding from the sea, while retaining fresh water in the estuary. The storm surge barriers' secondary function is to open during high discharges to let the river water flow into the ocean.

The structure of this section is as follows. First, in Section 7.1 the design of the dyke systems for the four different alternatives is shown. This design is on a conceptual level and focuses on the differences between the four alternatives. In the sections Section 7.2 to Section 7.8, the design of the storm surge barrier is described. This design is on a more detailed level than the dyke design but is also a preliminary design.

7.1 Dykes

In this subsection, a conceptual design of the dyke system is given. These dykes comply to the requirement of flood safety. Here, the design of the required dyke heights is shown, after which an overview of the dyke system is given.

The needed dyke system depends on the different alternatives. The length and needed height of the dyke system differs per alternative. In this design, a distinction between two dyke types is made: sea dykes and river dykes. The sea dykes are on the side of the structure that faces the sea and the river dykes facing the river upstream. This means that every alternative has a different dyke system design. Note that this design of the dyke system stops at the mouth of the river, while in reality the dykes continue at the coastline, but this is outside the scope of this project. First, the height of the sea dykes will be calculated, after which the height of the river dykes is given.

The sea dykes are the dykes that are exposed to storm surge levels and wave action. The current sea dykes have a height of 3.0 m as stated in Section 3.3.2. Due to the expected RSLR and other extreme weather conditions the dykes need to be elevated to protect the hinterland. To determine a future-proof crest height of the year 2100, the general approach for wave overtopping discharges given in the "Manual on wave overtopping of sea defences and related structures" has been used (Van der Meer et al., 2018). For safety reasons, the angle of the incoming wave is chosen to be 60°. Furthermore, a vertical wall has been placed on top of the dyke, with a height of 1.0 m. The choice for a wall on top of the dyke gives the opportunity for smaller width of the dyke, which creates less hinder for the people living around the dyke. The material of the dyke embankment revetment is grass as noted in Section 3.3.2. Due to the absence of a berm at the moment and the presence of houses close to the water, no berm will be constructed because this would also increase the width of the dyke. The dyke calculations, which can be found in Appendix E.1, result in a final crest-free board of 6.8 m, excluding the vertical wall with a height of 1.0 m. A drawing of the cross-section of the dyke can be seen in Figure 7.1. A width of the dyke crest of 4.5 m is chosen for the possibility of building a road on the dyke.

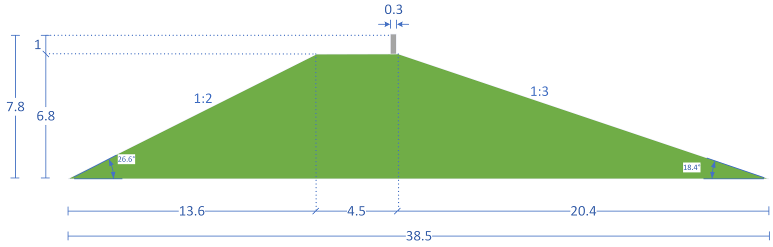


Figure 7.1: Cross-section of the sea dyke design, including dimensions of the height and width in m.

It has to be noted that this dyke height is designed on wave action, storm surge, and RSLR. This is relevant for the first stretch of kilometres land inward. As stated in Section 6.1.2 at a certain distance from the coast, the wave action at the dyke has reduced. This will lead to a reduction in the needed crest height.

The river dykes are the dykes that are exposed to high water levels in the river, which can be the result of tide or high discharge. However, the river dykes are not exposed to storm surges, as the river dykes are located in the hinterland of the storm surge barrier. Furthermore, no significant wave action on the river dykes is expected, as stated in Section 6.1.2. The height of the river dykes is based on the maximum expected water levels in the Ham Luong estuary during high discharge season, which includes RSLR. According to the Delft3D model, the water levels will rise to more than 3.5 m, see Section 6.1.1, and thus a needed dyke height of 4.0 m can be estimated. These dyke heights are not specifically designed for the case of a closed barrier during high discharge season, as the upstream effects of this scenario are not included in the Delft3D model. It is a model approximation, therefore a large safety margin of 0.5 m is chosen for the dyke height. The positions of the river dykes and sea dykes per alternative can be seen below in Figure 7.2. The existing dyke system in 2025 in Figure 7.2A is an estimation, based on information that was provided by ICOE. The dyke height for Alternative 4 (Figure 7.2E), would only be required for the first kilometres, after which a lower dyke would suffice.

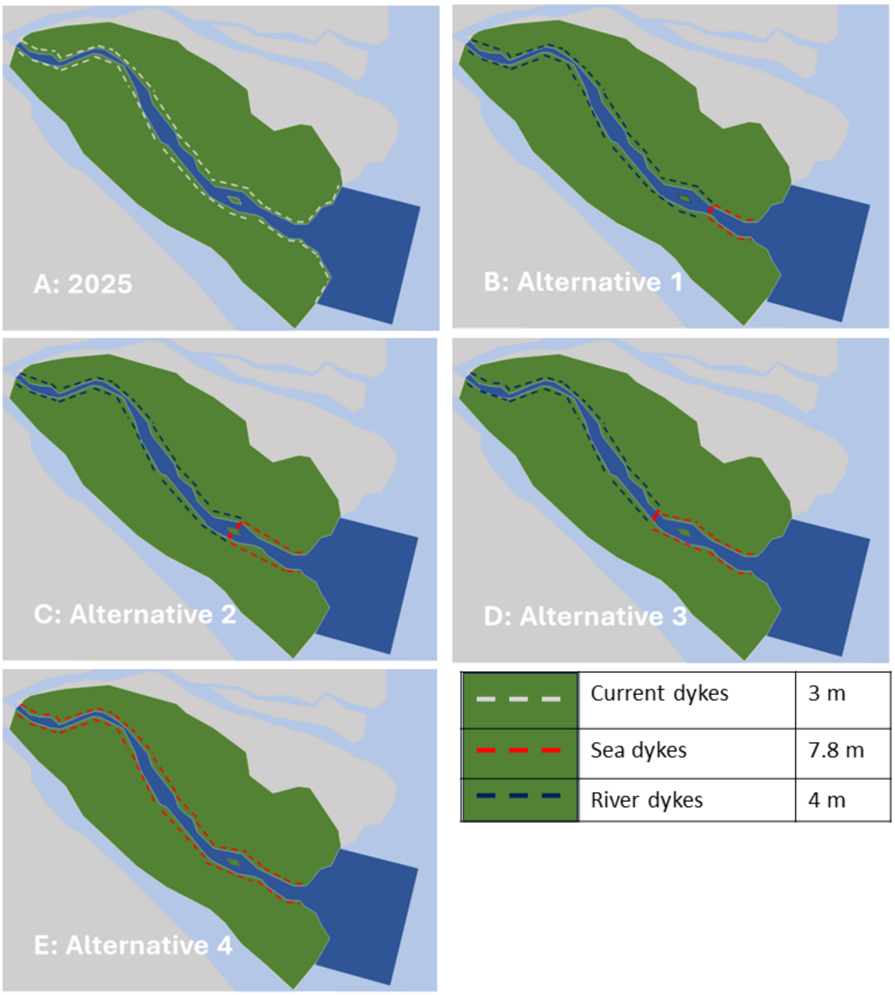


Figure 7.2: Dyke system: The existing dyke system for the current situation (A) and the proposed dyke systems for the four alternatives (B to E). The height of the sea dykes includes the 1.0 m height of the wall on top of the dyke

7.2 Reference projects

There are two projects in the Mekong Delta that are used as reference for the Ham Luong River barrier. The Ba Lai River sluice in Ben Tre Province and the Cai Lon - Cai Be sluice gates located in the province of Kien Gian, near the Gulf of Thailand. This subsection will elaborate on these structures, starting with the Cai Lon - Cai Be sluice gates.

7.2.1 Cai Lon - Cai Be sluice gates

In the province of Kien Giang, in the western part of the Mekong Delta, a large project for water control is carried out. The Cai Lon - Cai Be sluice gates are used to prevent salt intrusion in the agricultural areas in the provinces of Kien Giang, Hau Giang, Ca Mau, and Bac Lieu. Additional flood protection measures were taken, consisting of three barriers: The Cai Lon, Cai Be, and Xeo Ro sluices. There is a dyke connecting the sluices with the national highway on top of it. Furthermore, sluice gates along the An Bien and sea embankments are part of this 3.3 trillion VND (€136.8 million) project (Tuoi Tre News, 2022).

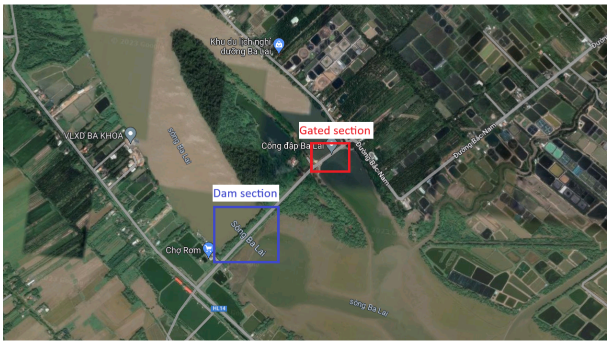
This barrier is the largest in the area and therefore a very interesting reference project, close to the Ham Luong River. The Cai Lon sluice in particular is very large, spanning 470 m and consisting of 11 gates, each 40 m in width. The gates are vertical lift gates and because of the large span, there is a large steel truss supporting the steel plates that form the barrier. The Cai Lon River barrier can be seen in Figure 7.3. It has two ship locks with a width of 15 m and a length of 100 m. Furthermore, the structure is also designed to have a bridge on top of it (GIZ, 2019).

Figure 7.3: Cai Lon River barrier (Tuoi Tre News, 2022)

While the purpose of constructing the sluice was to control the inflow of salt water, it is important to note that salt water was already used for agriculture prior to the construction of the sluice, due to the cost-effectiveness. Consequently, the river gates have to be open during high tide to allow salt intrusion, leading to high energy costs because the gates have to be open all the time. Furthermore, fresh water still needs to be pumped into the area from the Hau River, which is associated with relatively high costs. This information was obtained from a meeting with experts from Royal HaskoningDHV, see Appendix F.2.

7.2.2 Ba Lai River sluice

In the Ben Tre Province, just outside the chosen area of interest, there is a gated barrier in the Ba Lai River. It was built in 2002 and forms an almost permanently closed barrier. The barrier is placed at a position in the river where there is an island. Only on one side of the island, the barrier has gates, while on the other side, a closure dam has been constructed, which can be seen in Figure 7.4a. The gated section of the barrier can be seen on the right side of the island and the closure dam is on the left of the island. The entire dam has a total length of 544 m and has 10 gates, each 10 m in length (VNCOLD, 2014). There are two gate types in this structure. A barge gate, which is a gate that pivots around a vertical axis to close, and a vertical lift gate operated by a crane (Voorendt, 2022). In Figure 7.4c and Figure 7.4d the gate system and lifting crane for the gates are visualised. The gated section is only 100 m in length. For the Ham Luong River, the dam will have larger dimensions because the width of the Ba Lai River is much smaller than the Ham Luong River. However, it is a good project to refer to concerning the effects it has had over the past two decades on the area.



(a) Ba Lai River barrier top vieuw *Source: Google Maps*

(b) Gated section of the Ba Lai barrier

(c) Ba lai Gate system

(d) Ba Lai crane

Figure 7.4: Ba Lai River barrier

The Ba Lai River barrier has reduced salt intrusion in the area, which was the main concern at that time. However, it had some negative effects on people living nearby. Farmers working with salt water had to change their business to comply with the freshwater system. Fishermen faced a similar challenge because of the depletion of natural saltwater resources. Furthermore, the dam reduced the river flow circulation leading to the accumulation of different kinds of pollution. The largest factor leading to accumulated pollution is aquacultural discharge. Also, landslides at river banks have become an issue in the area since the building of the structure (Xuan Quang et al., 2017). These are possible side effects that must be taken into account for a barrier in the Ham Luong River. Currently, due to these effects on the area the Ba Lai River barrier is not considered to be a successful project.

7.3 Feasibility study

In this subsection, a feasibility study on the different types of gated structures is performed. There are different assessment criteria on which the structure feasibility can be assessed and there is only a limited number of storm surge barriers built worldwide. All of these structures show a great variety in hydraulic gate types, because of differences in function and environmental conditions (Mooyaart et al., 2014). This shows that there is not a clear guideline on how to choose a certain storm surge barrier type. Thus, an MCA is performed. The initial costs are an important factor, however, these cannot be quantified as the driving forces as costs are not well known. Therefore, they are left out of the analysis (Mooyaart et al., 2014). The structural requirements of the structure are shown in the list below (Molenaar & Voorendt, 2022):

- Constructability
- Stability
- Strength
- Maintainability
- Adaptability

To see how well the different alternative design options score on the structural requirements, evaluation criteria are formed. The evaluation criteria are derived from the system description. With the evaluation criteria, the different alternative options for design can be compared and the best option can be chosen. The list of design criteria is as follows (Molenaar & Voorendt, 2022):

- Ease of construction; this is about the simplicity of design and how easy it is to build such a design in the Ham Luong River. The depth of the river is for instance important for the type of structure that can be built. The construction time is also included in this criterion.
- Ease of adaptability; this is the ease at which the structure can be adapted to new conditions. For instance, the ease to improve the height of the barrier in the case of a higher RSLR than expected.
- Sustainability; this is about the influence of the structure on the ecosystems. The amount of CO_2 emission is one indicator, but the amount of materials used and how much of the local ecosystem must make way for the structure are also sustainability indicators.
- Ease of maintenance; this is a combination of future predicted maintenance costs, simplicity, and the strength of the structure.
- Durability; this says something about the strength and the robustness of the structure. The structure must be able to withstand the large forces that will be exerted on it by wind, water, and soil.
- Aesthetics; this is a difficult criterion because it considers the beauty of the structure, which is a personal consideration. It is assessed by how a structure fits in its surroundings and how impressive the structure is to people in general.
- Navigation possibility; this is the possibility of smaller and bigger boats to pass the barrier, in case of an open barrier. For some structure types, it is easy for all boat types to pass the barrier and for some structure types, it is not. For some structures, a sluice has to be included in the design to let boats pass.

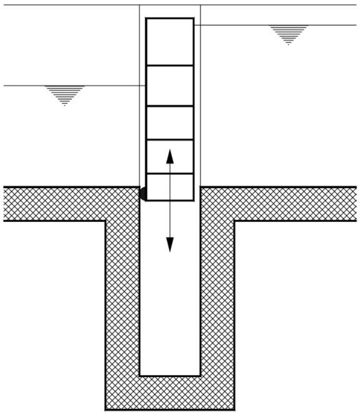
For the technical design of the barrier, there are various options to consider. Several types of water control structures can be used when building a barrier (partially) with gates in it. A couple of these structures can be seen in Figure 7.5 and are listed below and elaborated with the criteria (Voorendt, 2022):

- Vertical lift gates; these are gates that can be translated vertically into place from a higher position. The operating mechanism can consist of hydraulic jacks or a system of cables, pulleys, and counterweights. When closed, the gate rests on a sill beam. The vertical lift gates score very high on ease of construction because the design is easy and the execution is easier than for most other structures. Its design is very similar to that of the Cai Lon sluice mentioned in Section 7.2.1. Furthermore, it is a structure that can be maintained very well because the doors can be lifted out of the water. It can be adjusted in future works. Aesthetically it is not a very beautiful structure that fits in the environment. It is a robust structure so it scores good on durability. It is not very sustainable because it can block a lot of sediment and significantly change the river morphology. Also, the navigation of ships will be hindered. Lastly, the vertical lift gates move vertically which requires a large amount of power, although the use of counterweights could reduce this significantly (Molenaar W.F., 2011).
- Drop gates; these type of gates are very similar to vertical lift gates. They are designed to be translated into position from the bottom of the river bed. Because the gates are often submerged it makes ease of maintenance much more difficult. The construction costs are also relatively high and it costs a large amount of power to lift the gates. On the other hand, the drop gates are better for navigation possibilities because ships can easily pass over the gates when closed.
- Flat gates; these lay flat on the ground and can be rotated to a vertical position when water on one side of the structure has to be retained. Ships face no hindrance to passing this gate when the gate is lying flat on the ground. However, this type of barrier gate performs not very well at ease of maintenance since the gates are submerged. This makes the construction also a bit more difficult than for the vertical lift gates. They cannot be lifted out of the water easily. Furthermore, these gates are more difficult to adapt in the future.
- Visor dams; these are curved barriers that are rotated into place vertically. The curvature of the barrier is in the horizontal plane. Visor dams are very impressive large structures that score high on their aesthetics. They also have a lower impact on the river morphology and thus score high on sustainability. Ships can easily pass this structure. Visor dams are not easy to design, construct, and maintain because of their complexity. Since they are large steel structures they need more maintenance and are not the most durable structures.

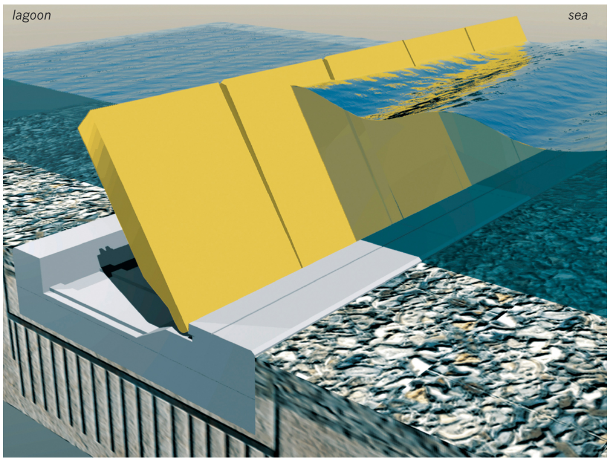
- Radial gates; these are gates with a radial arm that vertically rotates the gate into place. The curvature of the gate is in the same plane as the rotation. Radial gates perform well on ease of maintenance because the gates can be lifted out of the water. However, they are less easy to construct than for instance vertical lift gates because they are more complex. Also, the navigation possibility is low. A sluice would have to be built to let ships pass. Their impact on sustainability is also significant due to the change in river morphology.
- Sector gates; these are similar to radial gates because they also have a radial arm. However, these gates are rotated into places horizontally such as the Maeslantkering in The Netherlands. They score very high on sustainability because they have little influence on the river when the barrier is open. Their design and construction are complex, so they score low on these criteria. Furthermore, it is not easy to adapt this structure in the future. Aesthetically it is very good because of its futuristic looks. Lastly, the horizontal movement requires less power than vertical movement, the structure is therefore also sustainable.
- Inflatable dams; these are barriers that are placed on the bottom of a river and can inflate when water must be retained (Voorendt, 2022). The inflatable dam scores high on sustainability and aesthetics. It blends in with the environment very well when the barrier is open. Also, it lets ships pass very easily. However, the design on this large scale is very difficult and it is a structure that is not easy to maintain because it lays completely in the water. Furthermore, it is almost impossible to adapt it in the future. Although it can be a very large structure, it is not a very stable one because it is not a hard structure. Also, there has been little research on what the effect is of dynamic loading on the inflatable dam (Kuijper H.K.T., 1998).

Some of the options above are left out of consideration because they are, in general, not suitable for the function the barrier has to fulfil in this case. Mitre gates swing out from two side walls to form a barrier with an angle pointing towards the upper water level and are disregarded because they are usually relatively small and are thus not considered to be storm surge barriers. They are primarily used in locks for boats. Sliding gates cannot be closed in flowing water and are therefore not suitable (Kuijper H.K.T., 1998). Shutter weirs are crest walls built in a river with on-top shutters to regulate water flow. They are usually not used as flood protection but as water level control mechanisms and therefore not suitable for this design.

(a) Vertical lift gate *Source: (Watersnoodmuseum, n.d.-a)*



(b) Principal of a drop gate *Source: (Kuijper et al., 1998)*



(c) Flat gate *Source: (NPR, 2009), photo: Graziano Arici*

(d) Visor dam *Source: (iStock, 2013), photo: yellowpaul*

(e) Radial gates *Source: (USACE, n.d.)*

(f) Sector gates *Source: (Watersnoodmuseum, n.d.-b)*

(g) Inflatable dam *Source: (ZJA, 2023)*

Figure 7.5: River barrier types

To assess the different kinds of water control structures on the aforementioned criteria, an MCA is performed. The rating is done on a scale of - - - to +++, with - - - being a low performance on the specific criterion and +++ a high performance. A value of 0 is also possible if there is no significant upside or downside for the alternative on a criterion. There are therefore 7 possible values. In this MCA no 0 value was given. The ratings are based on the description of the barriers and their performance on the different assessment criteria. They are not compared to a basic situation but relative to each other. The results can be seen in Table 7.1.

Table 7.1: Criteria scores for water control structures

Gate type	**Vertical lift gates**	**Drop gates**	**Flat gates**	**Visor dams**	**Radial gates**	**Sector gates**	**Inflatable dams**
Ease of construction	+++	++	++	- - -	++	- -	- -
Durability	+++	+++	++	++	++	+	- -
Ease of maintenance	+++	-	++	- - -	+++	+++	- - -
Sustainability	- -	- -	- -	-	- - -	+++	++
Ease of adaptability	+++	++	- -	- - -	- -	- -	- - -
Aesthetics	- -	- -	+++	++	-	++	++
Navigation possibility	-	++	+++	++	- - -	+++	+++

Each of the criteria is also given a certain weight depending on their importance, as visible in Table 7.2. If a criterion is more important than another one, the most important criterion is rewarded a 1 and the less important criterion is rewarded a 0 value. When criteria are equally important they both receive a value of 1. Durability and ease of construction are the main drivers that contribute to the start of the construction so these are considered the most important criteria. They both receive a value of 1 relative to each other. Ease of maintenance and sustainability are quite important for the environment and the stakeholders so these criteria are slightly less important. Furthermore, the ease of adaptability is a little bit less important than the aforementioned criteria. The structure is built for a lifetime of 100 years so the adaptability is partially included in the design. The least important criterion is aesthetics as this is not of big importance for the stakeholders. Also, navigation possibility is regarded as least important criterion which corresponds to Section 3. The results can be seen in Table 7.2.

Table 7.2: Weight for each criterion

Gate type	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**Summed total**	**Weight**
Ease of construction (a)	x	1	1	1	1	1	1	6	25
Durability (b)	1	x	1	1	1	1	1	6	25
Ease of maintenance (c)	0	0	x	1	1	1	1	4	17
Sustainability (d)	0	0	1	x	1	1	1	4	17
Ease of adaptability (e)	0	0	0	0	x	1	1	2	8
Aesthetics (f)	0	0	0	0	0	x	1	1	4
Navigation possibility (g)	0	0	0	0	0	1	x	1	4

Finally, combining the weights and the scores of each structure type results in the final score for each structure. The scores of the criteria are converted to a value of 1-7 depending on how positive or negative the score in Table 7.1 is. The results can be seen in Table 7.3. According to this MCA, the vertical lift gates are the best option for this project. It is closely followed by the flat gates. Other types of gates are considered to be too complex to construct or have other unwanted features.

Table 7.3: Score with weight per gate types, where W = Weight and S = Score.

Criterion	Vertical lift gates		Drop gates		Flat gates		Visor dams		Radial gates		Sector gates		Inflatable dams	
	S	W · S	S	W · S	S	W · S	S	W · S	S	W · S	S	W · S	S	W · S
Ease of construction	7	175	6	150	6	150	1	25	6	150	2	50	2	50
Durability	7	175	7	175	6	150	6	150	6	150	5	125	2	50
Ease of maintenance	7	117	3	50	6	100	1	17	7	117	7	117	1	17
Sustainability	2	33	2	33	2	33	3	50	1	17	7	117	7	117
Ease of adaptability	7	58	6	50	2	17	1	8	2	17	2	17	1	8
Aesthetics	2	8	2	8	7	29	6	25	3	13	6	25	7	29
Navigation possibility	3	13	6	25	7	29	6	25	1	4	7	29	7	29
Total		**579**		**492**		**508**		**300**		**467**		**479**		**300**

7.4 Technical Requirements

In this subsection the requirements for design of the storm surge barrier are listed. These requirements follow from Section 3 and Appendix B and are needed to continue with the design of the structure. In Table 7.4 the different requirements with their corresponding values and dimensions are listed.

Table 7.4: List of technical requirements

Requirements	**Value**	**Dimensions**
Design lifetime	100	years
Design storm	75	years
Maximum volume of water discharge in 2100	7800	m^3/s
Minimum volume of water discharge in 2100	250	m^3/s
Flow from both directions	Yes	-
Type of gate	Vertical lift gate	-
Mean sea level	0	m+MSL
Elevation of bottom of discharge sluice	-10	m+MSL
Water level spring high tide (HAT)	1.38	m+MSL
Water level spring low tide (LAT)	-3.01	m+MSL
Storm surge	2.18	m
Expected relative sea level rise	1.56	m
Maximum water level east seaside of structure	5.12	m+MSL
Minimum water level east seaside of structure	-1.45	m+MSL
Maximum water level upstream side of structure	3.00	m+MSL
Minimum water level upstream side of structure	-1.60	m+MSL
Maximum head over structure	6.54	m
Maximum wind speed	40	m/s
Significant wave height at location 1	2.2	m
Peak wave period during tropical storm	9.7	s
Fresh water density	1000	kg/m^3
Salt water density	1020	kg/m^3

7.5 Load combinations

The storm surge barrier has to be designed for various weather conditions. Each situation results in different loads on the structure which all have to be withstood. Each Load Combination (LC) can be seen in Table 7.5. This table describes on what part of the structure the loads act and also gives the water levels during extreme weather conditions for both low discharge and high discharge season separately. It is important to note that the "lowest river water level" differs for low and high discharge season. To both will be referred in this section as "low river", which means the lowest river level in the given LC. The same applies to the "highest river water level", and the "lowest and highest sea water level". Furthermore, the storm is only present during high discharge season. The differences between the minimum and maximum water levels of both the river and sea are described in Appendix E.2.

The different forces on the structure are wind loads, hydrodynamic forces, and hydrostatic forces. It is important to note that when the gate is closed, it is only partially exposed to wind forces, so only the top of the gate is influenced by it. Moreover, it is assumed that wave loads, which are included in hydrodynamic loads, solely originate from the sea and not from the river discharge. Self-weight is excluded since it does not vary for the different LCs. Below, every LC is explained.

In LC1, during high discharge season when the sea is much higher than the river, the gates of the barrier have to be closed to prevent salt intrusion and flooding by the sea. The most critical situation would occur for a low river discharge, combined with a high sea level. Because of the high discharge season, a storm will result in the highest sea level.

LC2 describes a failure of the opening mechanism of the gates during high discharge season, when the river is high and the sea is low. In this situation, the gates should be open to let the river discharge flow out. However, if the gates stay closed, the hydrostatic load will become significantly more on the river side of the barrier.

The third critical load combination, LC3, describes another failure of the lifting mechanism during high discharge season. In this scenario, the gates fail to close during storm conditions. In this scenario, the critical conditions involve a high sea and a low river discharge. Due to the high discharge season, the sea will be highest during a storm. With the gates open, there is no head difference between both sides of the structure. However, there is a high flow velocity, resulting in drag and inertia loads, which are categorised as hydrodynamic loads. Additionally, as the gates are open, they are completely exposed to wind loads.

The fourth critical load combination, LC4, describes a low sea in combination with a high river during wet season. Therefore, the gates are open leading the same loads as in LC3, but the flow velocities are different and in the opposite direction.

LC5 is similar to LC1, but during low discharge season. So this load combination also has closed gates, a low river discharge and a high sea level. There is no storm surge, since this load combination is during the low discharge season.

For LC6, again a low discharge season is analysed. This is similar to LC2 and describes a low sea and a seasonal high river discharge. The gates are again closed.

LC7 is similar to LC3 and describes an open gate during a high sea level and a seasonally low river discharge during the low discharge season.

In the last load combination, LC8, also an opened situation is analysed. The water level of the river is high and the sea water is low tide. This is similar to LC4, except now during low discharge season.

In Table 7.5 the LCs and their details are listed. Some of the LCs will turn out to be not critical for this structure but for complete overview all of them are described in this section.

Table 7.5: Load combinations and conditions

LC	Season	Gate	Wind loads	Hydrodynamic loads	Hydrostatic loads	Water levels
LC1	High discharge	Closed	Piers Lifting structure Gates (partial)	Piers, Gates	Piers, Gates	Sea: RSLR High tide Storm surge River: Seasonal low
LC2	High discharge	Closed	Piers Lifting structure Gates (partial)	Piers, Gates	Piers, Gates	Sea: RSLR Low tide River: Seasonal high
LC3	High discharge	Open	Piers Lifting structure Gates	Piers	Equal on both sides	Sea: RSLR High tide Storm surge River: Seasonal low
LC4	High discharge	Open	Piers Lifting structure Gates	Piers	Equal on both sides	Sea: RSLR Low tide River: Seasonal high
LC5	Low discharge	Closed	Piers Lifting structure Gates (partial)	Piers, Gates	Piers, Gates	Sea: RSLR High tide River: Seasonal low
LC6	Low discharge	Closed	Piers Lifting structure Gates (completely)	Piers Gates	Piers, Gates	Sea: RSLR Low tide River: Seasonal high
LC7	Low discharge	Open	Piers Lifting structure Gates	Piers	Equal on both sides	Sea: RSLR High tide River: Seasonal low
LC8	Low discharge	Open	Piers Lifting structure Gates	Piers	Equal on both sides	Sea: RSLR Low tide River: Seasonal high

7.6 Loads

In this subsection, all the various loads that act on the structure are calculated. First, the hydrostatic loads and then the hydrodynamic loads for the different load combinations, which are discussed in Section 7.5. Then, the maximum wind load for a storm is calculated and the soil pressure is determined with Cone Penetration Test (CPT) data. Lastly, and overview of the complete load schemes, including hydrostatic, hydrodynamic, and wind loads for all LCs is given in Figure 7.7.

