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Reducing river inundation in the Hau River estuary

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Preface

This report is the result of a three-month study in Vietnam. During this study the Mekong Delta has been investigated, focusing on the Hau River estuary. During the study period, we stayed in Hanoi to work on the project.

In collaboration with the TU Delft and Thuyloi University this project came about. Within a multidisciplinary context, five students have carried out a research project. The multidisciplinary setting regards the students working together coming from different backgrounds: Hydraulic Engineering (Gerwin and Theun), Structural Engineering (Leander and Lucas) and Transport and Planning (Vincent).

During the project period we have been supervised by Dr. Son and Prof. Trung from Thuyloi University. Many thanks will go out to them for guiding us on a daily basis. They helped us to get in contact with other experts who have proved to be useful for the project. Moreover, we want to thank them for their contribution to the meaningful excursions we have undertaken.

Furthermore, we want to thank the Innovation and Impact centre of the TU Delft for putting us in touch with the people from Thuyloi University. Especially Lindsey Schwidder, who had a key part in getting in contact with the people from Vietnam. One of these contacts was Dr. Thom Bogaard who was of great help during the project. With his expertise in the area and other civil engineering consultancy project groups, he gave us a lot of guidance in the process.

Lastly, we want to thank our supervisors Dr. Ir. Cong Mai Van, Dr. Ir. van Binsbergen and Dr. Kavoura, for providing guidance for us to bring this project to a successful conclusion.

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Hanoi, Thursday 12th January, 2023

Abstract

The Mekong Delta is facing some complicated challenges in the near future. Its geographical location and the fact that it is a delta result in low elevation levels which makes it vulnerable to inundation. This problem will only become bigger in the future due to the effects of climate change. To get funding from organisations like the world bank it is important to propose multiple solutions that are beneficial to multiple parts of society. It is favourable to split a complex system like the Mekong Delta into subsystems to make it more feasible to build realistic models. The subsystem defined in this report is the Hau River estuary. This area mainly suffers from riverine inundation caused by tidal variation in the South Chinese Sea. The biggest city in the region is Can Tho with 1.3 million inhabitants.

The research question is: *Which integrated solutions reduce riverine inundation problems in the Hau River estuary while also considering socio-economical aspects?* To answer this research question the following four solutions are proposed and designed.

- Discharge sluice in the mouth of the Hau River to reduce the tidal influence
- Wetland with a double levee system and buffer zones to reduce peak discharge
- Bypass channel to the Gulf of Thailand to reduce discharge during the wet season
- Protection of valuable assets and adaptation of local citizens to the new natural balance

Based on desired discharges and water levels preliminary design parameters of the proposed hydraulic structures were determined. The effectiveness of these solutions was assessed based on their ability to reduce the water level in Can Tho. The reduction that the discharge sluice achieved was determined with a zero-dimensional model, whereas the water level reduction that the wetlands and bypass option achieved were determined by Delft3D models. The discharge sluice performed best in reducing the water level in Can Tho, as it opposes the tidal influence in the Hau River.

To assess the quality of the solutions relative to each other a best-worst multi-criteria analysis is done. In this assessment other factors such as financial aspects, socio-economics and transportation are taken into account. The most important criteria are flood reduction and funding opportunities. According to the assessed criteria, the discharge sluice and the wetland are the best-scoring solutions. These solutions have the most potential in reducing the river inundation problems in the Hau River estuary. This does not mean that the bypass and adaptation solutions should be neglected or are not useful. For a complex problem in a complex system like the Hau River estuary, one solution is not going to solve all the problems. A good balance between different aspects has to be determined by also considering other problems like sand mining, subsidence and salt intrusion.

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Acronyms

AHP Analytical Hierarchy Process. 17

BWM Best-Worst Method. 98

DWT Dead Weight Tonnage. 45

GIS Geographical Information Systems. 15

HCMC Ho Chi Minh City. 9

IMF International Monetary Fund. 11

LXQ Long Xuyen Quadrangle. 88

MCA Multi-Criteria Analysis. 93

MKD Mekong Delta. 1

O-D Origin-Destination. 37

RR Red River. 52

SIWRR Southern Institute of Water Resources Research. 16

TEU Twenty-foot Equivalent Units. 149

VCR Volume/Capacity Ratio. 48

1 | Introduction

The Mekong Delta (MKD) is part of the Mekong River which has its origin in China and flows via Thailand, Laos and Cambodia into the South Chinese Sea in Vietnam (Figure 1.1). The MKD is located in the southern region of Vietnam and is one of the first big deltas in the world that is in danger (Beckley et al., 2007). It is in danger due to a combination of subsidence, climate change and salinisation. A total of 17.3 million people live in the MKD. The region is the most studied delta in the world for its broad range of problems and complexity. Ultimately, solutions that seem beneficial in the MKD can be used to solve problems in other deltas that face similar issues.