7.6.1 Hydrostatic loads

The hydrostatic load on the structure is caused by the static water pressure from both sides of the gates. When the gates are open, the water pressure solely acts on the piers, while when the gates are closed the water pressure also acts on the gates. When the gates are closed, the difference in water head on either sides of the structure results in a large static load from the side where the water level is higher.

For the hydrostatic loads, the situations with a closed gate are important. These are: LC1, LC2, LC5 and LC6. When the gates are open there is an equal water level on both sides of the structure, which results in a resultant hydrostatic force equal to 0 kN. LC3, LC4, LC7 and LC8 are therefore disregarded for hydrostatic loads. Furthermore, LC6 can be disregarded for the calculation of the hydrostatic loads since the water levels are not significant compared to LC2. A calculation for these different LCs is made in Appendix E.2.

7.6.2 Hydrodynamic loads

Besides hydrostatic loads, hydrodynamic loads can also exert forces on the structure. When the gates are closed, the wave loads from the sea act on the gates and piers. When the gates are opened, drag and inertia forces, caused by water flow, will act on the piers. The flow direction can change depending on the water height of the river and the sea. Lastly, it is important to note that for the calculation of the hydrodynamic loads, the maximum value of the quantity for location 1, 2 or 3 is considered. This is a conservative assumption. First, the scenario with closed gates, which results in wave loads. Note again, that the waves are only coming from the seaside. Therefore, the LCs where the gate is "closed" and where the "sea is high" will be critical, during the low and the high discharge season, which is the case for LC1 and LC5. For the calculation of the hydrodynamic loads, first the wave length has to be calculated. This is done with the linear wave theory because it gives a good approximation for wave propagation in coastal areas. For calculations of the wave length, refer to Appendix E.3. Wave forces on vertical structures consist mainly of two components. These are the incident wave, propagating towards the structure, and the reflected wave propagating towards the incoming wave (Holthuijsen, 2007). Linear waves are non-breaking waves (Voorendt, 2022). The force on a vertical wall for non-breaking waves can be determined using the pressure distribution in vertical direction, see Appendix E.3.

The scenarios with open gates will also be analysed for hydrodynamic loads. Water flow past the piers, results in drag and inertia forces. The critical situations will occur when the flow speeds are high, so basically when there is a high water level difference. The flow speed from the sea to the river will be the highest when the sea is at its highest during either high or low discharge season. Therefore LC3 and LC7 are analysed. For the flow speed from the river to the sea, the situation has to be analysed where the river is higher than the sea, which is during LC4 and LC8, of which LC4 during high discharge season is critical. Therefore LC8 will be left out of the further calculation.

In the situation that the gates are open, a constant flow of river discharge will pass the piers. The piers can be regarded as slender structures as their length will be much larger than their width. Therefore, the Morison equation for flow past slender structures is be used to determine the forces acting on the columns. For the calculation of the drag and inertia forces with the Morison equation for LC3, LC4, and LC7, see Appendix E.3. Wheeler stretching is added to account for the wave impact on the structure. Wheeler stretching extends the height over which the water impacts the structure to the top of the wave height.

7.6.3 Wind loads

The wind load on the structure follows a logarithmic curve. For preliminary design, the lower wind speed at still water level is neglected. The total wind speed is modelled as a constant pressure over the height. The wind dynamic pressure can be calculated with the following formula (Voorendt, 2022):

$$q = \frac{1}{2} \cdot \rho \cdot u^2 \cdot C_d \tag{1}$$

In which:

q = Wind dynamic pressure [kN/m^2]

ρ = Air density (1.250) [kg/m^3]

C_d = Drag coefficient for wind (0.7) [-]

u = Wind velocity [m/s]

The maximum wind speed during a tropical storm is 40 m/s, while the average wind speed is 19 m/s. The values for the other variables are given in the description. This results in a total wind dynamic pressure of 0.7 kN/m^2 for storm conditions and 0.02 kN/m^2 for the average conditions. These forces are relatively small and therefore only the load combinations with open gates are assumed to include wind loading, since the area of the gate when lifted is very large. Furthermore, the wind dynamic pressure is assumed to be 0.7 kN/m^2 for all load combinations, which is an conservative assumption.

The wind puts pressure on the part of the structure that is above the water level during a storm. Integrating the pressure over this area leads to the total force on the particular part of the structure, which is a simplification of the real situation. The wind setup in this case is equal to the storm surge that is caused by a typhoon. This storm surge level is equal to 2.2 m as found in Appendix B.5.

7.6.4 Soil loads

To determine the soil pressure on the structure, the different soil layers have to be determined. This can be achieved with a CPT. No CPT data near the Ham Luong River is available and therefore CPT data at Tien Giang province in the Go Cong Dong district near the river mouth of the Mekong is used. The cone resistance can be seen in Figure 7.6 and the resulting pressure can be seen in Table 7.6. The different ground layers have been determined with the CPT and borehole data of borehole LK01 which can be found in Appendix E.4. The CPT data is taken at a different site (near Vung Tau), but still close to the region. Therefore, it is still usable for the design. The site near Vung Tau is connected to a different river branch of the Mekong River which could result in a different CPT compared to the Ham Luong River. Especially for the layers close to the surface, since these layers are influenced by a combination of river discharge and longshore sediment transport.

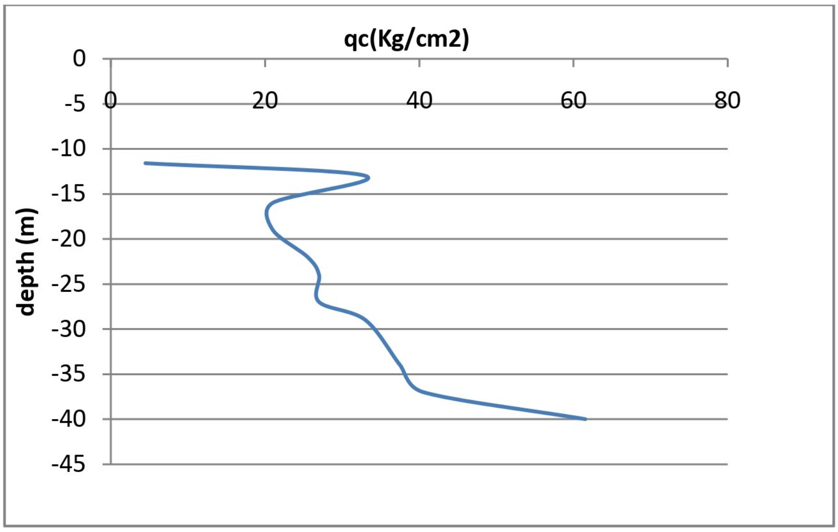


Figure 7.6: CPT at Vung Tau (Truong Hong, 2012)

Table 7.6: CPT results Vung Tau (Truong Hong, 2012)

Depth (m)	CPT	qc (kN/m^2)
-11.6	4.5	4500
-13	33	3300
-16	21	2100
-19	21	2100
-22	25.5	2550
-24	27	2700
-27	27	2700
-29	33	3300
-34	37.5	3750
-37	40.5	4050
-40	61.5	6150

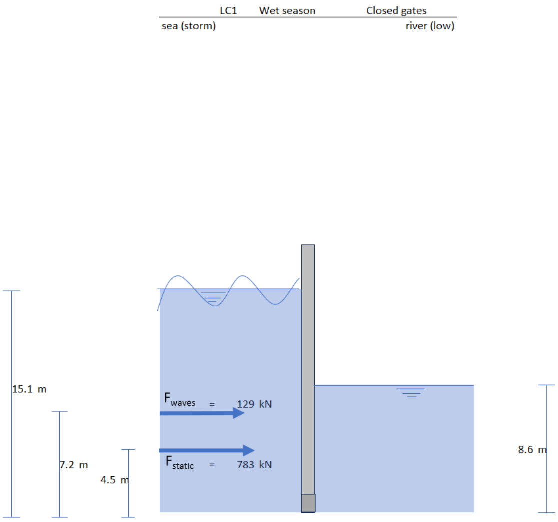
The soil consists of 5 layers. The top layer is a layer of fine grained sand. The second layer is a a sand layer with a medium particle size. Layer three is a stiff clay layer. Layer four is a sand layer which is characterised by its medium tight state, an layer five is a medium to course sand layer (Truong Hong Son, 2012).

Table 7.7: Soil distribution based on CPT data

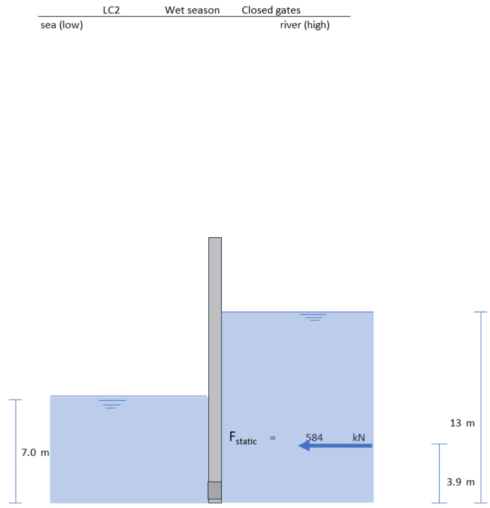
Depth [m]	Soil type
-11.6 to -13.6	Fine sand
-13.6 to -22.6	Medium sand
-22.6 to -25.6	Stiff clay
-25.6 to -40.6	Medium tight sand
-40 and lower	Medium to course sand

7.6.5 Load schemes

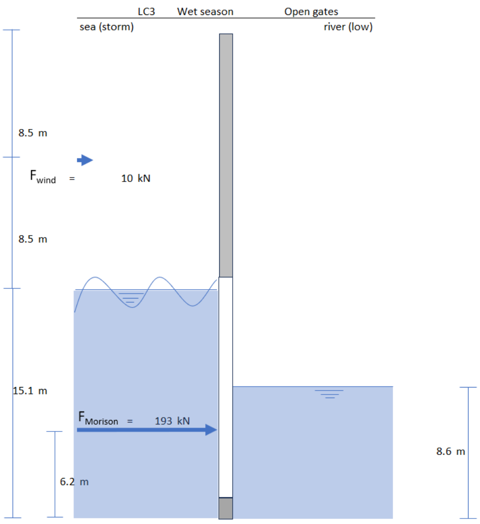
Figure 7.7 gives a visual overview of all the LCs. LC6 and LC8 are left out because they are definitely not critical for any situation as explained in Section 7.6.1 and Section 7.6.2. In the figure, the closed gates are visible in grey and if the gate is open, the opening is drawn as a white rectangle. The hydrodynamic, -static, and wind loading are translated to a point load at the centre of gravity of the original distributed load. Additionally, the water levels are visible and also whether a storm is present, which is schematized by a wave.



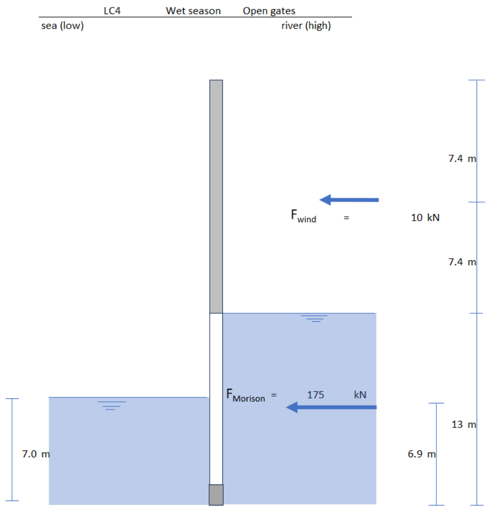
(a) LC1



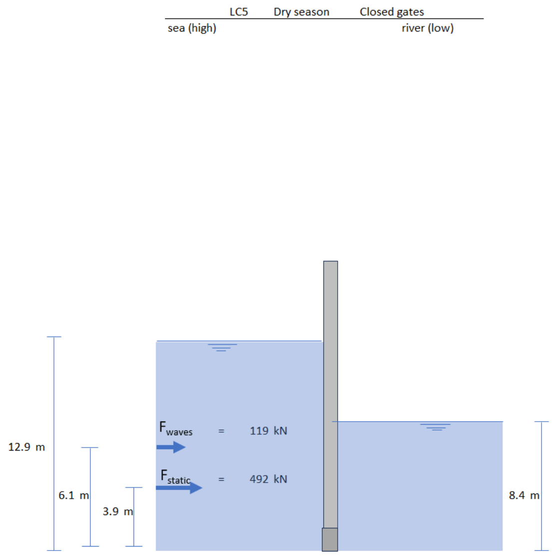
(b) LC2



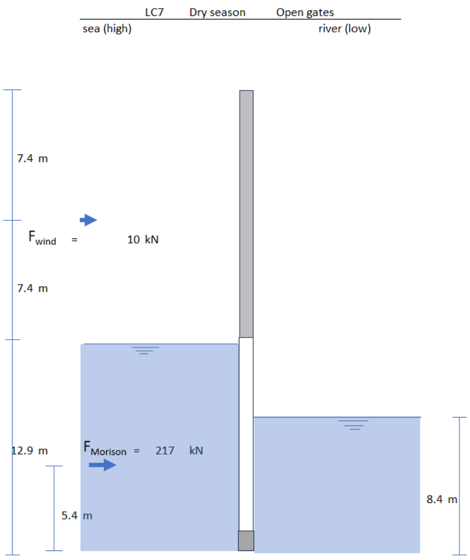
(c) LC3



(d) LC4



(e) LC5



(f) LC7

Figure 7.7: Complete load schemes for all critical LCs

7.7 Structural design

In this subsection a preliminary design of the storm surge barrier in the Ham Luong estuary is made. The preliminary design includes the design of the gates, sill, lifting structure, piers, foundation, and bed protection.

7.7.1 Gates

The gates will be placed between two piers with equal distances. The dimensions of the gate are very important. A larger gate size leads to less costs in construction and also a larger flow area for the release of river discharge during the high discharge season. However, the larger the gates the more difficult it is to lift them out of the water because of their weight. The height of the gates depends on the water height it has to withstand. The maximum water column consists of the depth, RSLR, Highest Astronomical Tide (HAT), spring tide, and maximum wave height. The height of the sill at the bottom is 1.5 m which reduces the height of the gate. The total gate height will therefore be 14.7 m.

There is a linear relationship between the opening size of the gates and the flow during mean tide for different storm surge barriers (Mooyaart & Jonkman, 2017). For this design, the mean discharge in the high discharge season is taken instead of the flow during mean tide. The mean discharge in the high discharge season is 4000 m^3/s as visible in Figure B.3. Using the graph in Appendix E.5, showing the relationship between opening size and peak tidal flow during mean tide, the total opening area must be approximately $A_{opening}$ = 10,000 m^2. With a mean depth of 10 m, the total width of all openings must be 1000 m. With piers of 4 m in width each, this results in 23 gates of 40 m. A width of 40 m is chosen for the gates because it approximates the width of a similar storm surge barrier in the area called the Cai Lon barrier, see Section 7.2.1.

Since the gates will be very large, a 3D truss will be made behind each skin plate for support. A similar truss has been constructed for the Hartelkering (Figure 7.5a) and the Cai Lon barrier. The truss consists of three large lens-shaped frames that support the vertical girders and the gate plate facing the river mouth. The steel frame of the Hartelkering with two lens-shaped frames is visible in Figure 7.8.

Figure 7.8: The design of the gate of the Hartelkering (Voorendt, 2014)

The gates rest on a sill, which is a concrete barrier wall that rests on the river bed and is supported by a pile foundation. The gates are lifted into or out of position with a cable system. Therefore tracks are built into the piers on both sides of the gate with wheels in them to easily let the gates slide.

The three lens-shaped structures are formed such that they will withstand the total momentum caused by the combined hydrostatic- and dynamic loads. These are visualised in Appendix E.6. The total combined force is assumed to be evenly distributed over the number of lens-shaped frames. In case of an open gate during maximum wind speed, the load on the gate should also be significant. A quick calculation with the wind load from Section 7.6.3, gives the distributed force of the wind on the gates. It turns out that the maximum wind pressure is about the same as the maximum water pressure. Due to the fact that the gates will probably be closed during maximum wind speed, and that an extreme value is taken for the maximum wind speed, the calculation of the frame will be continued with the maximum water level.

The loads on the gate are the largest for LC1. The forces act over the total width of the structure resulting in a line load on the gate frame. The maximum momentum is easily calculated with a forget-me-not for a simply supported beam and with load combination factors for static and dynamic loads as explained in Appendix E.7. These loads are again schematised in Section 7.6.5. To transfer the forces from the plate to the arcs, girders and beams have to be placed behind the gate that form a frame connected to the arcs. The chosen properties of the arc beams and the girders connecting these are shown in Table 7.8. Furthermore, an E-modulus of 210,000 N/mm^2 is used and a steel quality S235 is considered in the calculations.

Table 7.8: Properties of arc and girder beams

Beam type	**Outer diameter (m)**	**Thickness (mm)**	**Moment of inertia** (mm^4)	**Area** (mm^2)
Arc Beam	1.4	35	3.40×10^{10}	3.04×10^5
Girder Beam	0.8	25	4.57×10^9	124×10^5

The structure can be seen in Figure 7.9, visualised with MatrixFrame. The internal arm between the two arcs in the middle has a length of 6.8 m. There are 9 girders connecting the two arcs for stability that reduce in length when moving to the sides of the frame.

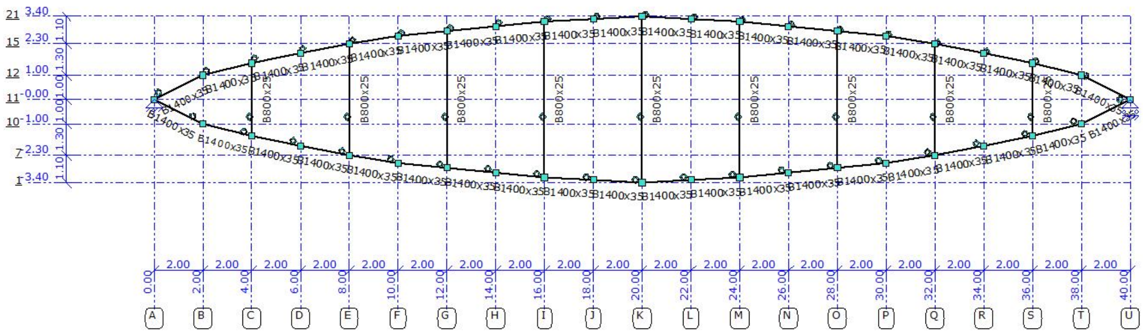


Figure 7.9: Top view of steel frame structure of the gate, showing the two arcs and nine horizontal girders.

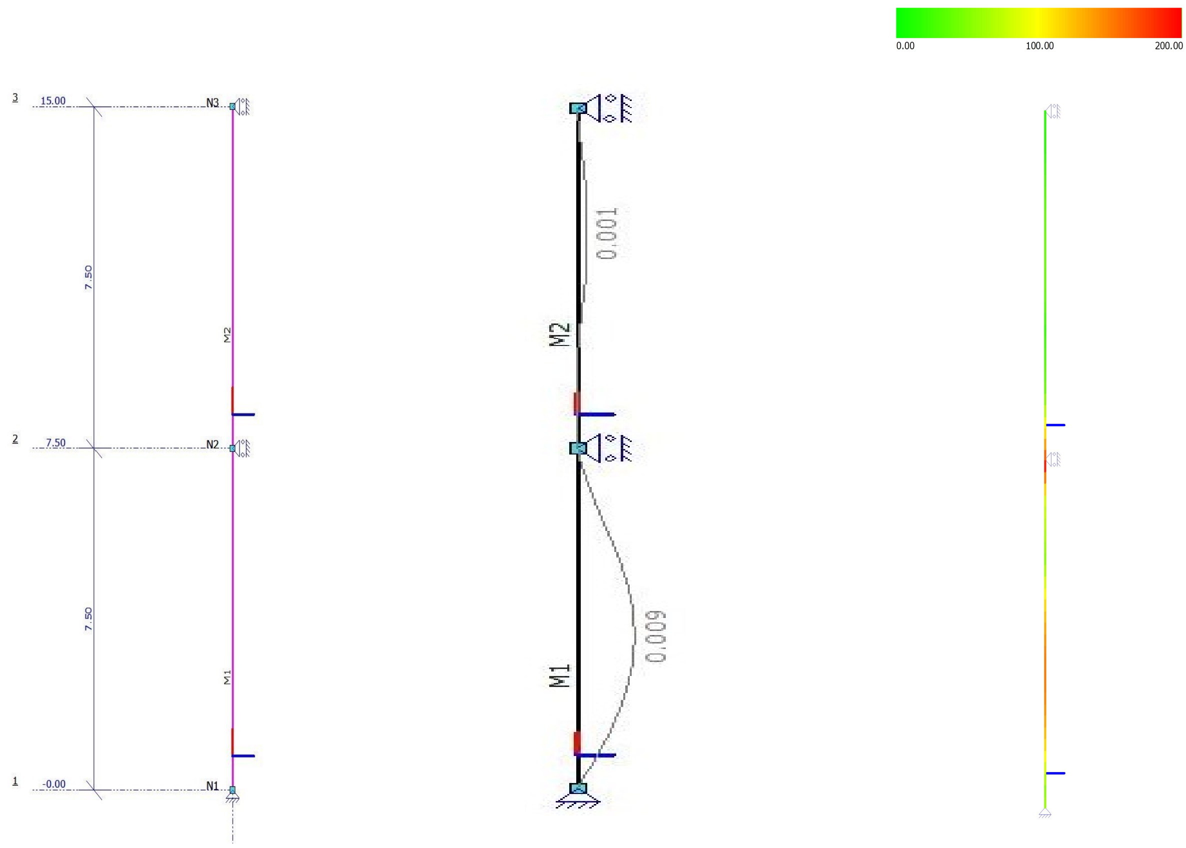
To calculate the stresses in the frame, the loads acting on top of the structure, the seaside, are given as input in MatrixFrame. The hydrostatic load is regarded as a permanent load and the hydrodynamic load is regarded as a variable load. The schematisation can be seen in Appendix E.8, in addition to the results for the stresses and the deflection of the structure calculated in MatrixFrame. The structure is strong enough to withstand the forces, since the total stress in the members is lower than the yield stress of S235. The Unity Check (UC) is $\frac{180}{235} = 0.77$. It can be seen that the total deflection in the middle is about 34 mm. This is a deflection of less than $\frac{1}{1000}$L.

The horizontal beams connecting the two arcs are checked individually on their resistance to buckling. For this calculation the formula for Euler buckling is used, see Appendix E.9. Because the cross-section is the same in both directions, only one direction has to be checked for this calculation. All girders have different loads but since the structure is symmetric only the first five girders have to be analysed. Girder 1 is the smallest located at the end of the truss and girder 5 is the middle one, which is the largest. The results for the buckling load of the girders are visualised in Table 7.9. The normal force caused by the loads is checked with the critical load for buckling, resulting in a unity check. All girders meet the requirements very easily with UCs << 1.

Table 7.9: Girder buckling check

Girder	L_b **(mm)**	P_{cr} **(kN)**	N **(kN)**	**UC**
1	3000	1.05×10^6	749	0.0007
2	4600	4.48×10^5	785	0.0018
3	5600	3.02×10^5	780	0.0026
4	6400	2.31×10^5	759	0.0033
5	6800	2.05×10^5	726	0.0035

The vertical girders that connect the frames to the gate plate have been checked in a similar way. The specific geometry can be seen in Figure 7.10a. The supports are the locations where the frame is connected to the vertical girders. The distance between girder centres is 4.0 m, as visible in Figure 7.9. The loads acting on the plate are distributed to the girders, following the distribution of hydrostatic and hydrodynamic loading acting on that plate, which can be seen in detail in Appendix E.6. This loading is multiplied with the centre to centre distance between the girders to calculate the distributed loads that can be seen in Appendix E.10. Both loads are multiplied with their corresponding safety factors to obtain the results. The resulting stresses and displacements are visualised in Figure 7.10b and Figure 7.10c. It can be seen that the stresses do not exert the maximum stress for S235. The UC is $\frac{200}{235} = 0.85$. The deflections are at maximum only 9 mm for a length of a single beam of 7.5 m. This is less than $\frac{1}{800}$L.



(a) Geometry vertical girder **(b)** Deflections vertical girder **(c)** Stresses vertical girder

Figure 7.10: Vertical girder geometry, deflection and stresses

The most common skin-plate thickness for large hydraulic structures is 12 or 14 mm (Daniel & Paulus, 2019). Therefore, an initial thickness of 14 mm is chosen. This is a thin steel plate and, in order to support this plate, stiffeners that will redirect the forces to the vertical girders must be added to the construction.

7.7.2 Sill

The width of the sill should not be less than the width of the gate, which is 6.8 m. Consequently, a width of 7 m is chosen for the sill. The height is based on a simple design rule which results in a sill height of $\frac{1}{25}\text{L} = \frac{1}{25}(40) = 1.6$ m (Tromp, 2013). For simplicity, a sill height of 1.5 m is chosen.

7.7.3 Lifting structure

On top of the pier, there is a lifting structure designed to lift the gate, allowing the maximum river water level to flow beneath it. This maximum river water level is 10 m, with an additional 3 m during high discharge, as indicated in Appendix E.2. This results in a lifting structure height of 13 m. The total height from the riverbed to the top of the lifting structure is therefore 16.2 m (pier) plus 13 m (lifting structure) = 29.2 m. See Appendix E.11 for the visualisation. The lifting barrier is made from reinforced concrete and it is assumed that it is square-shaped. The width and length will be the same as the width of the pier, which will be given in Section 7.7.4.

The height of the lifting structure is designed for the maximum river water level. During a failure of closure of the gate during a storm (LC3), the water level and waves would reach the bottom of the gate which would cause an extra force. This will not be significant compared to the other loads. This is better explained in Appendix E.12.

7.7.4 Piers

The pier is made out of reinforced concrete and distributes the forces from the gate to the foundation and soil. It has to resist the loads resulting from the sea and river and is an important part of the design of a storm surge barrier. The width of the pier is assumed to be 4 m, which is approximately the same width as the piers of the Cai Lon - Cai Be sluice. The pier should have a height equal to the gate height, which is 14.7 m as stated in Section 7.7.1, plus the sill height of 1.5 m. This results in a pier height of 16.2 m.

The length of the pier should be sufficient enough to have the required rotational stability. Furthermore, the length of the pier also has an influence on the sliding resistance and force distribution to the soil. The rotational stability will be calculated for LC1, in which the bending moment and horizontal force are the largest. The load combination factors, which are explained in Appendix E.7, are used in these calculations. The static loads are permanent loads and the hydrodynamic and wind loads as variable. The moments and horizontal forces resulting from the external loads are visible in Appendix E.13. The moments resulting from the internal forces (self-weight) are visible in Appendix E.11 The first estimation for the pier length is 14 m and will be verified in the following calculations.

To prevent rotation of the pier around its corners a calculation was done. The dimensions and forces for the design of the storm surge barrier are schematised in Appendix E.11. To calculate the moment resulting from the weight of the gate, the gate was chosen to be located close to the seaside between the piers. This is due to the fact that during conversations with SIWRP there was a possibility that a coastal highway would be included in the design of a potential storm surge barrier, as stated in Appendix F.1. It could also be more efficient to resist the large external forces from the sea. It is important to note that the barrier will be less efficient in resisting the forces coming from the riverside. Therefore, the maximum LC for the opposite direction should also be taken into account, which is LC2 as indicated in the table in Appendix E.13. The calculations show that the maximum bending moment from external hydrostatic and hydrodynamic loads at two points for the extreme LCs is sufficiently resisted by the self-weight of the structure. The values can be found in Appendix E.13. The distance from the middle of the lifting structure to the end of the pier (at the seaside) is chosen to be 4 m. Appendix E.14 shows the location of the lifting structure with a top view of the barrier.

To resist the sliding of the barrier, the horizontal stability is analysed. The maximum external horizontal force takes place during LC1 with a horizontal force of 55 MN as visible in Appendix E.13. By multiplying the friction coefficient with the sum of all vertical forces, the resistance against sliding is calculated, which should more than the acting external forces. The formula that is used is Equation (2):

$$\sum H < f \cdot \sum V \tag{2}$$

In which:

$\sum H$ = Sum of horizontal forces

f = Friction coefficient

$\sum V$ = Sum of vertical forces

The total sum of the vertical forces from all elements, shown in Appendix E.11, including the gate and sill, is 33 MN. The friction coefficient for clean fine to medium sand is equal to 0.45 to 0.55. Therefore, a conservative value of 0.45 is chosen for the friction coefficient. The resistance against sliding is consequently 15 MN which is less than the acting external horizontal sum of forces, equal to 55 MN. This means that the foundation should be designed for the resultant force of 40 MN to make sure that the structure will not start sliding.

7.7.5 Foundation

Both the sill beams and the piers will transmit the external forces to the pile foundation. The structure will have a pile foundation that rests on the strong sand layer located at MSL -25.6 m, see Section 7.6.4. The upper soil layers are not strong enough to support the structure. This makes the piles approximately 15.6 m long, but the length of individual piles vary depending on the location. The piles will be made out of concrete because steel foundation piles can corrode in wet conditions. Prefabricated piles are used because it is better for the ease of construction.

Horizontal and vertical loads will have to be transmitted resulting in vertical and horizontal loads on the piles. These loads are caused by the self-weight of the structure and the resulting horizontal load from hydrodynamic and -static loading. These loads have the effect that the structure might slide or rotate as mentioned in Section 7.7.4, which is why the foundation is extremely necessary. Piles that can take horizontal forces are driven under an angle to the vertical and are called 'raking piles' or 'batter piles' (Voorendt, 2022). The piles must be able to withstand horizontal forces in both directions the river can flow. An example of an embankment with batter piles is shown in Figure 7.11. If necessary, the batter piles could also be installed at multiple locations.

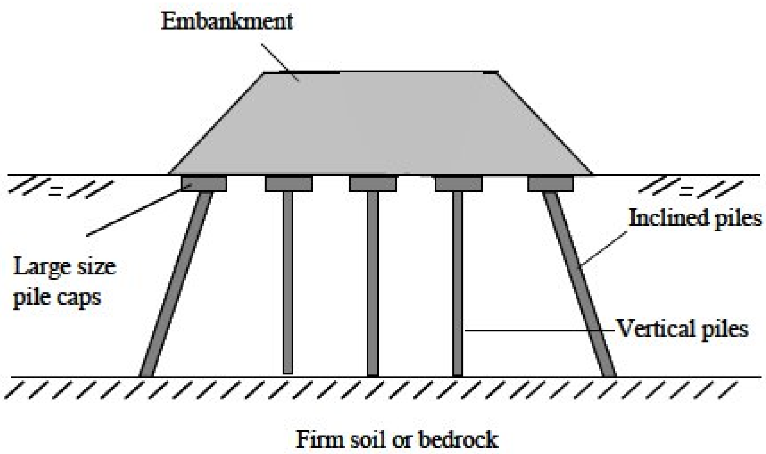


Figure 7.11: Piled embankment with batter piles, indicated as 'inclined piles' (Sakleshpur & Madhav, 2013).

7.7.6 Bed protection

When building a structure in a river, scour can occur because of a change in water flow. This can lead to a dislocation of soil layers on the river bed near the structure, which can cause instability of the structure (Voorendt, 2022). When scour is severe, bed protection can be used to protect the river bed from scour.

There are two types of scour that can occur at the storm surge barrier; one is scour due to flow acceleration through the open gates, and the other is scour induced by waves on the closed structure. Calculations regarding both types of scour, and the related bed protection are described in Appendix E.15. A more detailed analysis on bed protection would be needed when including the occurring flow speeds during operation of the barrier. In the time span where the vertical lift gates are lowered towards the sill, significantly higher flow speeds are expected underneath the gate on the sill. This bed protection is expected to be decisive for the area in near proximity of the gates. However, due to lack of information on the exact behaviour during operation, this bed protection is not included in this analysis.

To prevent scour near the structure, a total length of 850 m of scour protection into both flow directions is needed. The upper layer of this scour protection should consist of the grading LM_A 40-200, which has a D_{n50} of 34 cm. This grading prevents any movement of the bed protection. No calculations on the filter layers below the top layer are made, but simple filter stability calculations would lead to a sufficient design.

The expected scour depth as a result of wave action is very small, and one can assume that the designed bed protection to prevent clear-water scour is sufficient to prevent wave-induced scour.

7.8 Operation

The main function of the structure is that it must be closed in case of low discharges from the Ham Luong River and during storm surges, which can occur during both low and high discharges. The goal of the structure is to prevent saltwater intrusion and flooding from the sea while retaining fresh water in the estuary. The storm surge barriers' secondary functions are to open during high river discharges to let the river water flow into the ocean. This can be problematic in the case that there is high discharge from the river and a tropical storm at sea. The water from the sea can be stopped from entering the land but the river will still have a large discharge towards the sea. Because a storm usually occurs over the course of 1 to multiple days this will not cause a large problem. The river will probably not overflow the dykes in this time span. It is advised that when a barrier is built extra research into this situation is performed.

In the case of the opening or closing of the barrier, all of the gates will operate simultaneously. There is no need for very large ships to pass the barrier. The smaller ships can travel to other branches of the Mekong River to reach their destination. When the gates are put into action the sluices along the river will have to be closed as well to prevent the water travelling a different way. This must be coordinated precisely. If future research shows that a navigability option is required, a sluice could be constructed. Therefore the sluice and abutment are also depicted in Appendix E.14 with unknown dimensions.

It is difficult to say something about the effects of the barrier on water levels and salinity in the other river branches. Operation with structures that might be built in the future in other river branches is therefore not considered in this report.

8 Impact Evaluation

In this section the different alternatives will be evaluated on a set of criteria. Alternative 1 is a barrier at location 1, Alternative 2 is a barrier at location 2, Alternative 3 is a barrier at location 3 and Alternative 4 is no barrier but the dykes along the river are heightened to 7.8 m. For Alternatives 1, 2, and 3 the dykes between the barrier and the river mouth are heightened to 7.8 m and the other dykes behind the barrier are heightened to 4.0 m,as described in Section 7.1. The alternatives will be assessed on the criteria of freshwater supply, agricultural and aquaculture adaptation, biodiversity, stable riverbanks and navigability.

All alternatives will obtain a total score for all the criteria combined. Additionally, the alternatives will be assessed on costs, which is not one of the criteria in the criteria set but an independent factor. After these assessments, the preferred solution for the Ham Luong estuary will be selected.

8.1 Criteria assessment

This section describes how each criterion is evaluated. Criteria are assessed using a rating system ranging from 1 (the worst score, represented as "- - -") to 7 (the best score, indicated as "+++"). This score is relative to the situation now in the Ham Luong estuary. This means if a alternative has a ranking of "+++" it has the best possible scenario relative to the present. As mentioned in Section 4.1, "flood safety" is not considered as a criteria in this assessment but as a design requirement of the flood protection systems.

8.1.1 Freshwater supply

This criterion assesses the effectiveness of the different alternatives in retaining fresh water in the Ham Luong estuary. As mentioned in the introduction of Section 6.1, the scope of the project hinders the possibility to evaluate the salinity levels upstream of the closed barriers with the Delft3D model. For this reason, the salinity levels upstream of the barriers cannot be compared to the salinity levels downstream of the barrier, and no conclusion can be drawn on the effectiveness of blocking the saltwater intrusion with a river barrier based on the results of Delft3D. Hence, the evaluation of this criterion is based on a qualitative assessment. From theory and reference projects, it is generally understood that when a barrier is closed it retains fresh water upstream. The further a barrier is located to the sea, the more volume of fresh water can be retained upstream of the barrier. As this is more beneficial for the freshwater supply, Alternative 1 is awarded a +++, Alternative 2 ranks ++ and Alternative 3 receives a +. Alternative 4, as no intervention is placed in this system, is not able to retain any fresh water and therefore scores - - -.

8.1.2 Agricultural and aquaculture adaptation

The type of agricultural or aquaculture product that is cultivated in an area in the Ham Luong estuary is highly dependent on the salinity of the water at that location. In assessing the impact of the different closure alternatives on salt-intrusion, and thus on the types of agri- or aquaculture, there are three aspects which should be taken into account. The first is the time a farmer has to adapt to the new circumstances created by the alternative, the so-called "adaptation time". In case the Ham Luong estuary is closed off with a barrier, the system experiences a significant and relatively abrupt change, which prompts farmers to adjust their businesses in a short period of time. Whereas no intervention in the system will give climate change the free hand, and the estuary (and thus the farmers) will undergo gradual changes. The second aspect to bear in mind, is the profit a farmer makes per agri- or aquaculture type. Section 3.4.1 mentions the incomes of farmers per agri- and aquaculture type per hectare; shrimp: 45 million VND/ha, coconut: 70 million VND/ha, rice: 16 million VND/ha. Last but not least, the size of the agricultural or aquaculture area that is impacted by the changes in salinity also plays an important role. It is important to note that when a farmer would change to a different type of product, the investment cost, the complexity of the crop, the amount of new knowledge that is needed to cultivate a different product, and the risks involved in changing to a new business are usually considered negative. Therefore, the larger the area that needs to adapt to a new agricultural or aquaculture product, the more resistance can be expected on account of the aforementioned terms.

Besides these three important aspects, it should also be kept in mind that it is very difficult to predict exactly how the agricultural or aquaculture land use will change due to salt-intrusion. This is also highly dependent on the willingness of people to switch to a different product, which is something that is hard to predict. In order to be able to make an assessment, a number of assumptions have been made, which are stated in the list below. However, it should be kept in mind that changing these assumptions can possibly lead to a different outcome.

These assumptions are:

- A larger 'adaptation time' is considered more favourable compared to a shorter period of time in which farmers have to adapt.
- According to Appendix B.9, shrimp can be produced between salinity levels of 18 ppt and 24 ppt, coconut can be produced if the salinity level is ≥ 4 ppt, and rice can be produced if the salinity level is ≤ 4 ppt.
- If an area is not subject to changes in salinity levels, the type of agri- or aquaculture will not change.
- Whenever an area is subject to increased salinity values at which the current crops are no longer able to grow, the area will switch to coconut farms as this will lead to the highest profit for the farmer.
- The income per product remains constant over time.
- As mentioned in Section 5.5.3, the Delft3D model was not able to predict the exact salinity concentrations and salt-intrusion lengths. Instead, in this assessment the salt-intrusion length and concentration were used that was present in the Ham Luong estuary in 2020, as can be seen in Figure 3.1.
- The barrier will be closed for 2 months in 2100 and the salinity levels in the Ham Luong River can be observed in Figure 6.5. It is important to note that these salinity levels in the Ham Luong River are underestimated.

These assumptions were combined with the outcomes of the Delft3D model and have been translated to aerial maps which are depicted in Figure 8.1. According to Delft3D, the salinity levels at the seaside will be too high for shrimp farms if the Ham Luong estuary were to be closed off. Therefore, in case of closure, the shrimp farms near the coast will be replaced by coconut farms. In Alternative 4, fresh water still flows through the river in the dry season and the salt level will be less extreme at the seaside. For this reason it is expected that shrimp farms will remain at their original location. Estimating the other agricultural and aquaculture land use is difficult, but it can be expected that the salinity levels for rice will be too high and existing rice paddies will change to coconut farms. Agricultural land more inland of Ben Tre will probably be a mixture of fruit and coconut.

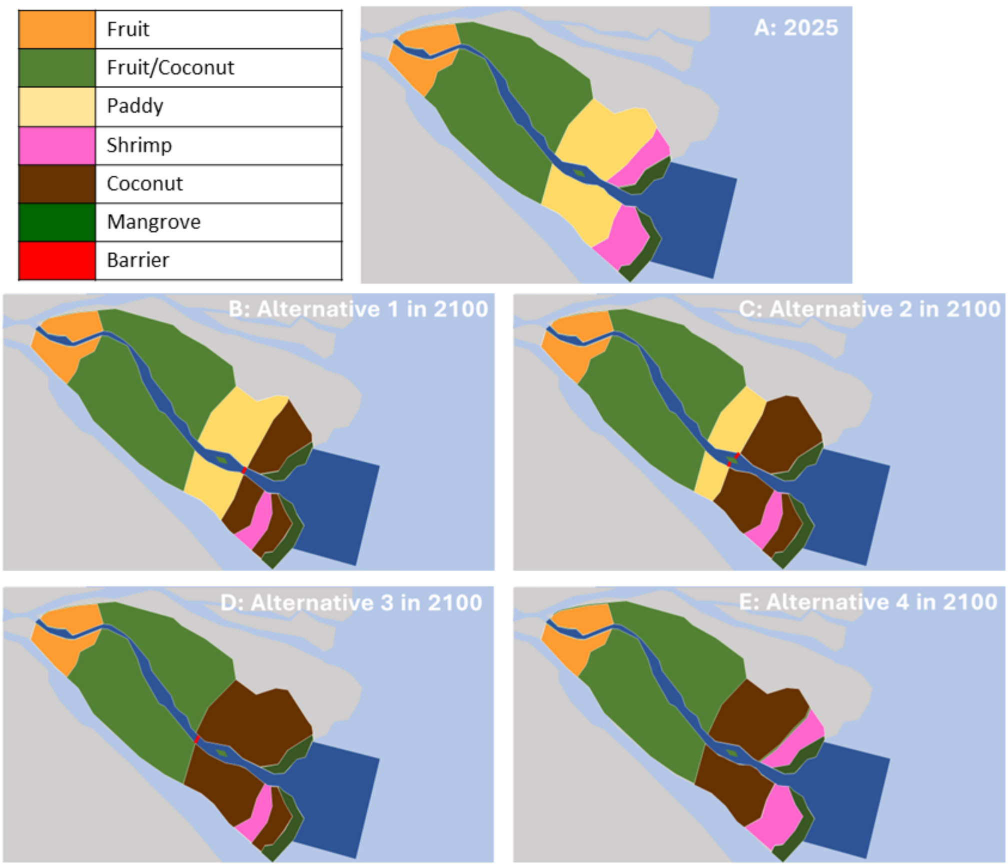


Figure 8.1: Rough visualisation of the distribution of agricultural and aquaculture land use in 2025 and the expected land use in 2100 for the alternatives.

In Table 8.1 an overview of each aspect is visible. It should be mentioned that this is a rough estimation. The area size and income are estimated with Figure 8.1. In each alternative some area should adapt to the changing salinity levels. Alternative 3 has the biggest area that should adapt. Relative to this area Alternative 4 has a slightly smaller adaptation area, while Alternative 1 and 2 have the smallest adaptation area. Each alternative has a higher estimated income than the current situation, due to a higher coconut area. Alternative 3 has the highest coconut area and thus the relative highest income. Alternative 4 has a somewhat lower income than Alternative 3 and Alternative 1 and 2 have the lowest relative income.

Table 8.1: Impact evaluation agricultural adaptation

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative 4**
Adaptation time	Short adaptation time	Short adaptation time	Short adaptation time	Long adaptation time
Area size	Small area	Small area	Large area	Intermediate size area
Income	Relatively low income	Relatively low income	Large income	Intermediate income

Examining Table 8.1, it becomes challenging to distinguish between the alternatives based solely on adaptation area and income. Alternatives 1 and 2 offer a smaller adaptation area, which has its advantages, but this is offset by lower income. Conversely, alternatives 3 and 4 require a larger adaptation area and result in higher income. Nevertheless, a clear differentiation becomes evident when considering the adaptation time; Alternatives 1, 2, and 3 having notably shorter adaptation periods compared to Alternative 4. For this reason Alternative 1, 2 and 3 will get a score of + and Alternative 4 a score of ++. Every alternative has a higher net income than the current situation, and this fact contributes to assigning a positive score to each of the alternatives.

8.1.3 Biodiversity

As mentioned in Section 3.3.4, the Ham Luong estuary is home to a significant population of fish that migrate through the channel. The species rely on the mixture of fresh, salt, and brackish water. The installation of a barrier would make it more challenging for fish to migrate through the channel. Also, most fish have migration cues, triggered by variation in water level or discharge. This principle, which was explained in Section 3.3.4, is also threatened in the case of a barrier.

Furthermore, installing a barrier would split the salt and fresh water when it is closed, reducing the mixture of fresh, salt, and brackish water. As mentioned in Section 3.3.4, mangroves also require a combination of fresh and salt water to thrive. If the barrier is placed further inland, there is a greater length of river over which this mixing can occur. Therefore, an inland closure is preferable to one near the sea. Furthermore, blocking the river with a closure might trap more pollutants and decrease the river flow. This results in a more polluted river and thereby reducing biodiversity.

Another process that threatens biodiversity is sedimentation. As stated in Section 7.2.2, the sedimentation near the Ba Lai sluice had negative impact on the biodiversity. Therefore, the outcomes of the sedimentation tool, as described in Section 6.2, are used to assess the effect of biodiversity. When a barrier in the Ham Luong estuary is closed for multiple days, the mud concentration at the seaside of the barrier increases most for Alternative 1, which is shown in Figure 6.8. Increase in mud concentration can affect the ecology of the estuary in different ways:

- The light penetration reduces, which limits photosynthesis.
- Water quality reduces, because mud can contain heavy metals and pollutants.
- Available food for filter-feeding species increases.
- Species could adapt or new species that are adapted to handle this change in sediment concentration could settle in this area.

Assuming that the closure of a barrier would not last longer than a few consecutive months, the adaptation and change of species does not outweigh the reduction of light penetration and water quality. This, combined with the effect on fish migration and mangrove growth, means that Alternatives 1, 2, and 3 all exhibit adverse effects on biodiversity relative to the 2025 situation, resulting in scores of - - . Alternative 4 receives a score of 0 since it entails no interventions that either positively or negatively affect biodiversity in the Ham Luong estuary. There are possibilities to act to increase biodiversity and help nature recover from current pollution, such as implementing Building with Nature (BwN) solutions. These are not taken into account in this alternative, which is why it is given a rating of 0.

8.1.4 Stable riverbanks

In the province of Ben Tre, the different agricultural and aquaculture activities and several residential areas are located close to the riverbanks. Erosion of the riverbanks can lead to damage to structures or agricultural land, and can consequently lead to the forced resettlement of inhabitants. As stated in Section 4.1, this criterion does not include erosion near the barrier itself, as the stability near the barrier is considered as a technical requirement, which will be fulfilled by adequate bed protection. This is discussed in Section 7.7.6.

In assessing the stability of the river banks, two sources of information will be used: Delft3D results and literature theories. The sedimentation/erosion rates from the Delft3D model indicate short-term effects only, during the simulated 5 months. From Figure 6.6 and Figure 6.7 in Section 6.1.4 it follows that the only difference in erosion or sedimentation rates between the four alternatives is observed in the direct proximity of the barrier locations. These rates are the result of local acceleration and deceleration of flow. These direct impact of the erosion rates can be counteracted by bed protection. When assessing the criterion of stable riverbanks, impact is defined to be negative if the banks show erosive behaviour on any location. Therefore, based on the short-term results of the Delft3D model, it can be concluded that all alternatives show negative effects on the stability of the riverbanks and no distinction can be made between the four alternatives.

Theoretical knowledge and literature on the effect of river barriers on downstream erosion rates include long-term effects. In the analysis of the impact of storm surge barriers on sedimentation processes, it has been found that the presence of a storm surge barrier leads to erosion of the tidal flats in an estuary, which are also present in the Ham Luong estuary. An example of those tidal flats can be seen in Figure 8.2. This was found in a research on the Western and Eastern Scheldt in the Netherlands (de Vet, van Prooijen, & Wang, 2017), as well as a research on the Haringvliet in the Netherlands (De Ronde, 1990). In order to illustrate the relevance of these findings for the Ham Luong estuary, the expected changes of a barrier on the estuary will be explained. First of all, as stated in Section 3, the Ham Luong estuary can be described as a tide- and wave-dominated estuary. The morphology of tide-dominated estuaries are expected to depend strongly on the tidal behaviour within the estuary (Bosboom & Stive, 2023). As stated in Coastal Dynamics by Bosboom and Stive (2023), the long-term morphodynamic responses on changes in estuary equilibrium can be described by empirical relations. These empirical relations link the tidal prism to the volume of the tidal channels. It is generally known that the construction of a storm surge barrier in a tidal inlet, such as the Ham Luong estuary, will reduce the tidal energy, and therefore reduce the tidal prism of an estuary (de Vet et al., 2017). As the Ham Luong estuary is tide- and wave-dominated, this change in tidal energy is expected to lead to morphodynamic changes. A reduction in tidal prism leads to a reduction of the needed tidal channel volume. As a response, the tidal channels are filled by sediment to reach the new equilibrium channel volume. This new sediment need of the tidal channels leads to less sediment transport to the tidal flats, and therefore erosion of the tidal flats. In the context of the above described theory, one should bear in mind that the river discharge and the corresponding sediment supply by the river is not included in this theory. However, as this river sediment supply is identical for all alternatives, it is not expected to affect the mutual differences in erosion patterns of the tidal flats. The above described theory can not be used to describe any difference in erosion between the three different possible locations of the barrier. However, it can be concluded that the alternative of no barrier will lead to less erosion of tidal banks, as no change in tidal prism occurs.

Considering all the erosion causes mentioned previously, there is no clear distinction among the three proposed barrier locations. However, Alternative 4 is expected to have the least impact on erosion rates, mainly because there are no substantial interventions in the estuary that would alter erosion rates. Consequently, Alternative 4 is assigned a score of 0, while Alternatives 1, 2, and 3 receive a score of -.

Figure 8.2: Tidal flats along the Ham Luong estuary. The photo was taken at Ben do An Hoa Tay

8.1.5 Navigability

Navigability is a criterion that is important for people that make use of the Ham Luong River for shipping. As mentioned in Section 3.4.7, there are fishing boats and tourist boats at small ports and near Ben Tre, in addition to local boats in the side channels. A barrier would possibly obstruct the passing of these boats. If the barrier were built close to the river mouth, sea fishing boats would be forced to go through the barrier which might only be possible under certain weather and flow conditions. A sluice would have to be added to let boats pass through.

The city of Ben Tre is very far from any of the barrier locations. It is a 2-hour boat tour from Ben Tre City to location 3. Tourist boats do not travel that far. Therefore, the placement of the barriers will not have a significant effect on the tourist boats. The boats that are located in the side channels are used for these channels mainly. The fishing boats located in An Thuy Port are therefore the most important stakeholders. For these boats, no river barrier would mean no effect on the navigability compared to the situation of 2025 and therefore this alternative receives a score of 0. A barrier closer to the river mouth would influence the boats more in a negative way. Therefore location 1 will get a score of - - - , location 2 a score of - -, and location 3 a score of -.

8.1.6 Overview criteria assessment

In Table 8.2 all scores mentioned above are summarised.

Table 8.2: Alternatives evaluation

Criterion	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Freshwater supply	+++	++	+	- - -
Agricultural adaptation	+	+	+	++
Biodiversity	- -	- -	- -	0
Stable river banks	-	-	-	0
Navigability	- - -	- -	-	0

8.2 Criteria performance of the alternatives

In this section, all criteria are given a weight corresponding to their importance. The importance of each criterion is evaluated based on the system description (Section 3), the field trip (Appendix A), meetings with experts in Ho Chi Minh City (HCMC) (Appendix F), and the survey (Appendix G). The weight determination is shown in Table 8.3. If a criterion is regarded more important than another one, the value of 1 is assigned to the important one and the value 0 to the less important one. If criteria are equally important they both receive a rating of 1. In this way all of the criteria will obtain scores which are eventually summed up. When a criterion receives a total value of 0 it eventually is assigned a value of 1 make sure that it is not let out of consideration in further assessment, and all other criteria are doubled. To obtain the weight for each criterion the doubled totals are summed together. The score of each criterion, divided by the total score and multiplied with 100, results in the weights.

Table 8.3: Weight determination of the criteria

Criterion	**a**	**b**	**c**	**d**	**e**	**Summed total**	**Doubled total**	**Weight**
Freshwater supply (a)	x	1	1	1	1	4	8	35
Agricultural and aquaculture adaptation (b)	1	x	1	1	1	4	8	35
Biodiversity (c)	0	0	x	1	1	2	4	17
Stable river banks (d)	0	0	0	x	1	1	2	9
Navigability (e)	0	0	0	0	x	0	1	4

The criterion of freshwater supply is the most important one because the shortage of fresh water is regarded as the highest risk to the people in the area. It is a primary need for everyone. Agricultural and aquaculture adaptation is just as important as freshwater supply. This is because agriculture and aquaculture is by far the most important occupation in the area. Biodiversity is important for both the people and the environment but is less crucial than freshwater supply and agricultural adaptation. Therefore it is regarded third in importance. Stable river banks are less important because it does not influence the province of Ben Tre less compared to the earlier mentioned criteria. Lastly, the navigability is rewarded with the lowest importance for the Ham Luong River because there are no large ships that make use of the river and shipping is not a very important business for this specific part of the Mekong Delta.

The final results of the scores of the different alternatives can be seen in Table 8.4. The weights have been multiplied with the corresponding score of the alternatives on each of the criteria. This leads to the total score.

Table 8.4: Weighted scores for alternatives, where W = Weight and S = Score.

Criterion	Alternative 1		Alternative 2		Alternative 3		Alternative 4	
	S	W * S	S	W * S	S	W * S	S	W * S
Freshwater supply	7	245	6	210	5	175	1	35
Agricultural and aquaculture adaptation	5	175	5	175	5	175	6	210
Biodiversity	2	34	2	34	2	34	4	68
Stable river banks	3	27	3	27	3	27	4	36
Navigability	1	4	2	8	3	12	4	16
Total score		**485**		**454**		**423**		**365**

8.3 Cost analysis

The costs depend on multiple factors. The option to build a barrier or not, the amount of (river) dykes that have to be constructed or heightened, and the maintenance costs of a barrier and the dykes all have a large influence. The length of the dykes that have to be heightened or built varies depending on the location of the barrier. Furthermore, when no barrier is built all of the river dykes have to be heightened to at least the maximum water level in the river.

The amount of information on the costs of coastal defences in Vietnam is very limited. Most estimations in literature are therefore based on simple calculations combined with expert judgement. The costs of building a storm surge barrier are not easy to estimate and vary a lot for different projects. In 2009, the cost price per metre width for storm surge barriers worldwide ranged between €500.000 and €2.700.000 (Jonkman et al., 2013). In Vietnam, the costs will probably be a bit lower due to low labour costs. The Cai Lon - Cai Be sluice gates in Vietnam have only cost €136.8 million (Tuoi Tre News, 2022). More information about this barrier can be found in Section 7.2.1. This project was for a river that is 500 m in width, which is about 3 to 4 times as small as the Ham Luong River. However, it shows the order of magnitude of the costs for building such a structure in Vietnam. Therefore, for the cost calculations an estimate of €300 million per kilometre is used.

The management and maintenance costs of complex storm surge barriers are very high. These costs have been estimated at 5–10% of the total construction costs (Jonkman et al., 2013). For the maintenance costs of this barrier, 5% is taken for further calculations since labor costs in Vietnam are relatively low.

Dyke heightening costs depend on the amount of heightening. For a kilometre stretch, the dyke heightening costs are approximately €750.000 for every metre of heightening. In 2009, maintenance of the dykes in Vietnam cost roughly €20,000 per km dyke per year (Hillen et al., 2010). For the calculation of today's value, an inflation rate of 5.76% is used. This has been the mean inflation rate in Vietnam from 1996 until 2023 (Trading Economics, 2023). It is observed that the maintenance costs of the dykes are between 2-3% of the initial costs of the dykes annually. This is common for dykes in Vietnam (van Ledden et al., 2020). The costs of the barrier and dykes per kilometre can be seen in Table 8.5.

Table 8.5: Coastal defence costs for a km stretch

	2009	**2023**
Storm surge barrier cost (€)	-	300,000,000
Maintenance costs/year for barrier (€)	-	15,000,000
Dyke heightening costs per metre (€)	750,000	1,640,000
Dyke maintenance costs/year (€)	20,000	43,800

For all barrier locations, the crest of the river dykes will be heightened to 6.8 m between the river mouth and the location of the barrier. This is 3.8 m higher than in the current situation. Furthermore, a wall is placed on top of the dykes which makes the total height 7.8 m. However, this wall is left out of the calculation of the costs, as no good estimate for the costs of this wall could be found. The crest height of the dykes located more inland will be heightened to approximately 4.0 m, which is only 1 m higher than in the current situation. For the calculation of the dyke height see Section 7.1. In the case no barrier is built, the dykes along the entire length of the Ham Luong River will be heightened to 7.8 m. The location of the different dykes can be seen in Figure 7.2. Furthermore, the total length of the barrier is dependent on the location of the barrier, which influences the costs a lot. The total initial costs of the dykes and storm surge barrier for each alternative are shown in Table 8.6. Additionally, the total maintenance costs for every alternative can be seen in Table 8.7. It has to be noted that these costs only include measures within this project's spatial scope. Additional needed measures in upstream areas are not included.

Table 8.6: Initial costs of the different alternatives

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
km storm surge barrier	2.25	2.65	1.60	0.00
km dyke heightened to 4.0 m	118.20	107.50	90.00	0.00
km dyke heightened to 7.8 m	20.20	30.90	48.40	138.40
Total initial costs (million €)	995	1,164	929	863

Table 8.7: Maintenance costs of the different alternatives per year

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Storm surge barrier maintenance (million €)	34	40	24	-
Dyke maintenance (million €)	6	6	6	6
Total maintenance costs (million €)	40	46	30	6

The initial costs and maintenance can be combined into a total cost for the 2100 forecast. The maintenance is assumed to remain constant in this calculation. There is a clear difference in costs for the different alternatives as is visible in Table 8.8. From most costly to least costly the order is: 2, 1, 3, 4. This is seen for both initial costs and maintenance costs.

Table 8.8: Total costs of the different alternatives for 2100 forecast

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Total initial costs (million €)	995	1,164	929	863
Total maintenance costs (million €)	3,066	3,528	2,315	467
Total costs (million €)	4,060	4,691	3,244	1,329

8.4 Preferred solution

From Section 8.2 it can be seen that the different alternatives have a total score that is relatively close to each other. The lowest score for Alternative 4 is 75% of the score of Alternative 1, which is the highest scoring alternative. At first glance, the difference of 75% between the best and worst alternative might look significant. Nevertheless, it is important to state that the outcome of the MCA is very sensitive to the weights of the criteria. This makes it difficult to identify one alternative as the best fitting alternative. However, the costs of the different alternative differ a lot. Alternative 4 is clearly the alternative that is the most cost-efficient. For this reason, when considering cost-efficiency as decisive aspect, Alternative 4 is the preferred solution for the Ham Luong estuary. This is the option where no barrier is built in the river and the dykes along the entire length of the Ham Luong estuary are heightened to 7.8 m.

9 Conclusion

The conclusions of this report are written down per research question. This will give a clear answer to the objective of this report; to find out what the impact of various closure alternatives will be on the hydraulic and social activities in the Ham Luong estuary, in the year 2100.

1. What are the key characteristics of the Ham Luong estuary considering economic and social activities and hydro-morphodynamic properties?

Ben Tre faces multiple challenges such as salt intrusion, land subsidence, erosion, and a rising sea level. The province has set up defences such as dykes and sluices. Land use and occupation of the inhabitants of Ben Tre are arranged based on the salinity levels. From east to west, the distribution of land use is: shrimps, paddy, coconut, and lastly fruits. The most important stakeholders are the agricultural sector, who make up 60% of the workforce, and the local authorities and Vietnamese government, who have the highest influence.

2. What is the impact of the partial closure of the Ham Luong estuary on the hydro- and morphodynamics of the system?

To determine the impact of the partial closure of the estuary, four alternatives are taken into account. Alternative 1, 2, and 3 have a barrier at different locations along the Ham Luong estuary and Alternative 4 has no barrier. In all alternatives the dykes are heightened. Delft3D is used to calculate and display the water level, sediment, and salinity levels in the Ham Luong estuary. The used Delft3D model is a result of a lot of assumptions and simplifications, which are further discussed in Section 10. Due to these assumptions and simplifications, it becomes challenging to precisely determine the effects of a partial closure on water levels, salinity levels, and sedimentation changes in the Ham Luong estuary. However, it is expected that salt intrusion will decrease, and both sedimentation and erosion rates will undergo alterations as a result of the partial closure. Due to RSLR, the maximum water levels in the Ham Luong estuary in 2100 will often be higher than the current river dykes, consequently these dykes should be heightened.

3. What would be the optimal design for a flood protection system?

For every alternative an optimal design has been made. For the alternives with a storm surge barrier the gates would be spanning 40 m and have a height of 14.7 m. These are connected to the piers, measuring 4 m in width and 14 m in length. The dimensions are based on all possible load combinations during both high and low discharge season. The gate needs to be integrated with a dyke system, with a crest height of 4 m on the river facing side. On sea facing side, a dyke of 6.8 m with a vertical wall of 1 m on top has to be constructed to counter the impact of the storm surge. For the alternative without a barrier all dykes have to be heightened to 6.8 m with a vertical wall of 1 m on top to counter the impact of the storm surge.

4. Considering the effect of the hydro-morphodynamic changes on the social and economic activities, what decision in terms of closure of the estuary can be regarded as the best fitting solution for the system?

For determining the best fitting solution an MCA in combination with a cost evaluation was carried out. The criteria used in the MCA are: freshwater supply, agri- and aquaculture adaptation, biodiversity, stable riverbanks, and navigability. Assessing each criterion is done qualitatively. This qualitative approach leads to large uncertainties as can be read in Section 10. The outcome of the MCA is that there is no clear distinction between a partial closure or no closure in the Ham Luong estuary. A flood protection system with a partial closure comes at a cost of approximately €3.2 billion to €4.7 billion, while one without a partial closure is priced at around €1.3 billion, taking into account both initial cost and maintenance costs until 2100. The most cost-effective choice is a flood protection system without a partial closure, making it the best fitting solution.

To answer the main research question: *"What is the impact of various closure alternatives on the hydraulic characteristics and social activities in the Ham Luong estuary, considering a 75-year forecast?"* It is expected that with or without closure of the Ham Luong estuary the system will change. The availability of fresh water will be improved by the presence of a closure, although more research is needed to specify this further. The increasing salt intrusion, as a result of RSLR will lead to agricultural and aquacultural adaptation in all alternatives either due to the construction of the barrier or due to the gradual RSLR. A closure also has an effect on the biodiversity, stability of the river banks, and navigability in the river. When implementing a closure these effects should be further investigated to assess the effect quantitatively.

10 Discussion

This section addresses the most important uncertainties, assumptions, simplifications, and shortcomings of this project. Each of these are grouped under their corresponding subjects. The uncertainties, assumptions, simplifications, and limitations identified in this section should be taken into careful consideration when interpreting and/or reproducing the results presented in this report.

10.1 Limitation of the scope

In hindsight, the spatial scope of the project is too restricted. The hydro- and morphodynamic processes and social activities taking place in the Ham Luong estuary are dependent on processes taking place outside the Ham Luong estuary as well. For instance, the discharge flowing through the Ham Luong estuary is not only dependent on what is happening in the Ham Luong estuary, but is also subject to changes in the other branches. Moreover, whether the local farmers want to cultivate a certain product depends on both the ability of the product to withstand salinity and the global market price of that product. Of course, the larger the scope, the more accurately the processes can be represented. However, this does increase the complexity, and for that reason the scope was chosen as it is. As a consequence, many assumptions were made to account for these processes outside the scope of this project. These assumptions should be taken into consideration when interpreting the results.

An important consequence of the limited scope of the project is how this affects the model. The upstream bifurcations of the Mekong Delta are not included in the model and, as a consequence, the interaction between the discharges in the branches is not captured. As this interaction influences the distribution of the discharge, this influences the processes in the Ham Luong estuary. The effect of this choice of the scope on the discharge especially affects the processes upstream of a closed barrier, as this is a situation where a redistribution of discharge between the branches is expected. Consequently, it was not possible to draw any conclusions regarding the water level, salinity, and sedimentation in the simulations with a closed barrier.

10.2 Uncertainties regarding collection of data

Uncertainties are inevitable when collecting data, especially in an area such as the Ham Luong estuary. In some cases there is limited data available, and in other cases there is no data available at all. Also the reliability of the datasets should be noted, as many of the datasets contain missing values or were given in Vietnamese.

The largest uncertainties in the data collection of this project arise from the prediction of future conditions taking into account the effects climate change. The climate change scenario of RCP8.5 was assumed throughout this project. This climate change scenario carries a lot of uncertainty in itself, as it is based on the extrapolation of data over large periods of time and is dependent on the way society decides to take action. This climate change scenario was used to extrapolate upstream river discharge, RSLR, storm surge, and the wave climate. As these datasets were used as input for the model and the design, a change in these values could influence the outcomes of this report.

Another important shortcoming in the data collection that should be discussed, is the lack of data on the future effects of the construction of hydropower dams and sand mining activities on the discharge and sedimentation rates downstream. As little is known, it was decided not to include these effects in the model. However, it can greatly impact the outcome of the results in the future scenarios.

Additionally, another aspect to bear in mind in the collection of data of this report is the bathymetry. It was found that the dataset of the depth profile of the Ham Luong estuary, which was provided by Thuyloi University, shows some curiosities. Upon superimposing the bathymetry data on the area in Google Earth using a GIS tool, it was found that the depth (of the dataset) at the river banks was equal to several metres. This is not realistic, as one expects the water depth at the river banks to be nearly zero (or negative).

10.3 Model limitations

In setting up a model and interpreting the results, many choices and assumptions are made which are accompanied with uncertainties. The most important choices are discussed here. Many concessions were made in view of computational time. The first concession which was made regards the dimension of the model. A 2DH model was used, instead of a 3D model. It is expected that one reason for the underestimation of salinity in the model can be attributed to this, as 3D models are able to capture salinity processes more accurately. Another concession concerns the grid size: a relatively coarse grid was used. This could be another reason for the fact that the salt intrusion reaches less far landwards than was expected. In view of computational time, only five months were modelled in the longest simulation, which is little in terms of erosion and sedimentation modelling. Therefore, the influence of the presence of the structure on the surrounding bathymetry overlooking a 75-year period was not considered based on model results. Also, the islands were modelled as so-called dry points, but in reality their shapes and sizes can change over time, which is a process that has been excluded from the model. Furthermore, another important concession in terms of computational time which should be discussed is the fact that it is impossible to model every weather scenario. For this reason, a selection has been made. In this selection, it was opted to only model the situations which lead to the most critical situations. No analysis has been done which assesses the probability of occurrence of these critical situations. This should be kept in mind when reproducing the results. The last thing to bear in mind on the limitations of the model is the representation of the sediment processes. Only one value in terms of friction and uniform grain size was assumed for the entire estuary, while in reality this is not the case. More on the effects of changing these parameters can be found in Section 5.6.

10.4 Flood protection system

There are many choices and assumptions in the design of a complex flood protection system for a large area. One of the assumptions in the design is that the hydrodynamic and hydrostatic loads are calculated at only a critical location. The maximum wave height at location 1 is chosen for all designs, which is a conservative approach. Additionally, equal dyke heights along the river and maximum and minimum water depths are simplified based on limited data. Another remark is that the hydrostatic and hydrodynamic forces acting on the steel frame of the gates are evenly distributed while in reality this is a non-linear distribution. These concessions on the calculation of the hydrostatic and hydrodynamic loads have a large influence on the dimensions of the elements for the final design.

Furthermore, for the calculation of the flow past the piers the Morrison equation was used. It is applicable to slender structures and assumes cylindrical bodies, which is not identical to the shape of the pier. This method is mostly used in offshore structure engineering in an undisturbed flow. The tables used for offshore wind turbines to determine drag and inertia coefficients might not be applicable for a river. When a different approach is used the results for these flow forces could change and the design could therefore change as well.

In the MCA for the gate type the weights for the different criteria are determined by making assumptions about the importance relative to each other. Changing these weights would change the outcome of the MCA and therefore the type of gate that would be constructed. Furthermore, the score of each of the alternative gate types on the different criteria also has a human factor. Changing the way that the different gate types score on the criteria would also change the choice of gate type significantly.

Concerning the operation of the structure, in the event of high flow discharge from the river and a tropical storm at sea, it is possible to prevent seawater from infiltrating the land. However, the river will continue to carry a large discharge towards the sea. The river will probably not overflow the dyke in a time span of 1-2 days but more research into this situation is needed. If this situation will lead to flooding of the area by the river, it will affect the operation and design.

10.5 Evaluation

In Section 8 a lot of assumptions are made which can drastically change the preferred solution. First, it should be mentioned that each criterion is qualitatively assessed. For example, the criterion agricultural and aquaculture adaption is more a thought experiment than a factual outcome. One could also use a different rating system, such as a rating system in which each alternative is ranked relative to the other alternatives. This would definitely give another outcome of the MCA. Each criterion is assigned a weight based on literature research and personal judgement after talking with experts and some local people. Another person could give other weights to the criteria leading to a different outcome of the preferred solution.

The calculation of the cost per alternative is a very rough estimation. It should be noted that in this cost estimation only the Ham Luong River is taken into account. In reality, if one only raises the dykes along the Ham Luong River and not those further inland and along the other Mekong branches, it is likely that Ben Tre province still will not be adequately protected against flooding. For a more accurate cost estimation, and coming back to the earlier statement about the limitation of the scope of this project, it is recommended to consider all other Mekong branches as well.

11 Recommendations

This study can be used to create knowledge about the potential impact of a storm surge barrier on the area of the Ham Luong estuary. However, the results and assumptions should be be treated with caution, considering the project's limited scope, which is elaborated upon in Section 10. In this section, recommendations are given on how to improve a similar study in future projects.

11.1 Scope recommendations

An expansion of the area of interest is recommended. This expansion will help analyse the impact of a barrier on upstream regions and other branches. Especially in the case of a long closure of the barrier, these upstream effects are important to understand. Lastly, additional weather scenarios could also be taken into account in addition to the assumed extreme climate scenarios. Building with Nature is something that could also be implemented when using a larger scope. Companies like Royal HaskoningDHV and WWF already have made plans relating to this and are useful to contact for extra information.

The alternative without any intervention, meaning no heightening of the dykes, should be investigated as well. This can show the necessity of intervening in this area as soon as possible.

To create a more accurate model, more thorough data concerning discharge, soil, sediment transport, salinity, and detailed bathymetry is needed. These datasets should be compared and used for calibration and verification. It is recommended to verify the reliability of the sources and compare datasets from different sources to find uncertainties. Future consequences of the upstream hydropower dams and sand mining should be taken into account as well, depending on the availability of reliable data. However, for every extension of the model, the additional computation time should be considered carefully.

For additional structural calculations, the foundation of the storm surge barrier has not been designed but is an important element of the construction. Obtaining more recent and precise borehole data is necessary to achieve this. For a more detailed design the hydrostatic and hydrodynamic load should be calculated at multiple locations. The dyke should be designed in more detail, rather than a quick estimation.

11.2 Evaluation recommendations

In Section 8, the criteria of agricultural adaptation, biodiversity, and navigability are being considered. For a more precise and substantiated assessment of these criteria, experts with backgrounds in economics, biology, and ecology are necessary. In general, the involvement of additional experts is essential for a thorough impact evaluation of a partial closure in the Ham Luong estuary. The given timeframe of 10 weeks with only 6 students is not enough for this goal.

Freshwater supply has turned out to be one of the most important criteria. For this reason research about the local water management and future possibilities for freshwater supply should be done. This could give solutions other than river barriers, which would be very interesting for the local citizens and the government.

11.3 Recommendations for other Multidisciplinary Project groups

To reach better conclusions about the social impacts of the structure, it is necessary to interview more people. For this project, thirteen useful surveys were conducted in approximately three hours with the help of three Vietnamese interviewers; more about the survey can be read in Appendix G. In Vietnam, the plans change more than in the Netherlands. Therefore, it is important to make arrangements about the survey schedule and plans, but remain flexible. This flexibility will help you in many ways during your stay in Vietnam.

Schedule wise, it is also advised to schedule the field trip to your area of interest in the first three weeks. During the field trip, a lot of new insights were gained and these could have helped earlier in the project. When taking a trip in the Mekong Delta, it is useful to know that it is not allowed to cross the maritime border near the coast.

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Appendices

Appendix A Field trip

The area of Ben Tre was visited by the MDP group to verify the system description and to see if some parts were missing. Also, a survey was conducted among several inhabitants in the area. This is described in Appendix G. During the field trip, the city of Ben Tre was visited and the agricultural areas in the province along the river and the coast. This was done by riding motorbikes. Furthermore, a river expedition with a boat was set up to investigate the river banks and river use of the Ham Luong estuary. An overview in photos can be seen in Figure A.1.

Ben Tre City is the biggest city in the area and has several markets and numerous small businesses. During the visit, the city seemed to be relatively calm and not busy. From Ben Tre City, tourist boat tours were also organised but these did not go very far along the river.

In the rural areas of the province, the main production seemed to be coconut, see Figure A.1d. The coconut industry was all around the area. Besides the coconut farms, a lot of coconut storage and trucks loaded with coconuts were observed. Shrimp production was also observed and can be seen in Figure A.1f, but less than coconut production. Furthermore, there were some paddy fields but those observed were not very large in numbers and size. Adaptation of the area was also observed; in Figure A.1e newly planted coconut trees can be seen. The hypothesis is that these coconut trees were planted on former rice fields. However, this was not confirmed.

A couple of smaller sluice gates along the river banks were visited. These can be seen in Figure A.1g and Figure A.1h. These gates seemed to be operational and were seen closed during the visit.

During the boat tour, the mangroves along the river embankments were very clearly visible. They can be seen in Figure A.1a with next to them a couple of fishing boats. The mangroves appeared to be everywhere along the embankments and new mangroves were growing as well, see Figure A.1b.

Fishing boats were not only observed along the river embankments but also in small harbours and in side channels. The sizes of the boats were not larger than the ones depicted in Figure A.1a and Figure A.1c, but could be heavily loaded with for example tree trunks.

(a) Boats and mangroves

(b) Mangrove growth

(c) Fishing boats

(d) Coconut field

(e) Coconut field adaptation

(f) Shrimp farm

(g) Sluice along the river bank

(h) Small sluice along the river bank

Figure A.1: Field trip photos

Appendix B Data collection

This Appendix focuses on the collection of the relevant data, which is needed as input for the Delft3D model and the design of the flood protection system.

B.1 Bathymetry

Thuyloi University (Hanoi, Vietnam) provided a dataset containing depth measurements at specific locations in the Ham Luong estuary. These depths were measured in 2022. The bathymetry, which can be seen in Figure B.1, was created by triangular interpolation of the provided depths using Delft3D. Particularly large depths can be observed at multiple locations in the estuary. These depths can be attributed to sand mining processes in addition to natural river and estuary processes.

This bathymetry is used as input for the Delft3D model. Note that the heights of the islands are not well-represented in this bathymetry due to the fact that there were no depths measured at the islands, for this reason the interpolation results in a too low elevation at the islands. In order to account for these low elevations in Delft3D, the grid cells corresponding to the locations of the islands were marked as "dry points".

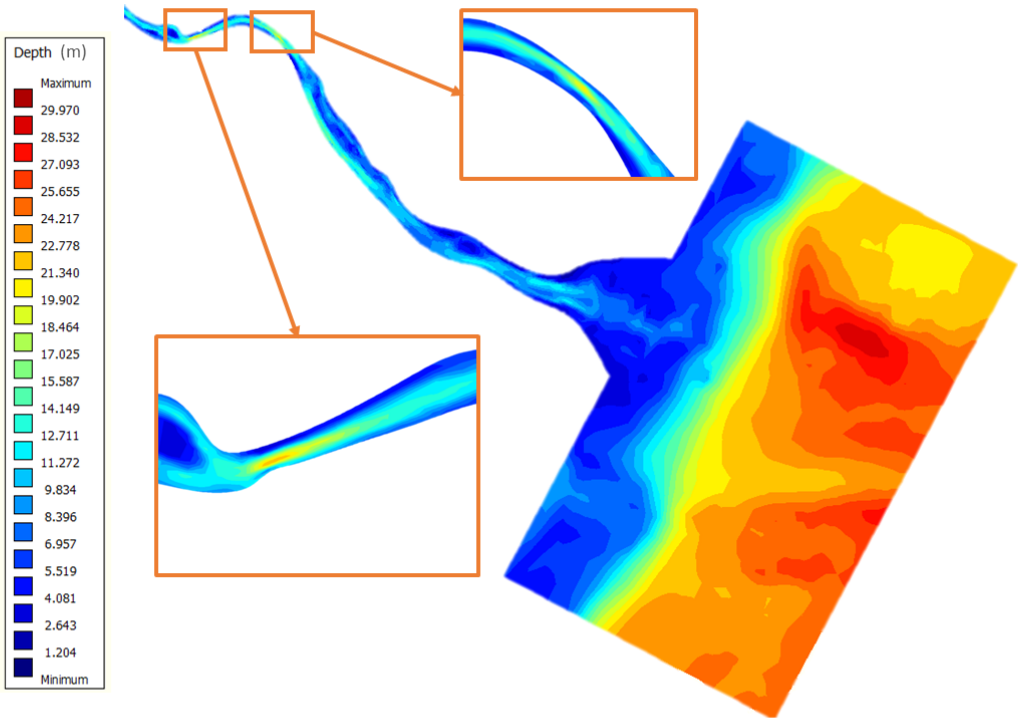


Figure B.1: Bathymetry Ham Luong estuary, recorded in 2022

B.2 Upstream river discharge

In Figure B.2, the daily average discharge entering the Ham Luong River during 2019 and 2020 is plotted in blue and orange, respectively. This data was retrieved from Thuyloi University. The original data consists of discharge measurements at My Thuan, located upstream of the Ham Luong estuary. Downstream of My Thuan, the Tien River splits into five branches. SIWRP uses a fraction of 15% of the total discharge of the Mekong, measured in Kratie (Cambodia) that flows into the Ham Luong estuary. This assumption is also used in this report. As the discharge in My Thuan is still affected by the tide, the daily average discharge is plotted.

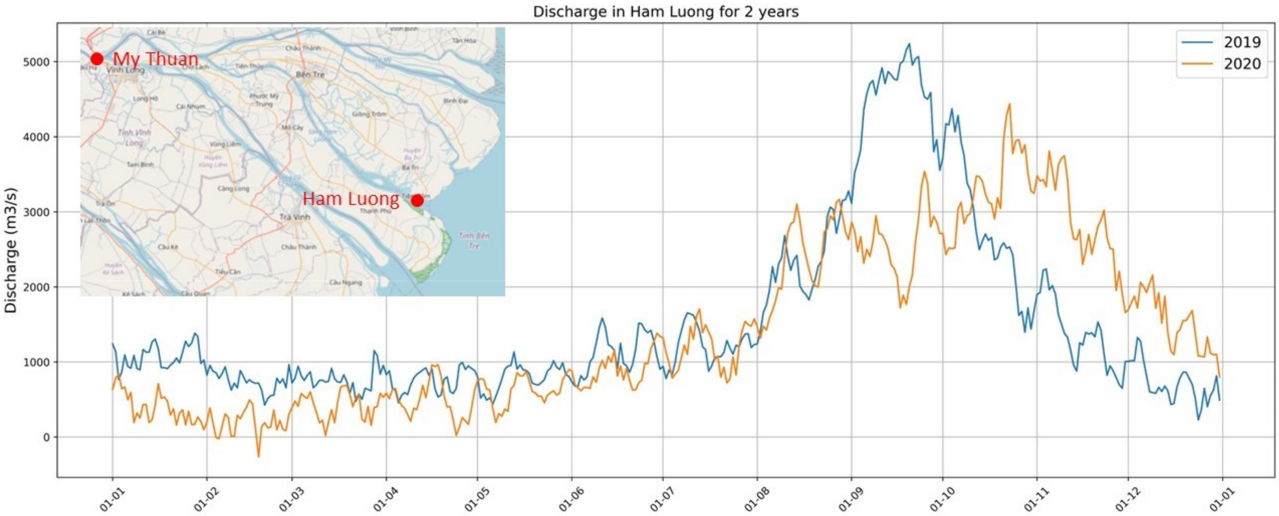


Figure B.2: Daily average discharge in 1982, 1998, 2019 and 2020 in the Ham Luong River

Although a lot of data about the discharge of the Mekong is available, the amount of future predictions is limited and shows a big scatter in prediction. In a summary of the Mekong River Commission (MRC) about the climate change impacts on the Mekong River basin, the projected discharge magnitudes and relative changes in Kratie are used to make an estimation on the predicted future discharge regime of the Mekong. These are predictions for the year 2060 and are based on the fifth assessment of IPCC (Assessment Report (AR)5). It includes different scenarios that are based on the emission scenarios of IPCC (RCP2.6, RCP4.5 and RCP8.5) (Mekong River Commission, 2023b). As stated in Section 4.4, the Vietnamese government advises to use the RCP8.5 scenario, which corresponds to the most extreme climate change scenario of the summary by MRC (Mekong River Commission, 2017). Therefore, the most extreme values for discharge were chosen. This results in an extreme low discharge during dry season and an extreme high discharge in wet season. The relevant numbers are stated in Table B.1.

Table B.1: Climate change predictions on the discharge of the Mekong River (Mekong River Commission, 2017)

	Minimum prediction	Maximum prediction	Extreme condition 2060
Peak flow wet season	-26%	+44%	+44%
Peak flow dry season	-43%	+20%	-43%

It is assumed that the discharge distribution into the different branches of the delta remains constant in the future. This makes it possible to use existing discharge data of the Ham Luong estuary and extrapolate this, using the predicted conditions of the future discharge regime in Table B.1. In this case, the most extreme values of the years 2019 and 2020 in Figure B.2 are taken, considering high and low discharge season. Combining these values with the climate change predictions results in the expected daily average discharge shown as the red dashed line below in Figure B.3.

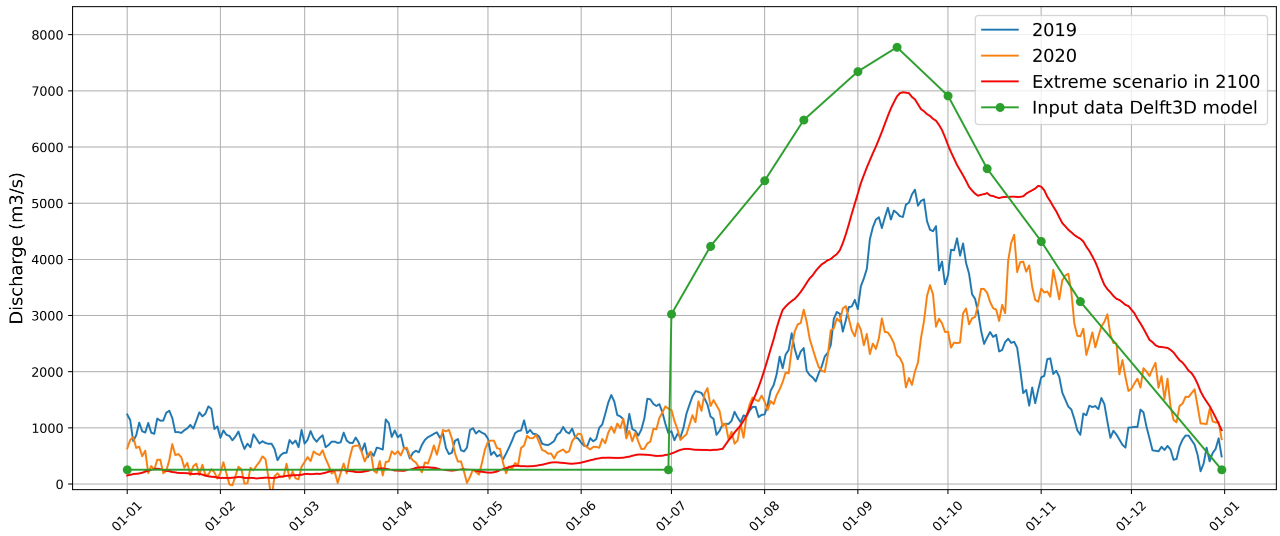


Figure B.3: Discharge time series in the Ham Luong estuary. Blue: discharge in 2019 based on My Thuan discharge. Orange: discharge in 2020 based on My Thuan discharge. Red: Extreme scenario in 2100 based on 2019 and 2020 data. Green: Input discharge data for the model.

In Figure B.3, different time series are plotted. In order to find representative discharge values to use as input data in the model, different data was analysed. First of all, daily averaged discharge data in My Thuan is used to estimate extreme discharge (low following dry season, high following wet season). These are the blue and orange line in Figure B.2 and Figure B.3. Secondly, more years of discharge data was consulted using the dataportal of the Mekong River Commission (Mekong River Commission, 2023a). In this case, daily discharge in Kratie was used to obtain the discharge in the Ham Luong estuary, using the percentage of 15%. This was done, in order to have data without the tidal influence because it is outside the tidal influence due to its proximity to the coast. Comparing the daily discharge in Kratie, including future extreme conditions, showed that the magnitudes of the extreme scenario based on 2019 and 2020 (red line in Figure B.3) is in the right order. However, when looking at earlier years of discharge data, it becomes evident that the high discharge peaks in 2019 and 2020 do start significantly later in the year. Therefore, the discharge peak of the chosen simplified discharge time series for the model starts earlier compared to 2019 and 2020 (green line in Figure B.3). As these discharge peaks differ from year to year, the highest overall discharge was used as input for the simulations with the storm in the high discharge season.

B.3 Tide

In order to identify the tidal regime at the Ham Luong estuary, a one-year water level time series of 2021 at An Thuan was used, which is located in the mouth of the Ham Luong estuary. This data was provided by the ICOE. This time series is analysed using the T-Tide analysis in Python. The goal of T-Tide is to identify the different tidal constituents in a time series, including the corresponding amplitude and phase (Pawlowicz et al., 2002). These values can be used as input for the Delft3D model. In Table B.2, the most relevant tidal constituents are stated. In Figure B.4, two days and one month of tidal signals are shown. It can be seen that the tide shows two high waters in one day, which verifies that the tidal regime is indeed “mixed, more semidiurnal”, as stated in Section 3.2.3. In the monthly tidal signal, the spring-neap tidal cycle can be seen. Analysing the data gives a maximum high tide of +138 cm and a minimum low tide of -301 cm, which makes the maximal tidal range 439 cm.

Table B.2: Most relevant tidal constituents

Constituent	Amplitude (cm)	Phase (°)
M2	77.7	170.7
K1	52.1	315.8
O1	35.2	37.1
S2	27.6	102.9
SA	27.0	28.89
P1	17.4	321.8
N2	15.4	2.49
K2	8.6	90.5
SSA	6.5	97.6
Q1	5.9	237.0
L2	4.3	335.8

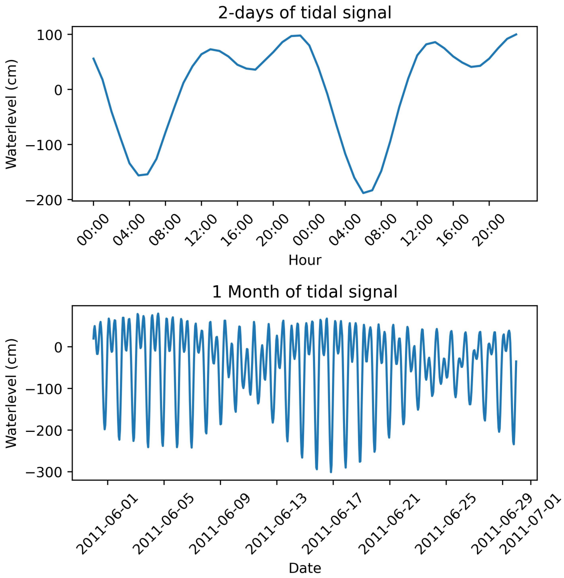


Figure B.4: Tidal signals

B.4 Relative sea-level rise

As stated in Section 4.4, the MONRE recommends to design for the IPCC scenario RCP8.5. In the corresponding report on climate change impacts in Vietnam, the predicted absolute SLR is also presented. For the region of of the Mekong Delta, an absolute SLR of 73 cm between 2005 and 2100 is predicted (Tran Thuc et al., 2016).

Besides absolute SLR, the significant amount of land subsidence makes it necessary to look into RSLR. In the report of MONRE, no values for land subsidence are given. In other research, a significant difference between urban and rural areas can be observed. For rural areas, the land subsidence between 1991 and 2015 has been 1.5 cm/year (Minderhoud et al., 2017). The main driver of this observed subsidence is groundwater extraction in the period of 1991 to 2015. As it is difficult to predict the groundwater extraction in the next centuries, in this report no significant change in groundwater extraction is assumed, thus a rate of 2 cm/year is used as subsidence rate. Combining absolute SLR and land subsidence into RSLR, results in a RSLR of 156 cm between 2005 and 2100.

B.5 Storm surge

In order to estimate the expected storm surge water elevation at the coastline, the tool Flooding, developed by Deltares, was used (Deltares, 2003). This tool takes wind speed, depth, fetch and properties of the water as input. In order to find a good estimation of the storm surge level at the mouth of the Ham Luong estuary, a set of assumptions were made:

1. The tool is used for a water depth of 30 m, which is the depth of the South Chinese Sea at approximately 100 km distance from the coastline.
2. The occurrence of storm surges is varying strongly along the coastline of Vietnam. The Mekong Delta is known as a coastline with a low risk of storm surges. In order to find the design wind speeds in the Mekong Delta, a document provided by the ICOE was used (Institute of Coastal and Offshore Engineering, 2020). This document states that all coastal dykes in the region of Ben Tre are built according to a new criteria to ensure resistance against wind speeds up to level 9 Beaufort. Considering the importance of a potential storm surge barrier, and increasing value of the hinterland, it is decided to design for wind speed up to level 10 Beaufort. This corresponds to a wind speed of 28.4 m/s.
3. Since typhoons are circular formed storms that travel along a certain path, the exact fetch is difficult to define. A simplification, used by Truong Hong Son (2012), defines the fetch length as 1.4 times the radius of typhoon. This simplification takes into account that the wind is not acting on a straight line due to the circular form of the typhoon and will be used for the estimation of the surge level.

Estimating the radius of a typhoon, and the corresponding fetch length, is a difficult task. Based on historical data of typhoons in Vietnam a storm radius of 80 nautical mile will be used (Thuyloi University, 2020). This corresponds with a fetch length of 112 nautical mile (208 km). The combination of this radius with wind speeds of up to 10 Beaufort have been observed in recent years, which makes these assumptions a valid reference storm. Using the mentioned tool by Deltares, leads to a storm surge level of +2.18 m.

To validate this number, some historical observations and future predictions of storm surge elevations along the coastline were used. An expected maximum surge level of 2.4 m is stated by Nguyen Tho Sao (2008). In the report of the MONRE, a possible maximum storm surge of 2.7 m at the coastline of the eastern Mekong Delta is mentioned (Tran Thuc et al., 2016). These values show a slight higher storm surge level than the calculated level. As the exact background of the two literature values is unknown, it is decided to use the estimated value of +2.18 m.

B.6 Sediment characteristics

The main soils in the Mekong Delta are the following with corresponding grain size distributions (Piman & Shrestha, 2017):

- Gravel > 2.0 mm
- Coarse sand 0.5-2.0 mm
- Medium sand 0.25-0.5 mm
- Fine sand 0.063-0.25 mm
- Silt and clay < 0.063 mm

The research from Piman and Shrestha (2017) shows that more than half of the sediment, about 60%, in the Lower Mekong Delta (LMD) consists of fine sand, 25% consists of silt and the rest consists of medium sand. There is almost no coarse sand or gravel in the area. For the sake of simplicity, a uniform grain size is chosen. This choice is based on the research of Tromp (2013). In this research, an average D_{50} of 200 µm has proven to be a good estimate, thus this assumption has been adopted in this project.

Suspended Sediment Concentration Data was retrieved by ICOE through measurements performed at the Hung Phong station, in the middle of the Ham Luong estuary. These hourly measurements were done in 2020 during a day in October, which is during high flow. The average of these measurements is 138.6 mg/L suspended sediment. This suspended sediment consists of cohesive mud and non-cohesive sand in approximately 85% and 15%, respectively. These percentages and the differences between high and low discharge originate from data of the Mississippi River and have been used by other researchers in the Mekong Delta, because these rivers seem to be similar concerning sediment transport (Tromp, 2013). This results in estimated suspended sediment concentrations during high discharge and low discharge which are shown in Table B.3.

Table B.3: Suspended sediment concentrations

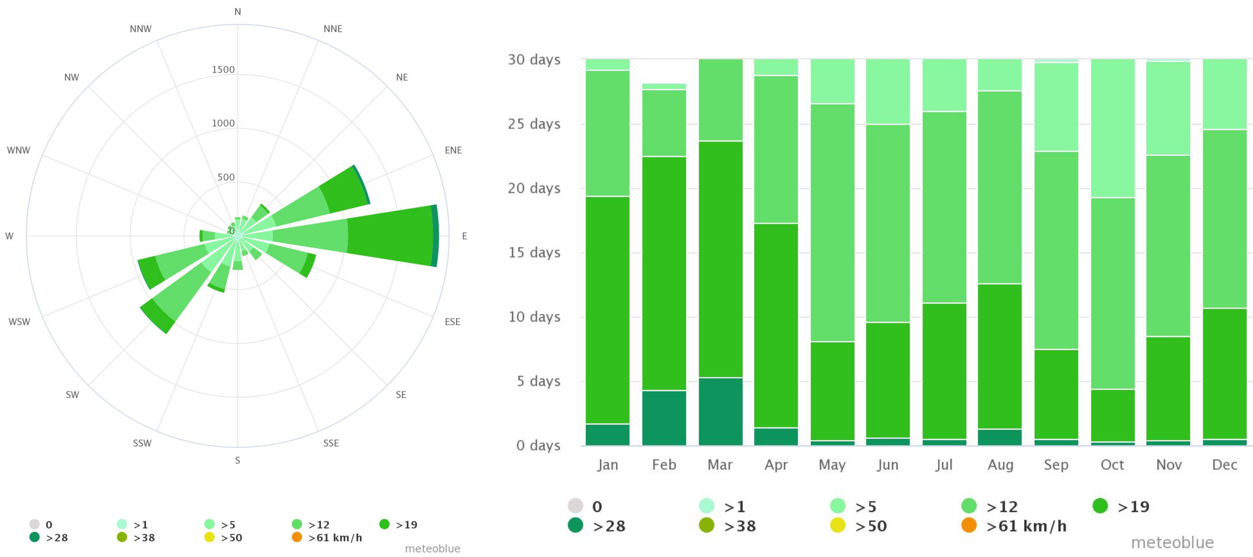
Sediment concentration in kg/m^3	**Mud**	**Sand**
High discharge	0.1178	0.0208
Low discharge	0.0094	0.0000

For the sediment transport of these concentrations, default formulas are used. For sand this is the transport formula defined by Van Rijn (2007), including bedload and suspended load. For mud the transport formula of Partheniades and Krone is used, only including suspended load (Deltares, 2023).

Lack of data and measurements in the Ham Luong estuary is the reason for the simplification of the values and the choice for default sediment transport formulas. This should not be done if detailed results for sedimentation and erosion are desired outcomes of a model. In the case of this report, the differences between alternatives can be shown by using the same simplified input and default formulas and the details are not of very high importance.

B.7 Wind conditions

The wind conditions in the coastal zone show clear monsoon characteristics. During the wet season, the SW monsoon occurs, and during dry season the NE monsoon occurs, with their corresponding dominant wind directions. In Figure B.5a the two dominant wind directions can be seen. The wind speed distribution throughout the year in Figure B.5b shows that the NE-winds during dry season have higher wind speeds with velocities up to approximately 30 km/h. The average wind speed at the Vietnamese coast is 6 m/s (Vietnam Energy, 2019).



(a) Windrose

(b) Annual distribution of wind speeds

Figure B.5: Wind conditions near Ham Luong River mouth (Meteoblue, 2023)

In exceptional situations, the highest wind speeds occur during tropical storms like typhoons. These winds can reach gust speeds up to 40 m/s, according to historical data of typhoons along the coastline of Vietnam (Thuyloi University, 2020). The effect of these wind speeds on the water level will be discussed in Appendix B.5.

B.8 Wave climate

The paper of Hoan Van Huan and Nguyen Huu Nhan (2006) refers to wave data measurements that were conducted between 1986 and 2006 at Bach Ho, an offshore wave station close to the coast of the Ham Luong estuary. The data can be found in Table B.4. These measurements were combined with data from nearby offshore oil platforms of Vietsovpetro and the significant wave heights and corresponding wave periods were determined for different return periods. Only the wave data originating from the NE and SW direction are taken into account in this report, as these are the result of the most frequent and most strong winds.

Table B.4: Wave climate data measured at Bach Ho station from 1986-2006 (Hoan Van Huan & Nguyen Huu Nhan, 2006)

Return period	NE		SW	
	Significant wave height (m)	Wave period (s)	Significant wave height (m)	Wave period (s)
1 year	3.5	8.1	3.0	7.9
10 years	4.5	8.7	4.1	8.1
25 years	5.5	9.2	4.4	8.5
50 years	6.4	9.5	4.8	8.6
100 years	7.2	9.7	5.5	8.7

The current averaged offshore significant wave height in January is 1.97 metre with a period of 7.72 seconds and in July 0.72 metres with a period 4.93 seconds. The expected averaged off-shore significant wave height for 2100 for the RCP 4.5 scenario in January is 1.84 metre with a period of 7.69 seconds and in July 0.77 metres with a period 4.94 seconds. As stated before in this report the used climate scenario RCP 8.5, but due to the lack of data of this RCP scenario above values are used (Xuan Hien Nguyen, Van Uu Dinh, Van Khiem Mai, Van Tra Tran, & Van Tien Pham, 2017).

B.9 Salinity levels for agriculture

Salt intrusion is likely to increase in the future in Ben Tre Province, as stated in Section 1.1. In order to incorporate the effect of salt intrusion in this analysis, the acceptable salinity for different kind of crops are used. Although no exact value for a critical salinity for rice crops is known, some research has shown acceptable values that can be used as an estimation. Salt tolerant rice shows significant yield losses at a salinity of 4 ppt (Kaveney et al., 2023). Coconut trees can withstand salinity levels up to 50 ppt, which is higher than that of seawater (Hebbar et al., 2021) and shrimp have a best fit range of salinity level of 18-25 ppt (Ministry of Agriculture and Rural Development, 2016).

Appendix C Simplified cross-section

The upstream boundary of the model is located around 80 riverkilometres (RKM) upstream of the mouth. At this location, the tidal influence is still affecting the discharge regime in the river. In order to create a grid of which the upstream boundary, including the inflow of discharge, is not affected by the tidal regime, the grid needs to be extended. In order to estimate the river bathymetry of this extended upstream reach of the river, the cross-section is described by an exponential function, as was proposed by Savenije (2012). This methods assumes a rectangular cross-section and that the cross-sectional area, river width and river depth can be described as:

$$A = A_0 \cdot \exp\left(-\frac{x}{a}\right) \tag{3}$$

$$B = B_0 \cdot \exp\left(-\frac{x}{b}\right) \tag{4}$$

$$h = h_0 \cdot \exp\left(\frac{x(a-b)}{ab}\right) \tag{5}$$

In which:

A = Cross-sectional area $[m^2]$

A_0 = Cross-sectional area of the mouth $[m^2]$

a = Cross-sectional convergence length parameter $[m]$

B = River width $[m]$

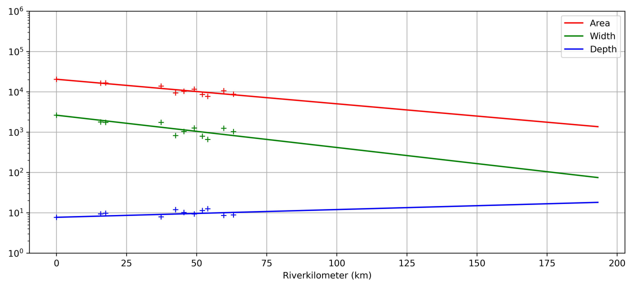
B_0 = River width of the mouth $[m]$

b = Width convergence length parameter $[m]$

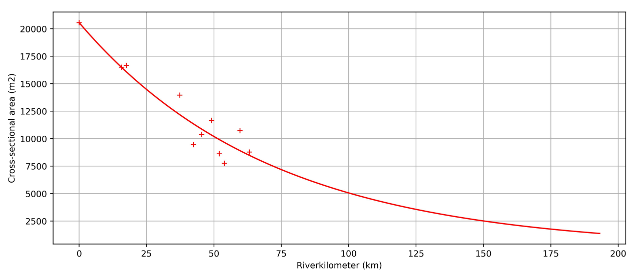
h = Depth $[m]$

h_0 = Depth at river mouth $[m]$

In order to find the fitted values for the coefficients a and b, the bathymetry, received from Thuyloi University, was used. In total 11 cross-sections where taken between the upstream boundary and the mouth. The most downstream cross-section is defined as the river mouth, with a cross-section of 20,565 m^2 and a width of 2.64 km. The remaining 10 cross-sections where taken at sections where no islands are present, since the calculations can not include the islands.

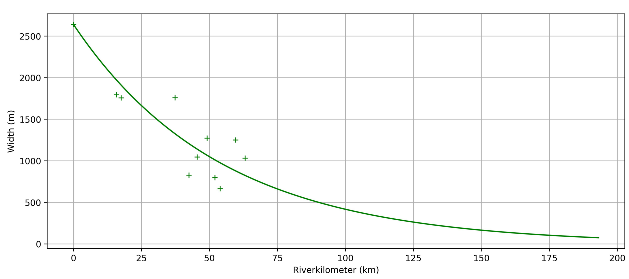


(a) Area, width and depth on a logarithmic scale

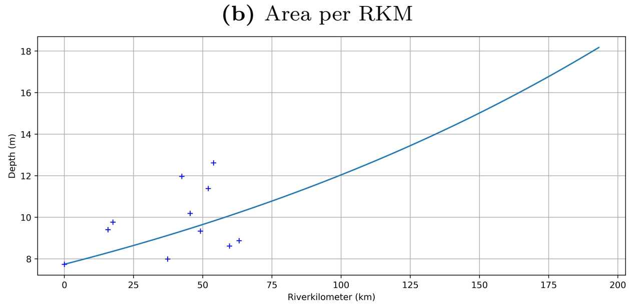


(b) Area per RKM

2



(c) Width per RKM



(d) Depth per RKM

2

Figure C.1: Exponential functions, fitted on the bathymetry data from the model

When looking at Figure C.1a, the graphs look like a good fit on a logarithmic scale. In Figure C.1b, Figure C.1c and Figure C.1d, a bigger scatter is observed. This is not unexpected, since the function is fitted based on only 11 cross-sections. However, in general it can be stated that the exponential function as defined by Savenije (2012), forms an acceptable fit to the received dataset.

For the extended upstream reach, it was decided to determine the cross-sectional area of the river on 10 locations. In total, a distance of additional 130 km is added to the model. By using the exponential function in Figure C.1b, the cross-sectional area of the upstream locations is determined.

The exponential increase in water depth in Figure C.1d is the result of the assumption that the cross-sectional area and width can be estimated for upstream reaches, and an assumed rectangular cross-section. The result of these assumptions is that numerically, an exponential increase in water depth is expected. However, this is not expected in reality. For the extended upstream reach, the average water depth of the most upward bathymetry section is taken as water depth. The determined cross-section and this constant depth leads to a upward decrease of river width.

The results that were obtained in this analysis were verified using previous research. In the thesis of Nguyen (2008), the the same method is used on the Ham Luong estuary. However, since the used bathymetry data is unknown, a new analysis has been done. The resulting values from Nguyen (2008) can be used as verification values. In Table C.1, the results of both analysis are stated. It can be seen that the assumptions related to the river mouth are slightly different. Especially the cross-sectional area that results from the bathymetry data is significant bigger than the area that was assumed by Nguyen. This difference leads to a different value for the a-parameter. The b-parameter, which is related to the river width, shows a good match between the two results. These values show that the result of the analysis, based on the bathymetry data, is close to literature values. In order to be consistent within the model, the results that are obtained with the received bathymetry data will be used to for the upstream reach.

Table C.1: Results and verification cross-section analysis

	Analysis results	**Verification values (Nguyen, 2008)**
a	71	55
b	54	55
A_0 (m^2)	20,565	17,000
B_0 (m)	2,640	2,800
h_0 (m)	7.7	6.1

Appendix D Sediment Tool

In Table D.1 below, the input values of the sedimentation tool are stated. This tool was used to estimate the sedimentation layer in front of a closed barrier and the mud concentration in this basin in front of the barrier. The bold numbers are location specific values: tidal range and area of basin. The italic values are default values that are not changed and are expected to match this case. The remaining number were defined for the Ham Luong estuary, but do not vary for the different barrier locations.

Table D.1: Input for sedimentation tool, calculating the mud concentration and sedimentation infront of the closed barriers.

Parameter		**L1**	**L2**	**L3**
dt (s)	Timestep	*300*	*300*	*300*
h_0 (m)	Water depth below MSL	10	10	10
b (m)	Entrance width	2500	2500	2500
A (km^2)	Area of basin	**18**	**30**	**50**
u_0 (m/s)	Peak velocity outside basin	0.18	0.18	0.18
n_0 (m)	Tidal amplitude	**1.31**	**1.33**	**1.40**
c_0 (kg/m^3)	Initial concentration in harbour basin	*0*	*0*	*0*
c_{01} (kg/m^3)	Constant concentration ouside	*0.1*	*0.1*	*0.1*
c_{02} (kg/m^3)	Variational concentration outside	*0.02*	*0.02*	*0.02*
$\Delta\rho_M$ (kg/m^3)	Maximum density difference	*3*	*3*	*3*
ρ (kg/m^3)	Mean fluid density outside basin	1025	1025	1025
w_s (m/s)	Effective settling velocity	*0.0003*	*0.0003*	*0.0003*
Δ_{dry} (kg/m^3)	Dry bulk density of deposited mat.	*400*	*400*	*400*
T (s)	Tidal period	43200	43200	43200
$F_{1,flood}$ (-)	Horizontal exchange coefficient	*0.025*	*0.025*	*0.025*
$F_{1,ebb}$ (-)	Horizontal exchange coefficient	*0*	*0*	*0*

Appendix E Calculations flood protection system

E.1 Dyke calculations

In this appendix, the calculation for the height of the river dykes for the year 2100 is made. Equation (6) and Equation (7) are used to determine the crest height of the dyke without settlements, compaction and safety margin. The maximum of the two is used for the final design of the crest height (Van der Meer et al., 2018).

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.026}{\sqrt{\tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot e^{-\left(\frac{2.5 \cdot Rc}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)^{1.3}} \tag{6}$$

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.1035 \cdot \exp\left[-\left(1.35 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma*}\right)^{1.3}\right] \tag{7}$$

In which:

γ_b = Influence factor for a berm [-]

γ_f = Influence factor for roughness elements on a slope[-]

γ_β = Influence factor for oblique wave attack [-]

γ_v = Influence factor for a wall at the end of a slope [-]

$\gamma*$ = Influence factor for non-breaking waves [-]

H_{m0} = Significant wave height estimate [m]

α = Slope dyke angle [°]

$\xi_{m-1,0}$ = Breaker parameter [-]

R_c = Crest free board [m]

q = Overtopping discharge [m^3/s/m]

g = Gravity acceleration [m/s^2]

At the existing dykes there is no berm present. For ease of constructability therefore no dyke berm will be constructed in the future. Existing dykes then do not have to be adjusted too much to match the design. The influence factor for a berm, γ_b, is therefore equal to 1.0. The influence factor for roughness elements on the slope, γ_f, is also equal to 1.0 because there is grass present (Van der Meer et al., 2018). Influence factor γ_β is equal to 0.8 for a wave direction of 60°. Furthermore, there will be a wall on top of the dyke to reduce the dyke height. This affects the influence factor γ_v, see also Equation (8). The height of the wall will be 1.0 m. In the case of a smooth dyke with a storm wall $\gamma_v = \gamma*$ (Van der Meer et al., 2018). This is the case for this dyke design.

$$\gamma_v = e^{\left(-0.56 \cdot \frac{h_{\text{wall}}}{R_c}\right)} \tag{8}$$

In which:

h_{wall} = Wall height [m]

R_c = Crest height of the dyke [m]

The difference between significant wave height H_s and the estimate of the significant wave height H_{m0} is often very small (Van der Meer et al., 2018). Therefore these are assumed to be the same, namely 2.2 m as determined with Simulating WAves Nearshore (SWAN) within Delft3D. The value for the outer slope of the dykes α is equal to $\frac{1}{3}$, this is taken from Section 3.3.2.

For the maximum accepted overtopping discharge guidelines are available. It depends on the design characteristics of the dyke. For a grass-covered crest and landward slope, maintained and closed grass cover and a value for $H_{m0} = 1 - 3$ m the overtopping discharge is equal to 5 l/s/m or 0.005 m^3/s/m.

For the determination of the breaker parameter Equation (9) is used (Van der Meer et al., 2018).

$$\xi_{m-1,0} = \frac{\tan\alpha}{\sqrt{\frac{H_{m0}}{L_0}}} \tag{9}$$

In which:

L_0 = Wavelength [m]

H_{m0} = Significant wave height estimate [m]

α = Slope dyke angle [°]

The calculation results in a crest height of 4.9 m without settlements, compaction and a safety margin. A compaction rate of around 5 % is assumed and added to the crest height, as well as RSLR. This results in a final crest-free board of 6.8 m, excluding the vertical wall with a height of 1 m.

E.2 Hydrostatic load calculations

To calculate the hydrostatic loads, the pressure caused by a water column has to be calculated first with Equation (10):

$$p = \rho \cdot g \cdot h \tag{10}$$

In which:

ρ = Density of the water [kg/m^3]

g = Gravity acceleration [m/s^2]

h = Height of the sea [m]

The density of the water differs per side. The density of the fresh river water is 1000 kg/m^3 and the density of seawater is 1020 kg/m^3. To calculate the hydrostatic force, Equation (11) is used:

$$p = \frac{1}{2} \cdot \rho \cdot g \cdot h^2 \tag{11}$$

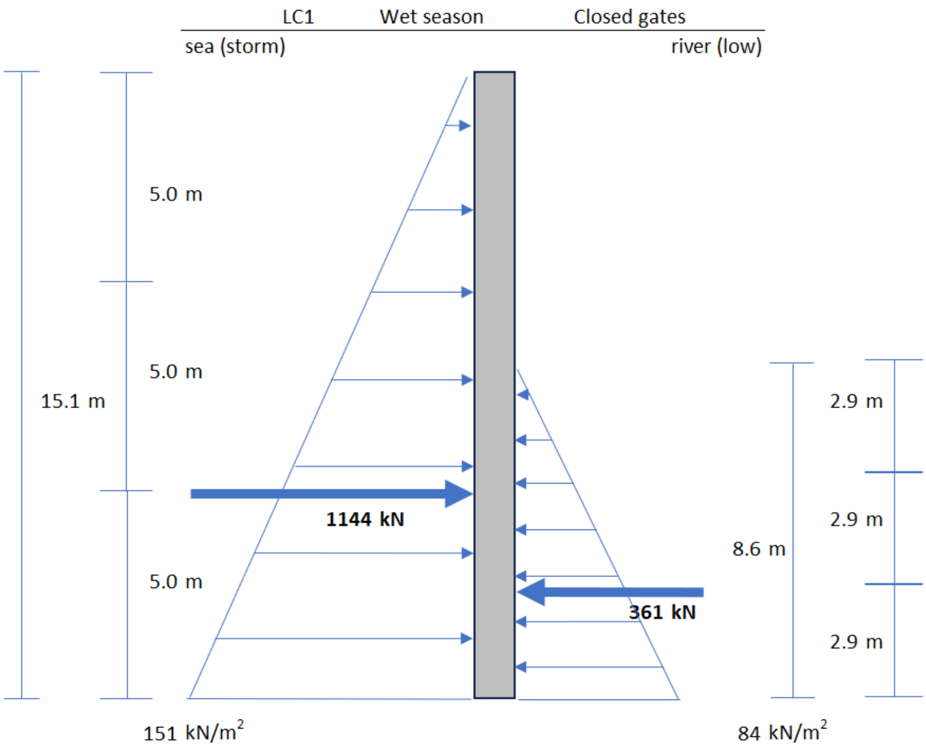
The critical water heights in 2100 are given in Table E.1. The maximum sea water level during the high discharge season is a combination of high tide, RSLR, and storm surge. The minimum sea water level during that period is caused by the low tide. The maximum water level is limited by the height of the river dykes. This is equal to 3.0 m along the Ham Luong River close to An Dien and My An (Institute of Coastal and Offshore Engineering, 2020). As said before in Section 3.3.2 it is assumed that this is with respect to MSL. Furthermore, it is assumed that the height of the river dykes is 3.0 m along the entire Ham Luong River. The minimum water height of the rivers is related to the minimum discharge during that period.

During the low discharge season there are no large storms so the maximum sea water level is not influenced by storm surge but by high tide and RSLR. The minimum sea level is caused by the spring tide or Lowest Astronomical Tide (LAT). The maximum river height follows from the maximum river discharge during that season and the minimum river height follows from the minimum river discharge. To determine these heights, water level data has been used from the measurement station My Thuan received from Thuyloi University. The resulting extreme water levels are visible in Table E.1.

Table E.1: Maximum and minimum water levels in 2100

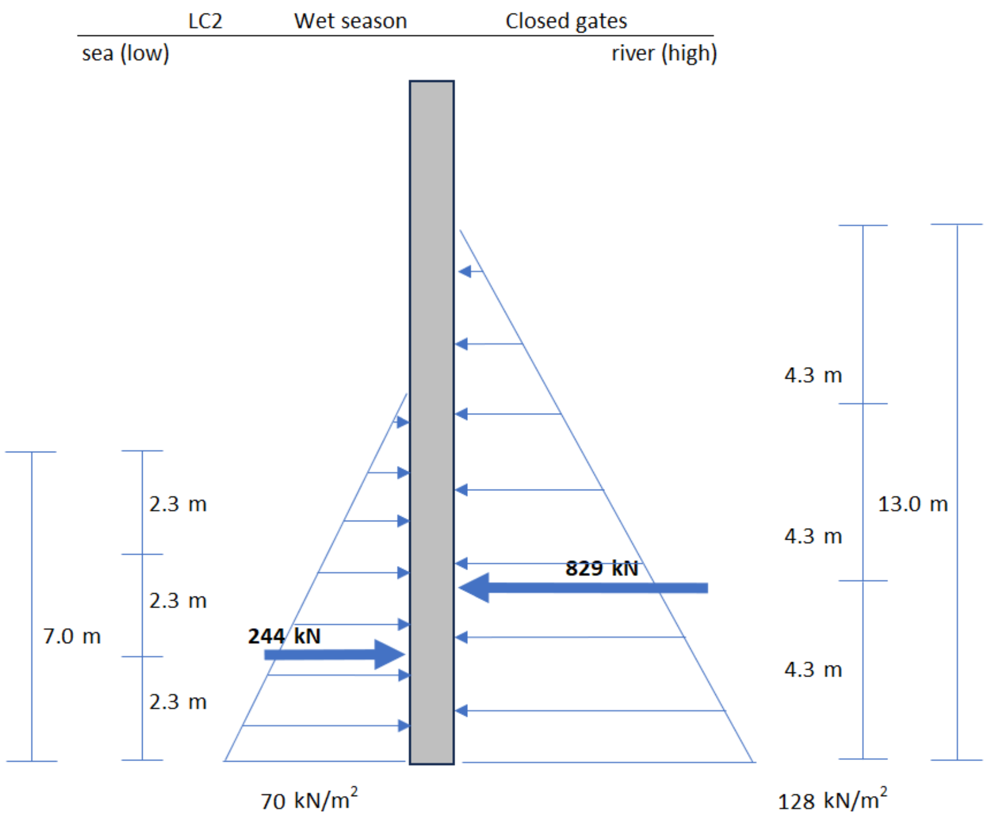
Season	Sea (max)	River (max)	Sea (min)	River (min)	Unit
High discharge season	5.12	3.00	-3.01	-1.42	m+MSL
Low discharge season	2.94	1.48	-3.01	-1.60	m+MSL

In Figure E.1a, Figure E.1b and Figure E.1c the different extreme situations for static loads are visualised. The stress distribution over the height of the wall can be seen, as well as the resulting forces. Note that in the figures, the hydrostatic distribution is given from the riverbed to the water level. The river bed is approximately -10 m + MSL in the Ham Luong estuary. This of course varies for each location but for preliminary design this is a good starting point.

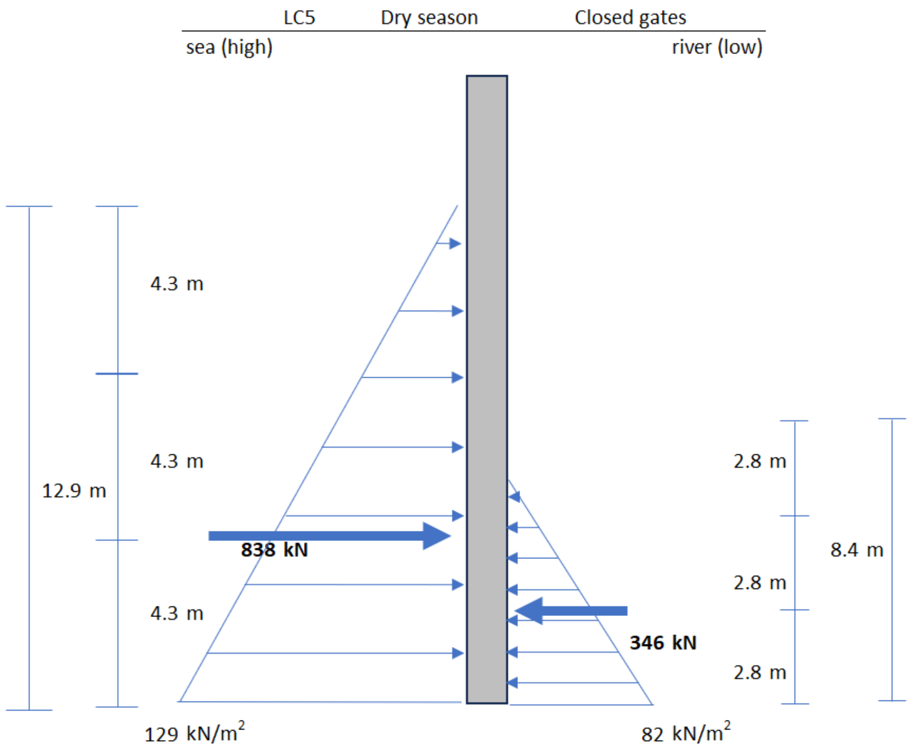


(a) Hydrostatic loads for LC5

Figure E.1: Hydrostatic loads for different load combinations



(b) Hydrostatic loads for LC1



(c) Hydrostatic loads for LC2

E.3 Hydrodynamic load calculations

In this appendix two different calculations for hydrodynamic loads on the structure are explained. The first calculation is for wave impact of incoming waves on a vertical structure. The second calculation is for drag and inertia forces of the water against the pier.

Linear wave theory is assumed to determine the wave length, which is needed in this calculation. The water depth is 10 m and the period is 8.7 s (SW wind and return period 100 years) on the sea and is not affected by the water depth when entering the river. By using Equation (12), the wave length could now be determined by iteration.

$$\lambda = \frac{g}{2\pi} T^2 \tanh\left(\frac{2\pi d}{\lambda}\right) \tag{12}$$

In which:

d = Water depth [m]

λ = Wave length [m]

T = Period [s]

This results in a wavelength of 78 m. By dividing the water depth by the wavelength, it is clear that the water is intermediate deep by using the intermediate water criteria visible in Equation (13): $\frac{10}{78} = 0.13$.

$$\frac{1}{20} \leq \frac{d}{\lambda} \leq \frac{1}{2} \tag{13}$$

By taking the water depth as unknown, the boundaries of the intermediate water zone could be determined. The boundaries are between 3.9 m and 39 m. Therefore, the Ham Luong River is characterised as intermediate water.

Wave impact on closed gate

For linear wave theory the pressure distribution by incoming waves is described with the following formula (Voorendt, 2022):

$$p = \rho \cdot g \cdot H_i \cdot \frac{\cosh(k \cdot (d+z))}{\cosh(k \cdot d)} \quad \text{for } -d < z < 0 \tag{14}$$

$$p = \left(1 - \frac{z}{H_i}\right) \cdot \rho \cdot g \cdot H_i \quad \text{for } 0 < z < H_i \tag{15}$$

In which:

H_i = Half of the wave height of an incoming wave [m]

k = Wave number of the incoming wave ($k = \frac{2\pi}{L}$) [m^{-1}]

ρ = Density of salt water (typically $\rho = 1020 kg/m^3$) [kg/m^3]

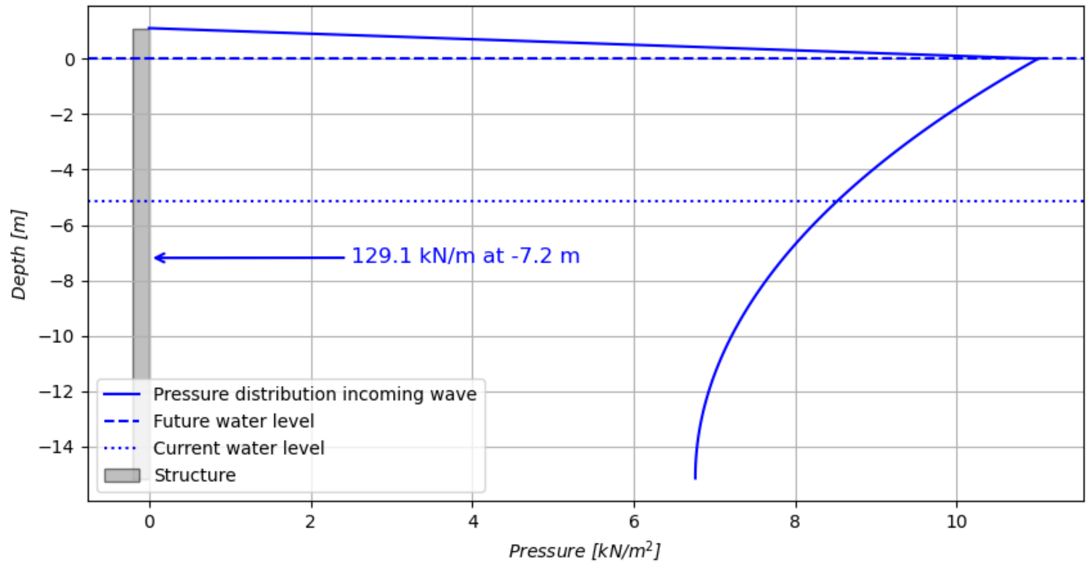
g = Gravity acceleration [m/s^2]

d = Total depth [m]

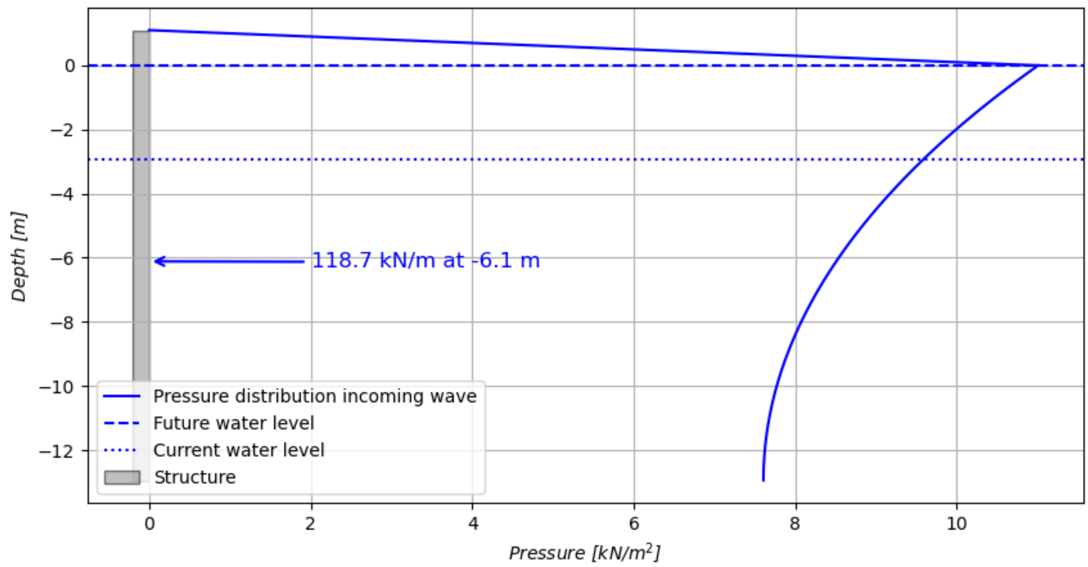
z = Depth level [m]

The wave height in the estuary is determined with using the wave module from Delft3D. This wave module uses SWAN. SWAN is a third-generation wave model that can model waves in coastal regions and inland waters (Holthuijsen, 2007). The wave height at sea and period are used as input for a Joint North Sea Wave Project (JONSWAP) spectrum used in the model. From Figure B.5a it can be seen that the direction of the waves coming from the east will enter the Ham Luong estuary. The maximum wave height is 7.2 m and the period is 9.7 s at sea estimated for 2100, see Table B.4. This results in a wave height of 2.2 m at location 1. This is at the location of the barrier closest to the river mouth, which is the critical location regarding wave action.

The resulting pressure distribution for a wave height of 2.2 m can be seen in Figure E.4. The pressure distribution from the river bed to the still water level is non-linear. The extra water pressure from the wave results in a linear pressure distribution from the still water level to the wave height. A mean depth of 10 m is used for the calculations. The total force (per metre stretch) that is acting on the structure is shown with the blue arrow pointing to the structure. The force acts over the complete length of the structure as a distributed load. It is found by integrating the entire pressure distribution over the height.



(a) Wave force, high discharge season LC1



(b) Wave force, low discharge season LC5

Figure E.2: Wave forces on a closed structure for different load combinations

Water flow past the piers

The drag and inertia forces of the water against the piers will be calculated with the Morison equation. To calculate the maximum force from the Morison equation, Equation (16) will be used. The drag and inertia components are out of phase.

$$f_{\max}(z) = \sqrt{f_{D_{\max}}(z)^2 + f_{I,\max}(z)^2} \tag{16}$$

For a cylindrical structure, the drag and inertia components of the Morison force are written as follows in Equation (17) and Equation (18):

$$f_{D_{\max}} = \frac{1}{2} \cdot \rho \cdot C_d \cdot D \cdot u_{\max} \cdot |u_{\max}| \tag{17}$$

$$f_{I_{\max}} = \frac{\pi}{4} \cdot \rho \cdot C_m \cdot D^2 \cdot \dot{u}_{\max} \tag{18}$$

In which:

D = Diameter [m]

u_{max} = Maximum flow velocity [m/s]

$\dot{u}_{max}$ = Maximum flow acceleration [m/s^2]

C_d = Drag coefficient

C_m = Inertia coefficient

For the calculation of the maximum flow velocity and acceleration Equation (19), Equation (20) are used.

$$u_{max}(z) = \gamma_{ws} \cdot u_{\text{wave}}^{\max}(z) + \gamma_{cb} \cdot u_{current}(z) \tag{19}$$

$$\dot{u}_{max}(z) = \gamma_{ws} \cdot \dot{u}_{\text{wave}}^{\max} \tag{20}$$

In which:

γ_{ws} = Wave spreading factor [-]

γ_{cb} = Current blockage [-]

$u_{current}(z)$ = speed of the current at z [m]

u_{wave}^{max} = Maximum wave velocity [m/s]

$\dot{u}_{wave}^{max}$ = Maximum wave acceleration [m/s^2]

The wave spreading factor is used to take into account that the environmental conditions are multi-directional and random. A wave spreading factor of 0.906 is chosen which is a standard value (Hoving & van der Male, 2022). During extreme weather events, this value could potentially change to a lower value. Furthermore, a current blockage factor is used because Morison equation only considers a single body which does not influence the current. But the presence of the structure and having multiple bodies with a significant length in the water interferes the current. Therefore it is estimated that the current blockage factor is 0.8.

The speed of the current is the flow speed in the river described in Table E.2. These values are obtained from Delft3D. For the maximum flow velocity and acceleration regarding the waves, the following calculations are made:

$$u_{\text{wave}}^{\max} = \max\left(\hat{\zeta} \cdot \omega \cdot e^{k \cdot z} \cdot \cos(k \cdot x - \omega \cdot t)\right) = \hat{\zeta} \cdot \omega \cdot \delta_u \tag{21}$$

$$\dot{u}_{\text{wave}}^{\max} = \hat{\zeta} \cdot \omega \cdot \delta_u \tag{22}$$

In which:

$\hat{\zeta}$ = Half of the wave height [m]

ω = $2 \cdot \frac{\pi}{T}$ = Frequency [rad/s]

k = $2 \cdot \frac{\pi}{L}$ = Wave number [-]

d = Total depth [m]

z = Depth level [m]

t = Time [s]

T = Time period [s]

L = Wave length [m]

δ_u = Depth decay function [-]

The depth decay function is described by:

$$\delta_u = \frac{\cosh(k \cdot (z + d))}{\sinh(k \cdot d)} \tag{23}$$

The drag and inertia coefficients that are needed in the Morison equation are calculated with the Keulegan–Carpenter (KC). This is a formula that describes the relative importance of the drag forces over inertia forces for a slender object (Journée & Massie, 2001). With Equation (24) the KC number can be calculated.

$$KC = \frac{u_a \cdot T}{D} \tag{24}$$

In which:

u_a = Amplitude of the flow velocity [m/s]

T = Oscillating flow period [s]

D = Cylinder diameter [m]

In this formula, the piers are assumed to be cylindrical. A diameter of 4.0 m allows the piers to still be slender structures, which is an assumption for the Morison equation. Furthermore, it is approximately the same width as the piers of the Cai Lon - Cai Be sluice. It is assumed that the amplitude of the flow velocity is similar to the flow velocity and the oscillating flow period is the same as the wave period. The flow speeds of the water are taken from the Delft3D model for the different LC's. They can be seen in Table E.2. For each LC the three barrier locations are checked upon the maximum value for the flow speed. This value is taken as the critical value for that situation.

The KC number in combination with the surface roughness can be used to determine the inertia and drag coefficients. The formula for the surface roughness can be seen in Equation (25). For the roughness height the value of $\epsilon = 0.005$ m is used for course concrete. This is because the concrete will be placed in an environment where organic matter can easily grow on it, increasing the surface roughness.

$$\text{Surface roughness} = \frac{\epsilon}{D} \tag{25}$$

In which:

ϵ = Roughness height [m]

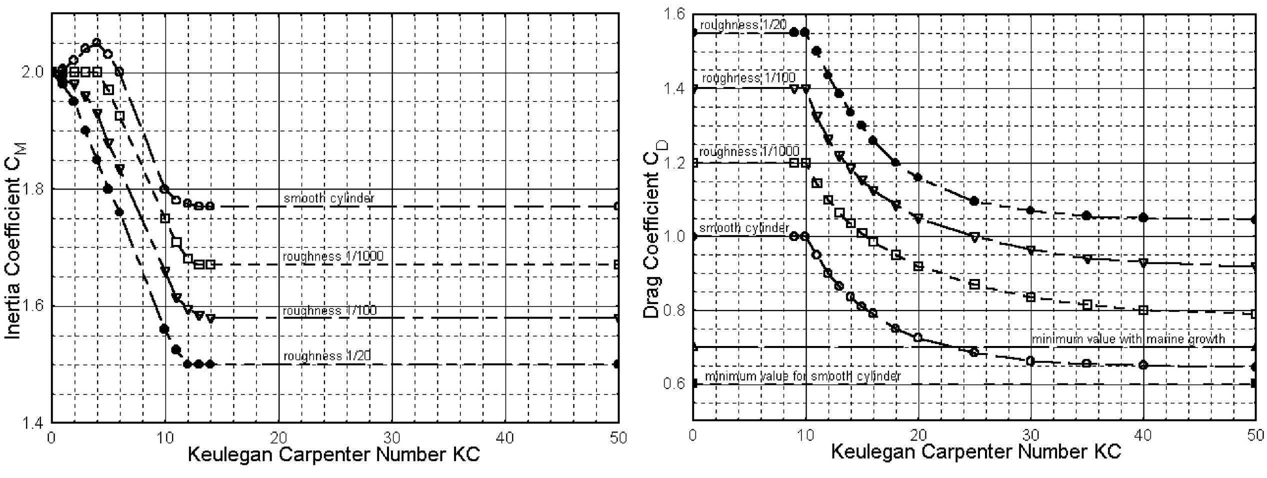
D = Cylinder diameter [m]

From Figure E.3a and Figure E.3b the right values for the drag and inertia coefficients can be determined for the different KC numbers for each situation. Note that the graphs are designed for vertical cylinders which is not the case. Because of the very low KC values for each situation all the values for drag an inertia are the same. The drag coefficient has a value of $C_d = 1.2$ and the inertia coefficient has a value of $C_m = 2.0$. The drag and inertia forces are then calculated with Equation (16).

In Table E.2 the resulting drag and inertia coefficients for each situation are visualised. The flow speeds from Delft3D and the corresponding KC numbers for every LC are also depicted. It is observed that the difference in flow speeds does not result in big differences in the drag an inertia coefficients. The values of $C_d = 1.205$ and $C_m = 2.00$ are therefore used for the calculation of the Morison forces.

Table E.2: Drag and inertia coefficients

	LC3	LC4	LC7
u [m/s]	1.00	2.00	1.50
KC [-]	2.18	4.35	3.26
C_d [-]	1.205	1.205	1.205
C_m [-]	2	1.975	2

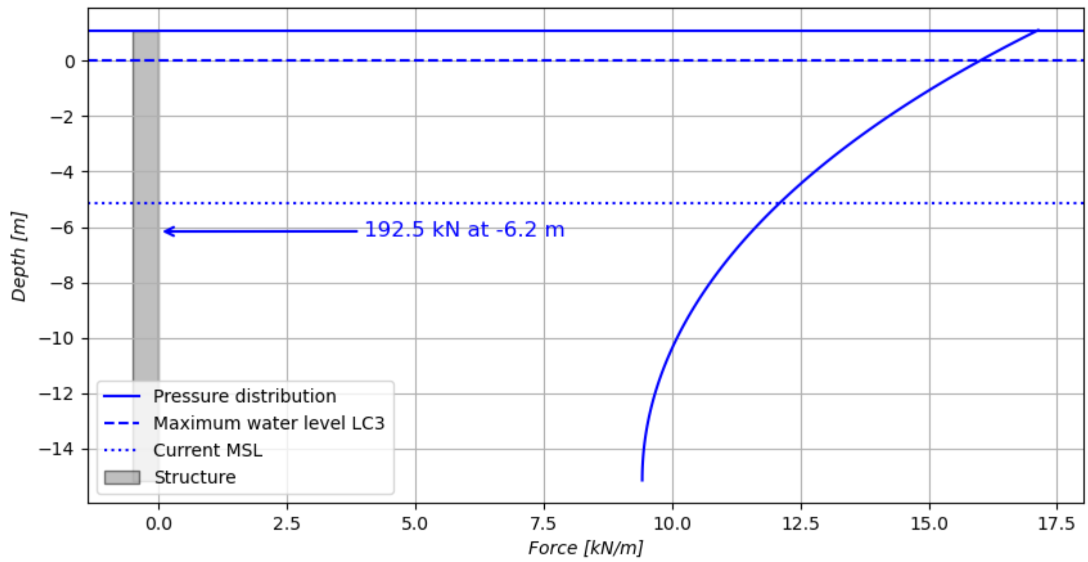


(a) Suggested inertia coefficient values (Journée & Massie, 2001) **(b)** Suggested drag coefficient values (Journée & Massie, 2001)

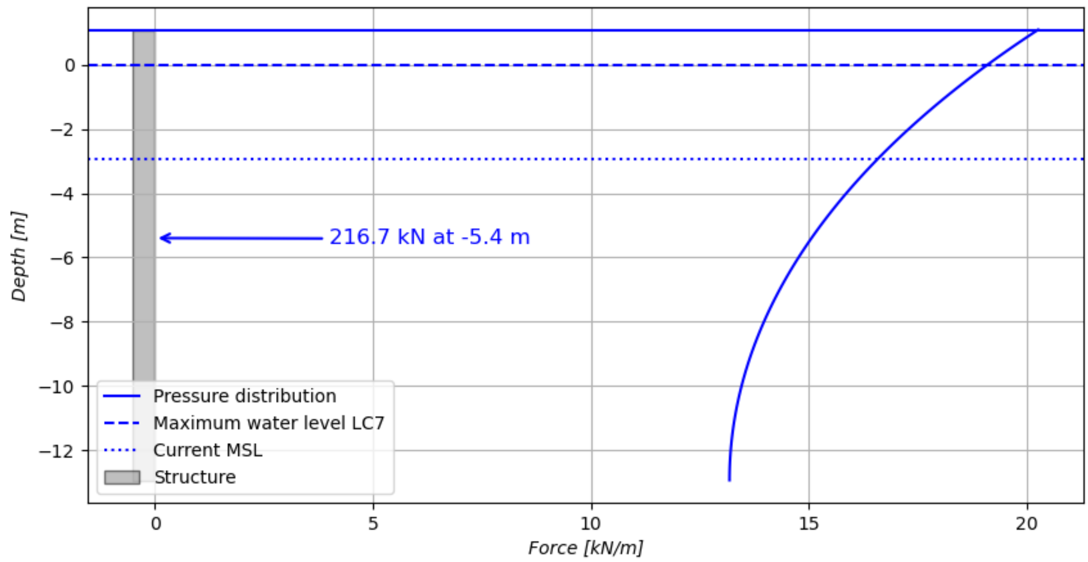
Figure E.3: Inertia and drag coefficients, based on Keulegan Carpenter Number

Now, all previous formulas will be filled in. The incoming drag and inertia forces for flow coming from the sea in both the high and low discharge seasons are calculated and visualised in Figure E.4a and Figure E.4b. These situations correspond to LC3 and LC7. Storm surge is not regarded for the water height of the sea during the low discharge season as there are no storms then. These situations normally only occur when the gates fail to close as discussed earlier.

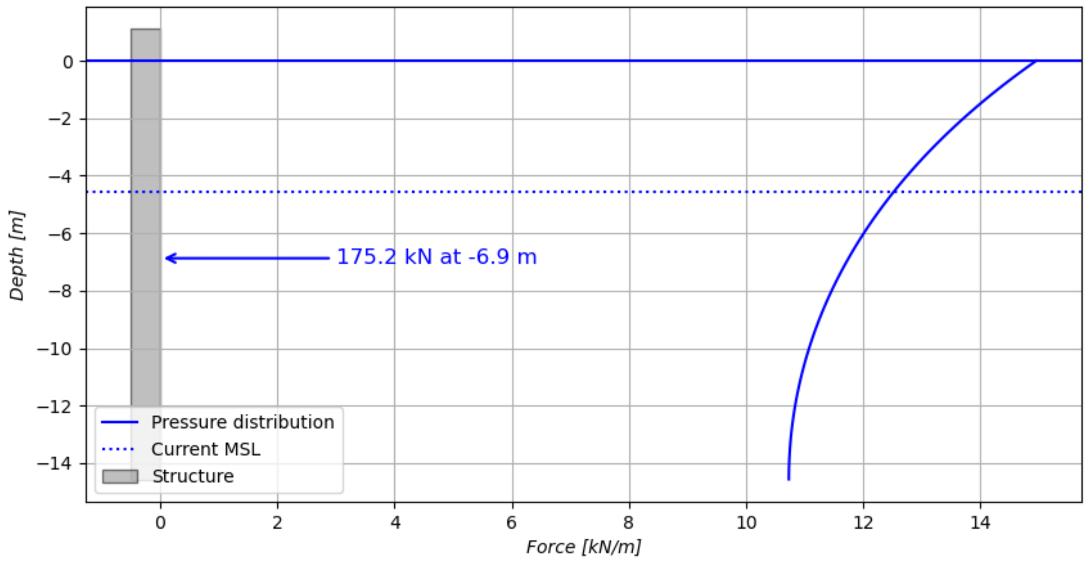
During the high discharge season, the water level in the river is very high. In the case the gates are opened this leads to large drag and inertia forces on the piers. A steady flow is assumed without large waves. Furthermore, the maximum water height of the river is the height of the dykes above MSL, which is 3.0 m as mentioned in Section 3.3.2. This situation corresponds to LC4 and is visualised in Figure E.4c. This is the visualisation of the total distributed Morison force acting on a single pier. This is in kN because the diameter of the structure is already included in the calculation.



(a) Morison force sea, high discharge season, LC3



(b) Morison force sea, low discharge season, LC7



(c) Morison force river, high discharge season, LC4

Figure E.4: Morison forces on the piers for different load combinations

E.4 Boreholes

In this appendix different boreholes in the sea between the Go Cong Dong district near the river mouth of the Mekong and Vung Tau are displayed. The locations can be seen in Figure E.6a. The actual boreholes itself can be seen in Figure E.5, the one used for the determination of soil stresses is the LK01 borehole on the left. In Figure E.6b the geological index of the different boreholes is visualised.

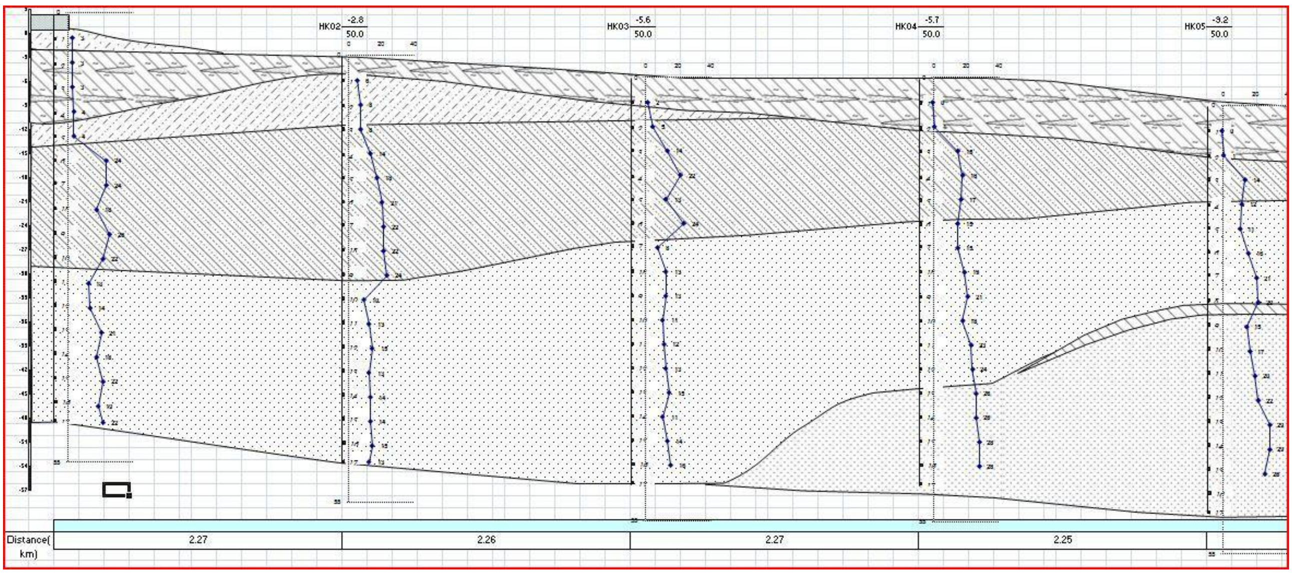
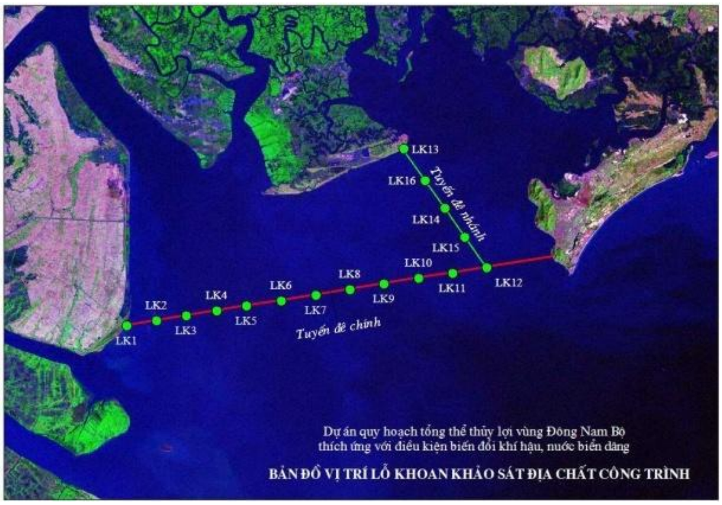
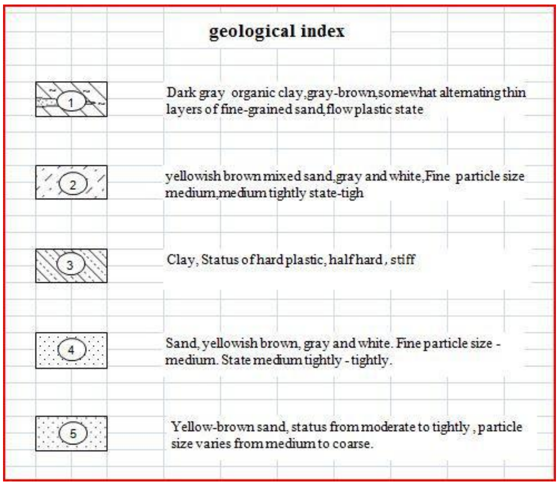


Figure E.5: Soil layer distribution near Vung Tau (Truong Hong Son, 2012)



(a) Boreholes locations near Vung Tau (Truong Hong Son, 2012)



(b) Geological index of the soil layers (Truong Hong Son, 2012)

Figure E.6: Location and soil layers of boreholes

E.5 Relationship between opening size and peak tidal flow during mean tide

The graph in Figure E.7 shows a relation between opening sizes of storm surge barriers and peak tidal flow during mean tide. The figure shows different ranges for peak tidal velocities. For the determination of the total area of the gates for the storm surge barrier in the Ham Luong River a peak tidal velocity of 1.5 m/s was chosen. This value is the mean value of the maximum flow velocities given in Table E.2. Therefore this is a good approximation for all alternatives.

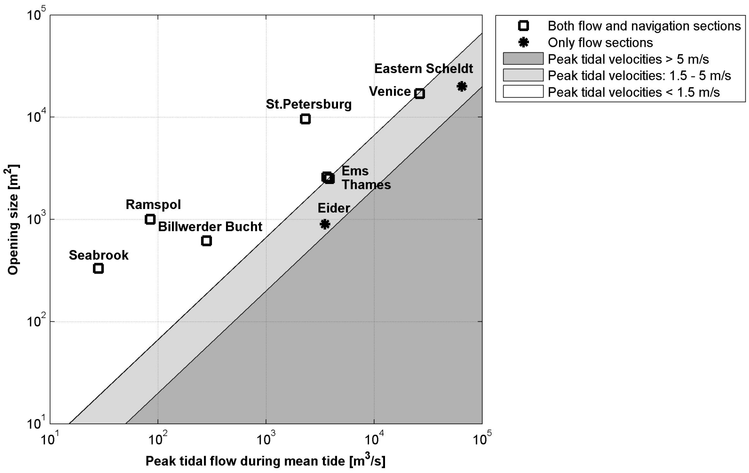


Figure E.7: Relationship between opening size and peak tidal flow during mean tide (Mooyaart & Jonkman, 2017)

E.6 Combined hydrodynamic and -static load on the gate

In Figure E.1a the hydrostatic and -dynamic loads for LC1 are visualised. This is a combination of relatively large hydrodynamic load from wave impact and a high hydrostatic load on the gates. The components of the the total load are visualised with red and green colour. The total load on the gate is visualised with blue colour. The maximum load is depicted with the red dot marker. For LC2 and LC5 the same calculation is made. The hydrodynamic and -static loads are different resulting in different total loads on the gates. LC2 has no hydrodynamic loads acting on the gate.

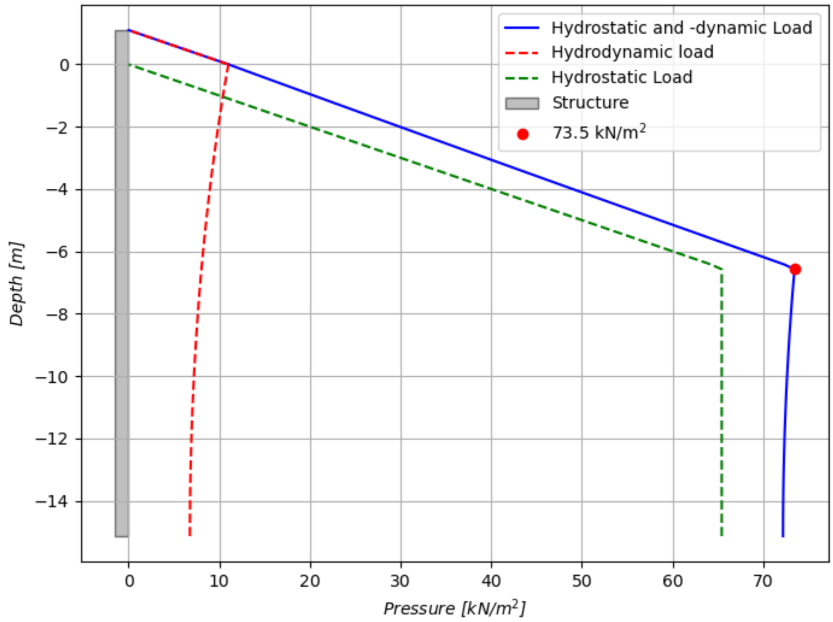


Figure E.8: Hydrostatic and -dynamic Load LC1

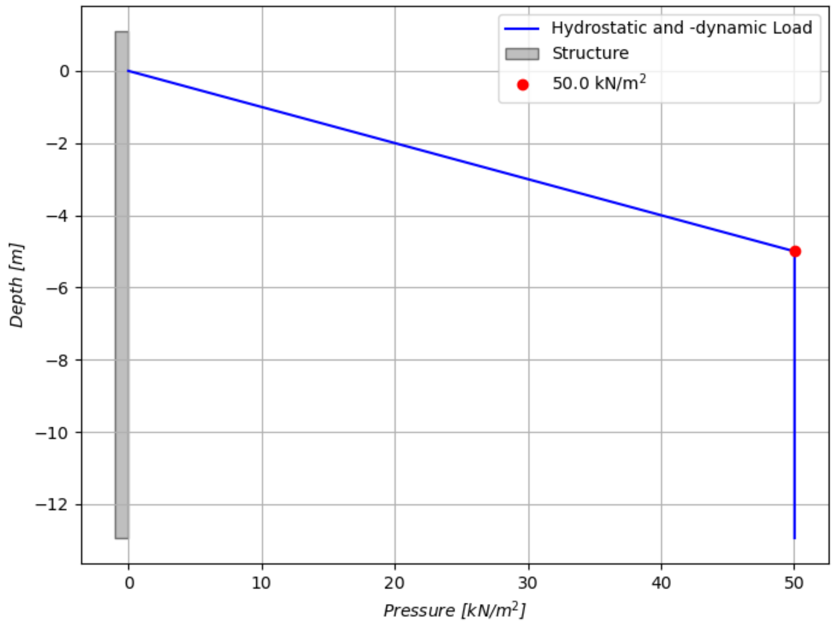


Figure E.9: Hydrostatic and -dynamic Load LC2

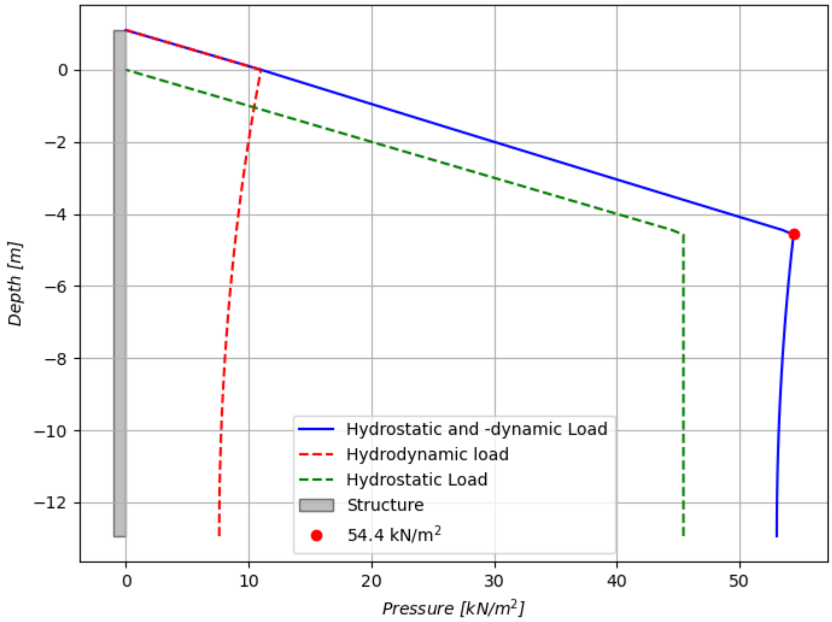


Figure E.10: Hydrostatic and -dynamic Load LC5

E.7 Load combination factors

For the load combination factors, the Eurocode is used. This is done because there is not a very good guideline for structural calculations in Vietnam and often Eurocode is used as well. The design value of the load effect E_d, the fundamental combination, is as in Equation (26). This is according to Eurocode 0 for structural design (CEN, 2002).

$$E_d = E\left\{\sum_{j\geq1}^{n} \gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \sum_{i>1}^{n} \gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i}\right\} \tag{26}$$

In which:

$G_{k,j}$ = Characteristic value of permanent load j

$\gamma_{G,j}$ = Partial factor for permanent load j

P = Representative value for the pre-stressing load

γ_P = Partial factor for the pre-stressing load

$Q_{k,1}$ = Characteristic value of the main variable load

$\gamma_{Q,1}$ = Partial factor for the main variable load

$Q_{k,i}$ = Characteristic value of variable load i

$\gamma_{Q,i}$ = Partial factor for variable load i

$\psi_{0,i}$ = Combination reduction factor for variable load i

For the self-weight of the structure and permanent loads, the load combination factor $\gamma_{G,j} = 1.35$ is used. For the live loads; water pressures, wind loads, and other variable loads, load combination factor $\gamma_{Q,1} = 1.5$ is used.

E.8 Load schematisation on the gate

In Figure E.11 and Figure E.12 the loads on the gate structure are visualised. These are the loads without load combination factors. For calculating the results the load combination factors for these loads have been applied.

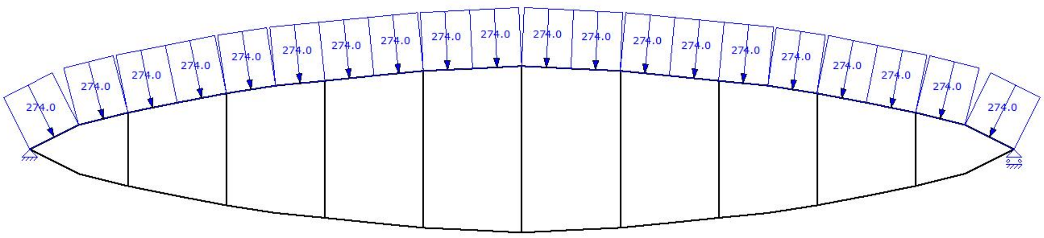


Figure E.11: Hydrostatic load on the gate

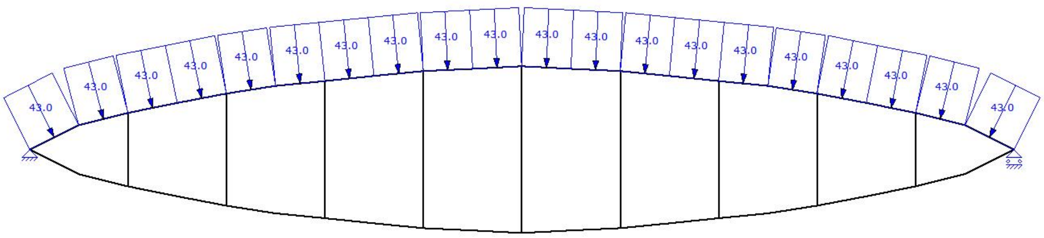


Figure E.12: Hydrodynamic load on the gate

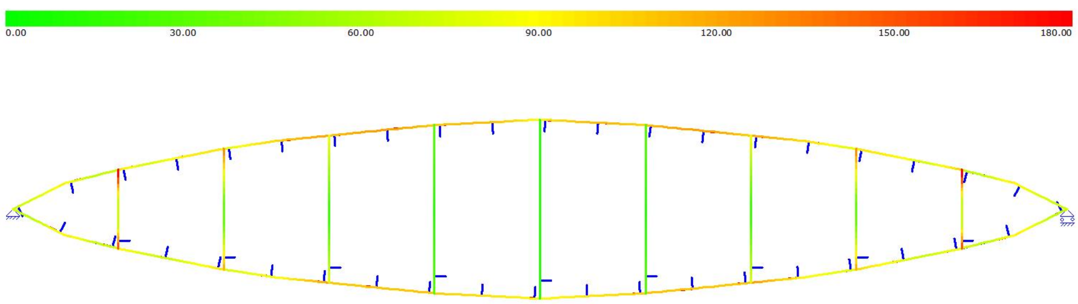


Figure E.13: Steel frame stresses

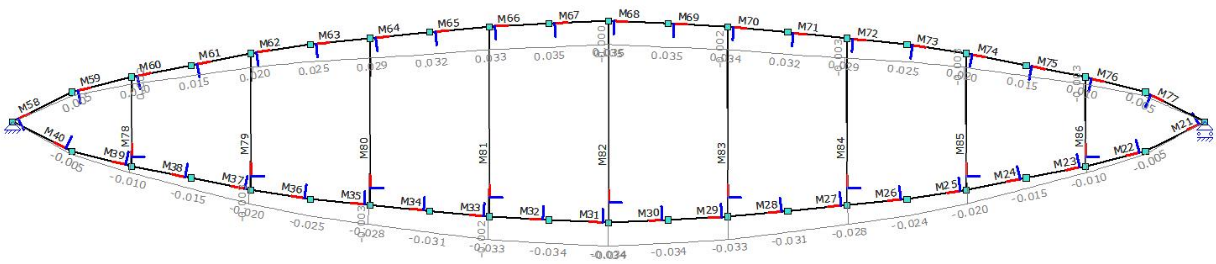


Figure E.14: Steel frame deflections

E.9 Euler buckling frame beams

The beams that connect the two arcs that form a single lens frame are compressed when loaded. This may lead to buckling. The beams are regarded as hinged on both sides for this particular structure, resulting in a buckling length of $L_b = L$. Euler buckling; Equation (27) is used for the UC on buckling.

$$P_{\mathrm{cr}} = \frac{\pi^2 \cdot E \cdot I}{L_b^2} \tag{27}$$

In which:

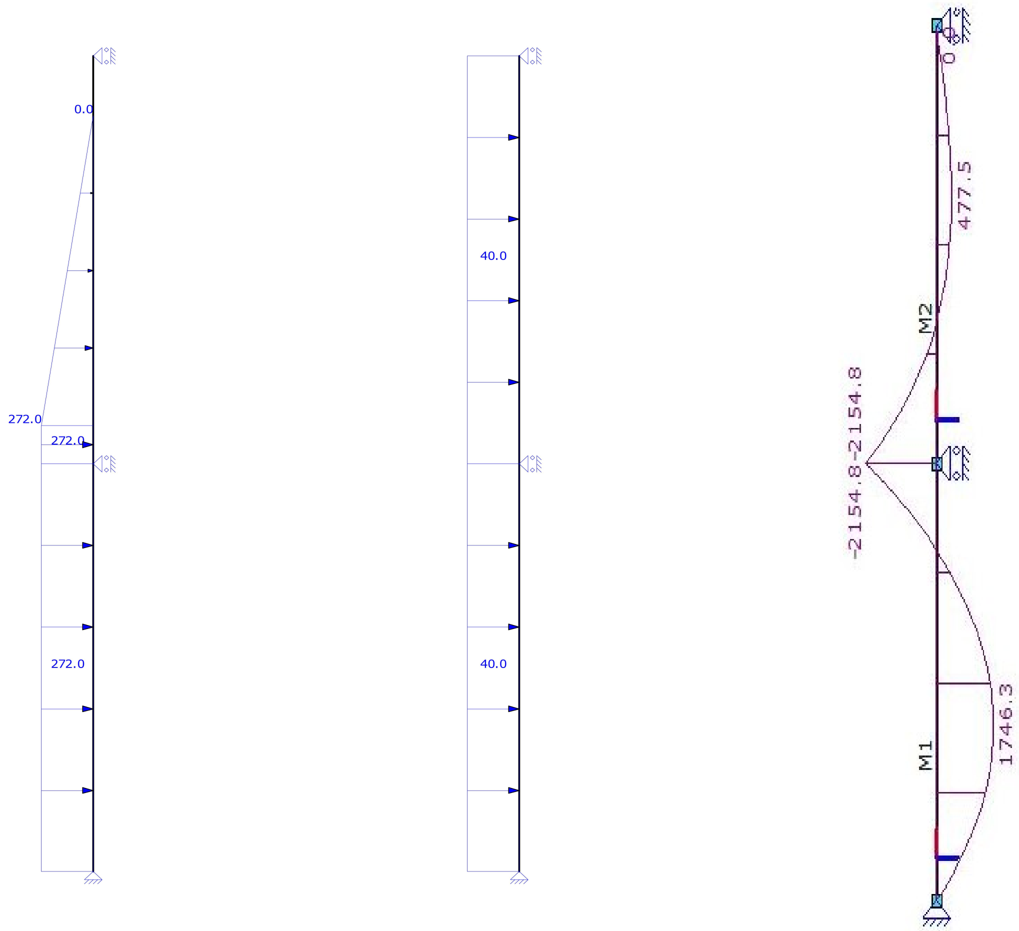
E = Elastic modulus [N/mm^2]

I = Moment of inertia [mm^4]

L_b = Buckling length [mm]

E.10 Load schematisation and moments girders

In Figure E.15a and Figure E.15b the hydrostatic and hydrodynamic loads on the girder are schematised. In Figure E.15c the resulting moments can be seen.



(a) Hydrostatic load on vertical girder

(b) Hydrodynamic load vertical girder

(c) Moments vertical girder

Figure E.15: Loads and moment vertical girder

E.11 Dimensions and internal bending moments of the storm surge barrier

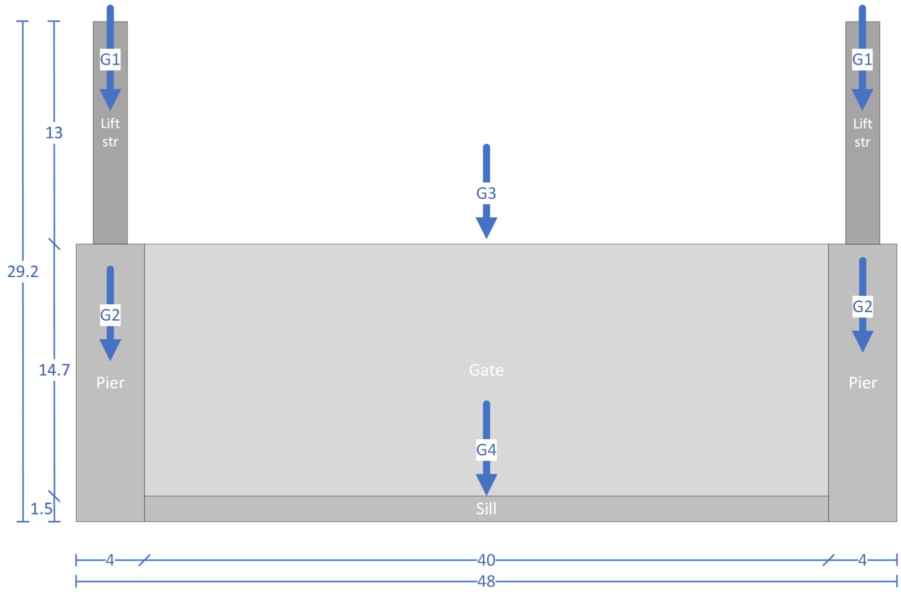


Figure E.16: Front view of the storm surge barrier

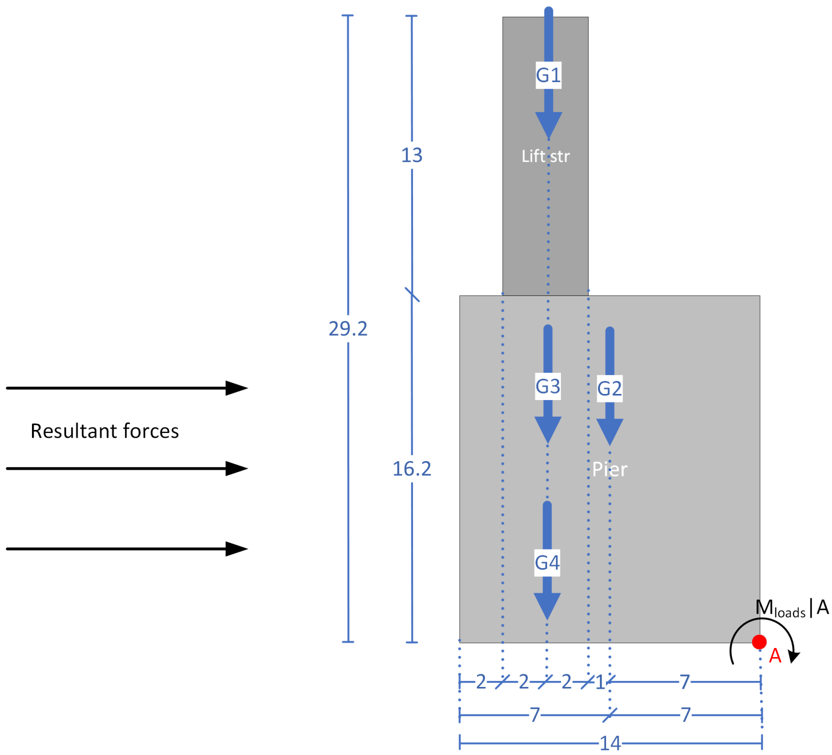


Figure E.17: Cross section with loads of the storm surge barrier for LC1

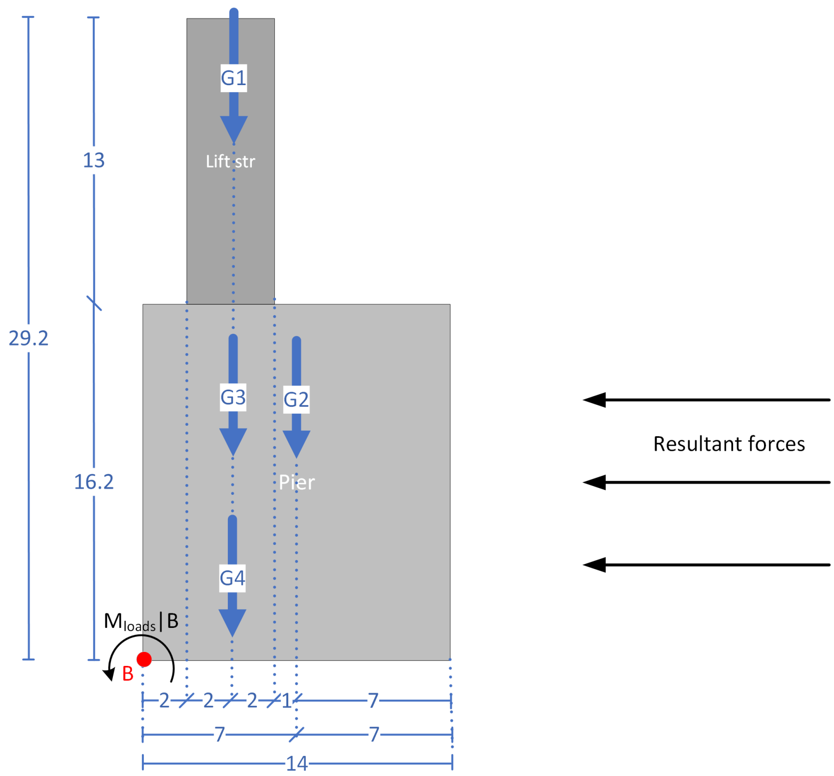


Figure E.18: Cross section with loads of the storm surge barrier for LC2

G1 until G4 are calculated by multiplying the volume of the element by the density of reinforced concrete (2500 kg/m^3) and subtracting the buoyancy force. The buoyancy force is dependent on the current water level on both sides of the gate. This is a too detailed calculation for a primarily design. It is conservative to assume that the water level is equal to the maximum water level of the sea, so this assumption is made for the pier. Therefore, the buoyancy force will also work halfway the length of the pier. For the gate, the buoyancy is also dependent water levels and whether the frames are submerged or not. Furthermore, it is also dependent on what side of the gate is submerged, because only 1 side is shielded by a skin plate. This skin plate prevents the frames from becoming submerged. For this simplicity of this calculation it is therefore assumed in which the maximum buoyancy takes place. This is when the river water level is at its maximum, which is the case for LC4 with a river water level of 13 m. Around 90% of the gates volume is then submerged. For the calculation of the buoyancy fore, the density of salty seawater (1020 kg/m^3) is multiplied by the "submerged" volume.

Table E.3: Internal forces acting on the storm surge barrier

Element	Self weight [MN]	dA [m]	M|A [MNm]	dB [m]	M|B [MNm]
G1 (Lifting structure)	5.1	10.0	-51	4.0	20
G2 (Pier)	13.9	7.0	-97	7.0	97
G3 (Gate)	8.1	10.0	-81	4.0	32
G4 (Sill)	6.1	10.0	-61	4.0	24
Total	33.1		-290		174

E.12 The elevation of the water and barrier during operation

The height of the gate has been determined in a way, such that the maximum significant wave height at location 1 will be stopped while the maximum sea water level of 15.1 m is present (=LC1). Therefore, the gate height is equal to 14.7 m, as visible in Figure E.19. For the lifting structure, the height has been designed to be able to let the maximum water level of 13 m flow underneath the gate (=LC2). This resulted in that the top of the lifting structure is 27.7 m. In case of a gate opening failure (=LC3), the gate is open when there is a storm coming from the sea. In that case, not all the water will be able to flow underneath the gate, because its designed to allow the maximum river water level to flow underneath the gate. The sea water level from the sea is higher, so 2.1 m of the water will cause a hydrostatic load and 1.1 m will be exposed to wave impact against the gate. For this primarily design, this calculation will not be executed. For this calculation, it will be assumed that the gate will be raised 3.2 metre further out of the water such that the sea water could flow underneath. The wave impact is in the same order of magnitude as the wind load which supports this assumption. For LC4 and LC7, the gates are also opened but water levels are low enough to let the water flow underneath.

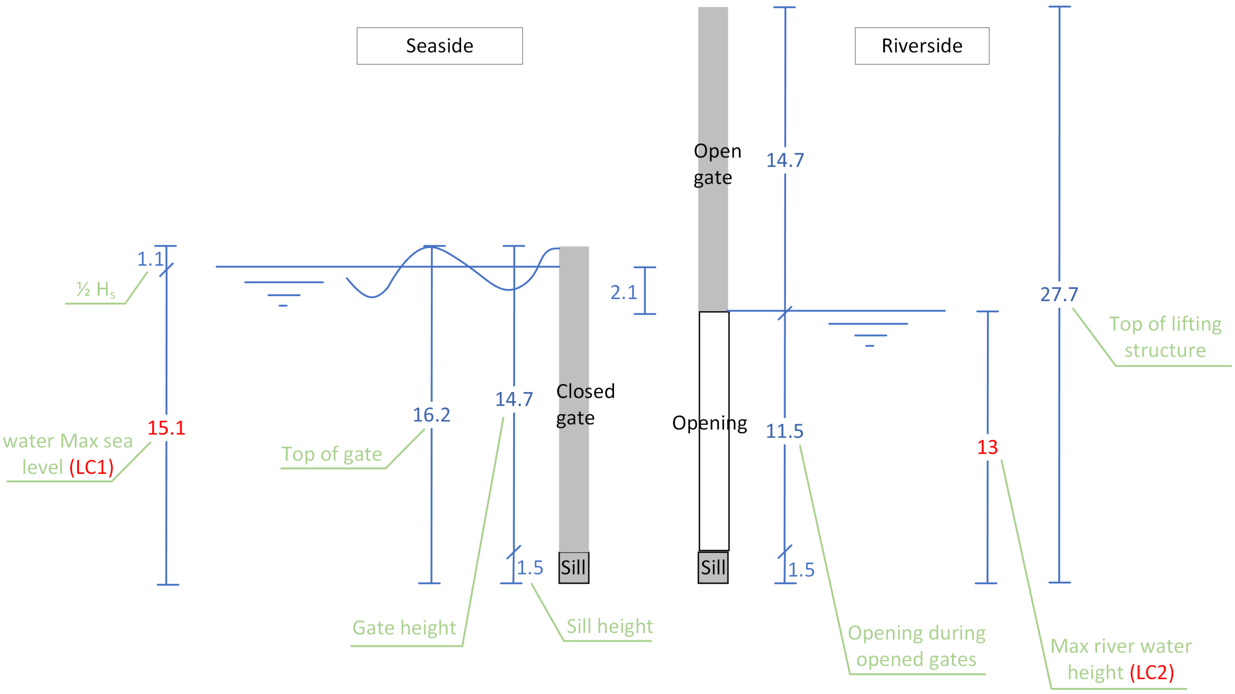


Figure E.19: The heights of the water and barrier during operation and rest. For this figure, the sea water level for LC1 is drawn on the left and the river water level for LC2 is drawn on the right, both in red. This is not an existing LC, but is used to explain complications during operation.

E.13 Moments and forces resulting from external loads

With the help of Figure 7.7, the moments and horizontal force can be calculated. The static hydrostatic load is multiplied by the permanent safety factor and the wind load, Morison load or wave load are multiplied by the variable safety factor. These factors are 1.35 and 1.5 relatively. Furthermore, the static loads, wind loads and wave loads are multiplied by the width of the gate and pier. So now, the moments and loads are not per metre depth anymore. The results are visible in Table E.4

Table E.4: Bending moments and horizontal forces per LCs, resulting from the load schematisation

	LC1	LC2	LC3	LC4	LC5	LC7
$\sum M$ [MNm]	271	-135	18	-16	161	16
$\sum F$ [MN]	55	-35	1.0	-0.9	37	1.0

For LC1, the maximum bending moment resulting from the external hydrostatic and hydrodynamic loads around point A, is equal to 271 MNm (clockwise). The bending moment resulting from the self-weight of the structure is -290 MNm (anticlockwise) so the pier will not start to rotate around point A. The UC is 0.94 for LC1. Note that the gate and sill will also resist the rotation of the pier with its self-weight.

For LC2, the maximum bending moment resulting from the external hydrostatic and hydrodynamic loads around point B, is equal to -135 MN (anticlockwise). The self-weight of the structure creates a bending moment of 174 (clockwise) which is enough to resist the rotation around point B. The UC is 0.77 for LC2.

E.14 Top view storm surge barrier

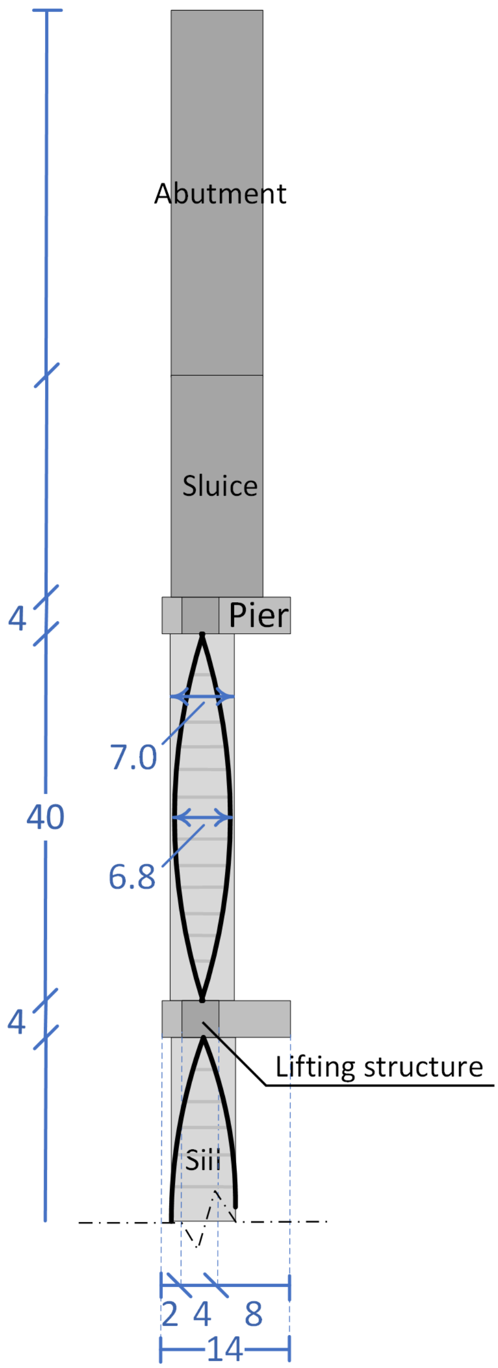


Figure E.20: Top view of the storm surge barrier with a potential sluice and abutment for future plans with unknown dimensions

E.15 Bed protection calculations

For the design of the bed protection to prevent clear-water scour behind the sill, the following formula was used (Schiereck & Verhagen, 2012):

$$\frac{h_{se}}{h_0} = \frac{0.5\alpha\bar{u} - \bar{u}_c}{\bar{u}_c} \quad (28)$$

In which:

h_{se} = scour depth [m]

h_0 = initial water depth [m]

$\alpha = 2$ [-]

$\bar{u}$ = flow velocity [m/s]

$\bar{u_c}$ = critical flow velocity [m/s]

For the calculation of the needed length of the scour protection, a situation with very low water levels (LAT = 7 m) and the highest occurring flow velocities (2 m/s) is assumed. The critical flow velocity is based on the assumed grain size of 200 μ m (Appendix B.6) and is defined as 0.35 m/s. A value of 2 for α is taken, as the relation between the sill height (1.5 m) and water level gives a value of 0.125 (see Figure E.21).

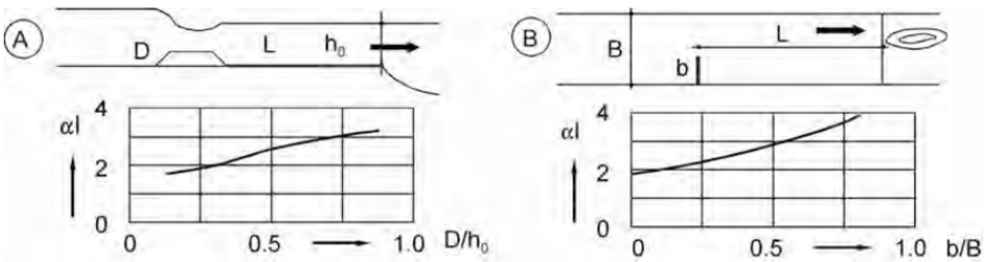


Figure E.21: α value for scour protection (Schiereck & Verhagen, 2012)

This calculation results in an expected scour depth of 56 m. Assuming a slope of slide of 1:15 gives a needed protection length of 850 m.

In order to make a first estimation on the needed grain size on the scour protection, the Shields formula is used (Schiereck & Verhagen, 2012):

$$D_{n50} = \frac{{K_v}^2 u^2}{\psi_c \Delta C^2} \quad (29)$$

In which:

D_{n50} = grain size of top layer [m]

K_v = separation factor [-]

u = flow velocity [m/s]

ψ_c = Shields parameter [-]

Δ = relative density [kg/m^3]

C = Chézy coefficient [m$^{1/2}$/s]

The most critical location regarding the needed grain size of the protection layer, is just behind the reattachment zone downstream of the barrier. This is the location where the flow velocity is at its highest. The factor K_v is accounting for the induced turbulence due to the separation of flow behind the sill. By using the initial water depth of 12 m and the sill height of 1.5 m, a value of 1.27 for the K_v-coefficient can be determined in Figure E.22.

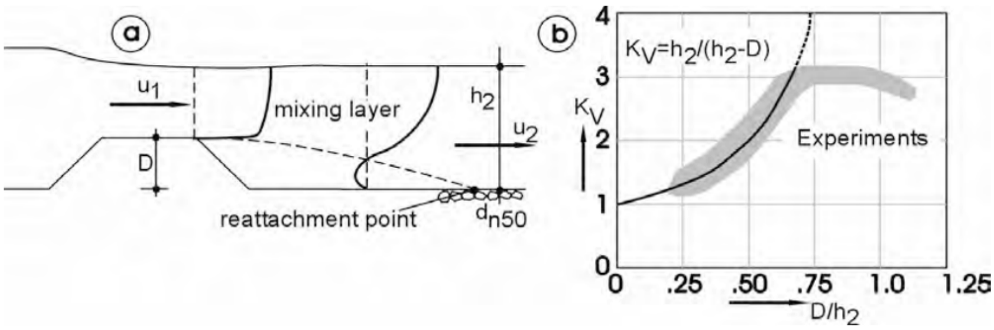


Figure E.22: K_v coefficient behind sill (Schiereck & Verhagen, 2012)

Besides the turbulence related to the reattachment zone, in general a turbulence related to turbulent flow should be included when defining the flow velocity:

$$u = u(1 + 3r) \tag{30}$$

This results in an effective flow velocity of 3.52 m/s. The value of ψ_c (Shields parameter) is chosen as 0.03, as this value is considered as the safest value that corresponds to no transport and highest stability (Schiereck & Verhagen, 2012). The relative density is related to the density of the used material and the density of the water. Using material with a density of 2650 kg/m^3 and a density of 1000 kg/m^3 for fresh water leads to a value of Δ=1.65. The value of the Chézy coefficient is iteratively calculated with:

$$C = 18 * \log\left(12\frac{h}{k_r}\right) \tag{31}$$

In which:

h = initial water depth [m]

k_r = roughness ($\approx 2D_{n50}$)

In an iterative way, these equations are used to determine the grain size of the upper protection layer. The result is a D_{50} of 0.34 m (D_{n50}= 0.28 m). This corresponds to the grading LM$_A$ 40-200.

For calculating the needed bed protection to prevent scour induces by wave action on the closed barriers, the following equation is use (Voorendt, 2022):

$$h_{\max} = 0.4 \cdot H\left(\sinh\left(\frac{2 \cdot \pi \cdot h_0}{\lambda}\right)\right)^{-1.35} \tag{32}$$

In which:

H = Wave height [m]

h_0 = Water depth [m]

λ = Wave length [m]

The most critical combination of water depth and wave height is formed by LAT (7 m) in combination with the maximum expected wave height (2.2 m). This situation leads to scour depth of 0.002 m. Is is expected that the designed scour protection to prevent clear-water scour will be sufficient to prevent scour due to wave action at a closed gate.

Appendix F Meetings

During the time in Vietnam the research mostly took place in Hanoi, the capital of the country. During a two-week trip to the south of Vietnam to study the area of interest, HCMC was also visited. In this city, a lot of government institutions and companies are situated that relate their research to the Mekong Delta. During the stay, research was done at the SIWRP which provided a lot of helpful information. There were meetings with experts from this institute about the Ham Luong River. Furthermore, Royal HaskoningDHV, a Dutch company that is an expert in consulting engineering and has done a lot of research on the Mekong Delta, was visited. The company has contributed to the Mekong Delta Regional Masterplan and is involved in various projects in the area. Also, the ICOE was visited, which is another institution from the Vietnamese government. They also provided information and insights about the subject. During all of the visits, a presentation was given by the MDP group about the progress of the project and the preliminary findings. The institutions and company also prepared their own presentations about their work related to the Mekong Delta. Afterwards, a fruitful discussion was held about the topics. In this appendix, the different meetings are reported in more details, but the most important take-aways are:

- The Delft3D model is quite limited in scope and processes, which should be taken into account in evaluating the results.
- Closing one estuary has a big effect on other estuaries and will only protect a limited area. The dykes need to be raised in the case of a barrier placement, as well as the case of no barrier.
- The increase of salinity is not necessarily a bad thing, and could also be considered as an opportunity. The affected people can adapt to it
- In agri- and aquaculture the tidal fluctuation is used for watering and draining, while saving energy.
- The Vietnamese people already adapt to the changing circumstances and they can continue to do so, since climate change is relatively slow.
- Adaptation can be combined with Building with Nature.
- The Cai Lon barrier, in the west of the Mekong Delta, was deemed necessary but the operation schedule still allows for salt intrusion and there is a lot of controversy over that barrier.

F.1 Meeting SIWRP

Date: 25-09-2023

Location: SIWRP office HCMC

Present:

D. Duc Do	Head of the institute
L. Thanh Dang	Deputy Director of the Institute
D. Thanh Nguyen	Vice Director of the Center for Disaster and Climate Change
B. Hong Tran	Employee
L. Nguyen	Employee
S. Bao Ngoc Hoang	Employee
H. Thu Thi Nguyen	Employee
N. Trung Nguyen	Employee

The SIWRP is an institute that is connected to the MARD. It focuses on research about irrigational planning, and water flows in the Mekong Delta and the southern regions. A short summary about the meeting is given below. The discussion has been subdivided into several main topics but they are all interconnected and were discussed interchangeably during the meeting.

Figure F.1: Presentation at SIWRP

Modelling
At the SIWRP the modellers work with Mike11 in 1D which can be used to obtain flow speeds. This program uses Qgis and Gis, and they use Sobek as well. A 1D-model of the entire Mekong Delta exists within the SIWRP. The used discharge values are based on the discharge upstream in Kratie, Cambodia. About 10% of this discharge goes into the Ham Luong estuary. During the dry season, 3000 m^3/s comes in from the Upper Mekong Basin. Then 70% is divided over the 9 river mouths.

Our Delft3D model that is used for the Ham Luong River, is a 2D model for only the Ham Luong estuary. The 2D is considered to be sufficient, according to SWIRP. There is a huge discharge from the river into the sea, so the water distribution will change. The effect of the closure of the Ham Luong estuary on other rivers is important, but this effect is not included in our model. Our model is more useful to choose the location of the sluice gate than the impact on connected rivers and the upstream. The shortcoming of our model must be reflected on in our report. The brackish area in the Ham Luong estuary makes it easy to see the effect on salt water. However, water level changes take longer to see in the model. Biodiversity changes take very long and are impossible to see now at this moment. Literature raises this issue. A comparison with the big barrier in the Netherlands could be useful. It rarely closes and is only operated for big storms. It is good to see the big picture.

Furthermore, the RCP8.5 is correct for long term. For mid term, the RCP4.5 is used. For the return period, 100 years must be used for a structure. So 0.5% or 1%. There are some standards for that, but in general, 100 years is considered.

Barrier
When building a barrier the most important questions are: Is the Ham Luong estuary important for the Mekong Delta or not? Should we build the gate and where? To answer these questions the model and project need to cover more of the Mekong Delta and Delft3D might not be suitable for that.

The SIWRP has used a number of criteria for the choice of location:

1. Transportation with a connection between the gate and the road
2. The road along the sea dyke; connect with the sluice gate or not
3. Smallest width of the estuary for the gate placement
4. Effects on fresh water and salt intrusion
5. Hydrodynamic loads (tidal range, storm surge, waves)

The goal is to get control of fresh water in the Mekong Delta. The effect of the barrier on the shortage of fresh water, with the SLR, salt intrusion and inundation.

Considering storm surge from sea. The SIWRP did not study heavily about the environment. The tidal change in the West Sea and East Sea are different but very high. The environmental impact has to be considered when a big structure like the Ham Luong barrier would be constructed.

The geology is not very different over the length of the Ham Luong estuary. For a big structure, it can be regarded the same, because the foundation is 40 m below ground. In the early Mekong Delta Plan, hydraulic impacts from the sea were the main focus. The newer plan looks more upstream and more to the freshwater storage upstream. A barrier on location 3 has less hydrodynamic impact and less storm surge impact. Before, the SIWRP looked into other locations (more downstream), but now we prefer location 3. Small side channels will be (or are) closed with sluices and freshwater intake gates.

Multi Criteria analysis
Regarding the MCA it was not yet clear what was meant with agricultural adaptation. It must be clear what is meant with this in the report. Disaster prevention and water supply are clear. It is also good to look at more specific criteria. Change and social effects are interesting. Furthermore, river morphology was not mentioned, this could be a good criteria to investigate as well.

Figure F.2: Group photo with Bao in front of the SIWRP building

F.2 Meeting Royal HaskoningDHV

Date: 26-09-2023

Location: Royal HaskoningDHV Office HCMC

Present:

A. Le Ngoc	Senior Coastal Modelling Engineer
H. Hoang	Modelling Specialist

Royal HaskoningDHV has been contributing to the Mekong Delta Master Plan. There were 2 studies made, one in 2013 (not approved by the government) and one in 2021 (funded by the Vietnam government, the first regional planning approved in Vietnam). They have been involved in projects in the Mekong Delta for years, making them experts in the area. Below is a short summary given about the meeting. The discussion has been subdivided into several main topics but they are all interconnected and were discussed interchangeably during the meeting.

Adaptation
In the coastal area, the land use could change from agricultural to forestry. This is more sustainable and water quality will increase. Taking into account cost-benefit analysis, the rice is very cheap, shrimp is more valuable. Upstream, along the border of Vietnam the proposed solution is flood-based agriculture. Irrigation in the area is really developed; there are 3.5 rice crops a year. Soil quality becomes reduced due to extensive harvesting. With flood-based agriculture: Fish in the flood season, and rice in the dry season is a solution for this problem. More sediment from the floods will be on the land. The bed will become better and no pesticides have to be used. Regarding the brackish area; do not make it fresh, but keep it brackish. That is the new approach from Royal HaskoningDHV. An intermediate/intermittent zone must be kept, not completely fresh like before. Change rice for shrimp for the agricultural sector. Coconut can also survive in brackish area.

In the Go Cong district shrimp farms are right next to the sea. The people have to accept brackish-fresh zones. People are already adapting to salt water. There have not been any direct interviews done by Royal HaskoningDHV, however this was observed from satellite imagery. People have learned from their own experiences. For example they know that, when they need fresh water, they collect and store it in April and May, so they retain the water, because later in the year there will not be enough fresh water.

If everyone in the coastal area changes to shrimp and coconut, prices will not decrease. Shrimp and Coconut have a price on the global market, so it will not be affected that much. Considering food security in Vietnam there is enough rice for the people. If some areas change to shrimp and coconut this is not an issue. Rice fields have 1.8 million hectares, only 300.000 hectares can be changed into intermittent zone. Pineapple has a domestic and global market as well.

About fresh water: Fresh water for domestic use is small part. They can use fresh water from upstream for instance from My Tho. Furthermore, is agricultural fresh water necessary? During low tide you can also take the fresh water in. Side channels are also used. Use pumps for a freshwater supply more upstream. Groundwater extraction results in land subsidence, salt in the soil and polluted soil. Currently they use a deep layer to get groundwater. Problems could be caused by upstream factors, such as outtake of fresh water in upstream areas.

Modelling
For the upstream boundary of the model My thuan is not far enough for the Delft3D model. If the branch were to be closed, water would flow to another branch. For a thesis, include the Mekong River to the border of Vietnam and Cambodia. Furthermore, there is a 1D model of the Mekong from Cambodia to the sea in Mike11.

Storm surge is only one case (in 20 years, there has been 1 storm), there are no storm surges in Southern Vietnam. Storm surge is not significant. Flood is not related to the wet season but to tidal amplifications.

Local people
For irrigation the inhabitants of the Mekong Delta use tidal fluctuation, when to drain it wait for the low water, if they need water they wait for high water. The tidal difference of 3 m/day, while the land is 1 m below sea level, is useful to save energy. They use this to make their living. Shrimp can use brackish water. When a barrier is closed during dry season, farmers have to use fresh water for all activities, since there will not be any brackish water available due to the closure. Shrimp farms will also need salt.

People are also willing to change. A lot of locations on maps were shown where adaptation already took place. People changed to shrimp farms. Besides, the experts at Royal HaskoningDHV think the brackish border only moves up about 10-12 km inland, for SLR of 1 metre. A 100 year time period is a lot of time to prepare for adaptation and climate change.

In Tra Vinh area there is a brackish area and a shrimp area. There is a change from fresh to brackish water. People will adapt to their income. If we close it off, fresh water will only be there. Water will be used from inland channels and rivers.

The income from shrimp is high, while investment is also high. Some of the farmers like to work the easy way and keep the fresh water. They don not want high investment and keep their rice crops. If you accept that some parts will become saltier, salt water is not a problem.

Barrier

For the barrier it must be taken into account that an island (location) may not be a stable location. An existing barrier is located in the Ba Lai River. Due to the barrier the water quality is very low and there is an sedimentation issue. For Ba Lai it was also the idea to store fresh water but this is a failure.

The Cai Lon barrier in the west of the Mekong Delta, is 500 metres wide. They want to close it for salt water and get fresh water from the Hau River. But people already use salt for their agriculture. The cost of water is very high because it is pumped from the Hau River. Rice is not that beneficial, so you have to think why you want to keep the fresh water area. Shrimp is more beneficial. 15 years ago the Cai lon was planned, then they thought it was a good plan. Now people have questions about it. The river gates still has to be open at high tide so the salt will still intrude in the channel.

Mekong Delta plan was presented. The MARD said that they want to build a barrier. An alternative approach is to make a dyke along the rivers. It is cheaper and easier to build. One gate has impact for 500 hectares only. The Mekong Delta has more mouths: closing one has effect on others. If you build one gate, you should make more gates. More adaptation is the better way.

Figure F.3: Interaction and discussion during the meeting at Royal HaskoningDHV

F.3 Meeting ICOE

Date: 29-09-2023

Location: ICOE Office HCMC

Present:

H. Manh Phan	Head of the section mathematic modelling and GIS
Several other employees	

The ICOE is an organisation that conducts research on hydraulic engineering, sediment, climate and coastal areas in Vietnam. The institute is connected to MARD. During the meeting several experts from different disciplines were present. There were experts on oceanography, geoscience and remote sensing, forests, hydraulic structures, environment management, hydrology, natural resources and environment, coast protection and infrastructure. The focus of the ICOE in Ben Tre is on hydrodynamics, rainfall, climate change. Below a short summary is given about the meeting. The discussion has been subdivided into several main topics but they are all interconnected and were discussed interchangeably during the meeting.

Figure F.4: Presentation from ICOE concerning the Mekong Delta

Climate
It was confirmed that during the dry season storms do not occur. Every two years there is one storm. Wind velocities are about 16 m/s. A lot of dams are built which has caused the flow from upstream to decrease.

Adaptation
Upstream flow decreases because water is transferred to other areas (for example for irrigation purposes). Sluice gates are considered by the government because of the shortage of freshwater supply; to keep fresh water in the Mekong Delta. Vietnamese are good at adapting. Land use changes because of SLR, fortunately, the profits are also higher for saline agriculture.

Climate change/SLR change, but slowly. The structure is very sudden, so the change is significant. The effects are clearly visible. Before, the shrimp farm area was very small. Due to SLR more salt intrusion occurs. Therefore the land use changed from rice crop to shrimp farm gradually.

Upstream flow decreases because water is transferred to other areas (for example irrigation purposes). Sluice gates are considered by the government because of the shortage of freshwater supply; to keep fresh water in the Mekong Delta. Vietnamese are good at adapting. Land use changes because of SLR, fortunately, the profits are also higher for saline agriculture.

The ICOE has made a tool that predicts the water levels at multiple locations in the Mekong Delta. It alerts local people when to protect their property. There are three levels of warnings. This information is passed to the local administration and they will inform the local people. The tool is based on measured water level data from 20 years before.

Modelling
The tidal range is increasing. The tide is higher every year with about 10 mm/year. SLR is about 3 mm/year, subsidence is around 7-8 mm/year. Subsidence rates are about three times larger than SLR. Ben Tre area is average in elevation with respect to the rest of the Mekong Delta. SLR in Binh Dai in Ben Tre was roughly 41 cm in 30 years, also including land subsidence. Some areas have more problems than other areas, which is why they receive more money.

Furthermore, rainfall decreases, but extreme rainfall increases. The flow percentage of the Ham Luong River from the upstream discharge at Kratie is the following:

Year 2000	9%
Dry season	12%
Flood season	7%

Local people

A barrier affects the Southern people. They heard a lot about building with nature. This type of structure is not "building with nature". The structure is built for salt intrusion and storm surges. It will affect biodiversity, it will change the habitat/lifestyle of the local people. When a structure is built they have to change agriculture. They just use rice crops. But they have to adapt if this type of structure is built.

Barrier
Just two years ago, the Cai Lon barrier was built. A lot of people did not want the barrier. When looking at cost-benefit it might be a good idea. The occupations of the people in the west is also agriculture. Similar to people living in Ben Tre Province. The ICOE did not decide on the project, but they were involved in the research. In their research, they mainly focus on the effect of salinity on agriculture. The conclusion is: we have to built. There was more benefit than cost so it was built. Vietnam government has not yet decided yet about the Ham Luong River.

There is a lot of sedimentation in the Bai Lai branch. This was shown during the discussion on a map.

Provided data
The ICOE has no data on water quality in Ben Tre, but mainly on the provinces in the west of the delta. The institute has discharge and current data in Ben Tre, water level, and sediment. The measurement stations are from the institute. Salinity data from January to May in An Thuan. The institute provided data about the following:

- Water level and discharge for 20 years in Ham Luong River
- Salinity data from January to May (dry season) in An Thuan
- Suspended sediment data in the Ham Luong River
- Dyke heights and failure of the dykes

Figure F.5: Group photo with the employees of ICOE

Appendix G Survey Ben Tre

As stated in the Section 2, a survey was conducted to gather local stakeholders' current opinions and knowledge in Ben Tre Province. The survey questions were designed to find out what functions or aspects of the Ham Luong estuary are most important in their daily life.

The survey was short and consisted of three parts. First, personal information about age, location, and occupation was asked. After that, the participants were asked if they have noticed changes related to climate change and if they could give examples of it. Then the participants were asked to put the statements below in the boxes that they associated it the most with. Each box could only contain one number. To the right the issues with which the participant most strongly disagreed were listed and to the left the issues with which the participant the most strongly agreed with. This is an interview method based on Q methodology, also known as Q-sort. This method is used to study the viewpoint of people on a certain topic using psychology. Q-sort is based on the fact that participants have to rank a group of questions or statements, in this case the issues around the Ham Luong River that are listed below. This is done in such a way that it reflects their viewpoint the best. The participants have no choice but to rank the options, as they can not be all equally important (van Hamel, 2018). The last questions were open questions that allowed the participants to comment on the choices that they had made. Below the list of statements is displayed:

1. Availability of fresh water
2. Availability of both fresh and salt water
3. Enough fish to catch
4. Ability to use boats on the river
5. Avoiding floods
6. Preventing erosion
7. Stable employment
8. Environment, ecology, and landscape
9. Management and intervention in the river and estuary area

This structure was chosen to make the survey fast and clear. The questions were answered on paper. The participants were randomly selected, with the aim of including a diverse range of people with different occupations. During the survey crowded places were visited such as a ferry station and a local coffee shop.

The results of the survey turned out not to be very useful. Although we had three Vietnamese people with us to make clear to the participants what the survey was about, it turned out to be difficult to gather good results. In the end only thirteen filled-in surveys were collected. There were various reasons why the survey was not a great success:

- The participants sometimes did not understand the survey correctly. For instance, multiple numbers were placed in the same box and sometimes not everything was filled in.
- Participants seemed to influence or copy each other's answers. Some participants sat together to fill out the survey. One of the participants did not fill in the survey because he said he had the exact same opinion as another participant. They mentioned this on their survey sheet.
- The explanation and filling out of the survey took very long per person. Therefore not a lot of answers could be collected in the short time that we were in the area.
- Participants seemed not to care so much about the survey. They only filled in what they found interesting and left the other parts blank.
- Some of the results were also influenced by a Vietnamese translator who helped us to explain the survey to the participants. When the results were incomplete, they were filled in by the translator instead of the participant.
- Some of the participants did not trust the survey and did not give honest answers, being afraid that he/she might give away information that could affect him/her negatively.

- Some experts mentioned that people in Ben Tre do not often think about the effect of climate change but are more busy with their day to day activities. If they are asked to give their opinion about our subject, they have not thought about their opinion yet.

During collecting results people also gave information about their experiences. A woman working at a café mentioned that occasionally the water pumped for domestic use has a salty taste. One fisherman said that some of his fish die. He believes that the water is more polluted than it used to be, which he thinks is the reason for his fish dying. What also emerges from the thirteen survey results is that most people considered statement 1, the availability of fresh water, important. Additionally, certain individuals, such as fishermen, emphasized the significance of statements 2 and 3. Furthermore, in our conversations with the local people, we noticed that they primarily value statements that have a large impact on their daily lifes. For instance, statements 6, 8 and 9 were frequently seemed unimportant by the people in Ben Tre.

For surveys in the future, it is recommended to visit public places as was done for this survey. People from different kinds of occupations visit these places so it is easier to get fast and diverse responses. A cafe, restaurant or other place where people are not busy with their job is also recommended. For the layout of the structure itself it is recommended to make it simpler. Probably, most participants had not seen a survey like this before which made it difficult to explain and eventually for the participants to fill out. Therefore, yes and no questions are recommended. Furthermore, it is almost impossible to explain a survey when Vietnamese is not your spoken language. Bring translators to explain the survey, and even then it can be very difficult as was experienced. The Vietnamese people that are used as translators must be instructed carefully because otherwise they can influence the results. With only 4 hours for conducting our survey, it is recommended to have at least a full day with Vietnamese translators to conduct the survey effectively. Officially for conducting a survey in Vietnam it is necessary to get permission from the local authorities. With this permission people trust the survey and they are more likely to fill in the survey. The survey used in this project can be seen on the next page.

Khảo sát từ sinh viên Hà Lan

về sự phát triển ở khu vực

Cửa sông Hàm Luông

Ngày………. Tháng………Năm………………

Tên:……………………………………………….

Tuổi:………………………………………………

Giới tính………………………………………..

Quê quán:…………………………………………

Công việc:……………………………………..

Công việc của bạn có liên quan đến:

Trồng lúa: Có/Không

Cây ăn trái: Có/Không

Đánh bắt cá: Có/Không

Nuôi Tôm: Có/Không

[1] Bạn có cảm nhận được sự thay đổi về biến đổi khí hậu trong cuộc sống hàng ngày không ? Có/Không, làm ơn đưa ra 1 hoặc 2 ví dụ cho sự cảm nhận của bạn

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………………………………..……………………………………………………..

[2] Đối với chất lượng cuộc sống của tôi gần sông Hàm Luông, chúng tôi đã đề xuất 9 vấn đề liên quan như sau:

1. Có đủ nước ngọt
2. Có cả nước ngọt và nước mặn
3. Có đủ cá để đánh bắt
4. Có thể sử dụng thuyền di chuyển trong sông
5. Không bị ngập lụt
6. Không bị xói lở
7. Có công việc ổn định
8. Môi trường, sinh thái & cảnh quan
9. Việc can thiệp, chỉnh trị khu vực sông sông, cửa sông

Hãy đặt 9 vấn đề này vào các ô trong bảng sau, mỗi ô chỉ có thể có một vấn đề, xin cám ơn

Rất đồng ý ++	Đồng ý +	Trung lập 0	Không đồng ý -	Rất không đồng ý - -

[3] Ý kiến, mong muốn góp ý khác của bạn (nếu có)

Vấn đề bạn rất đồng ý vì:

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Vấn đề bạn rất không đồng ý vì:

……

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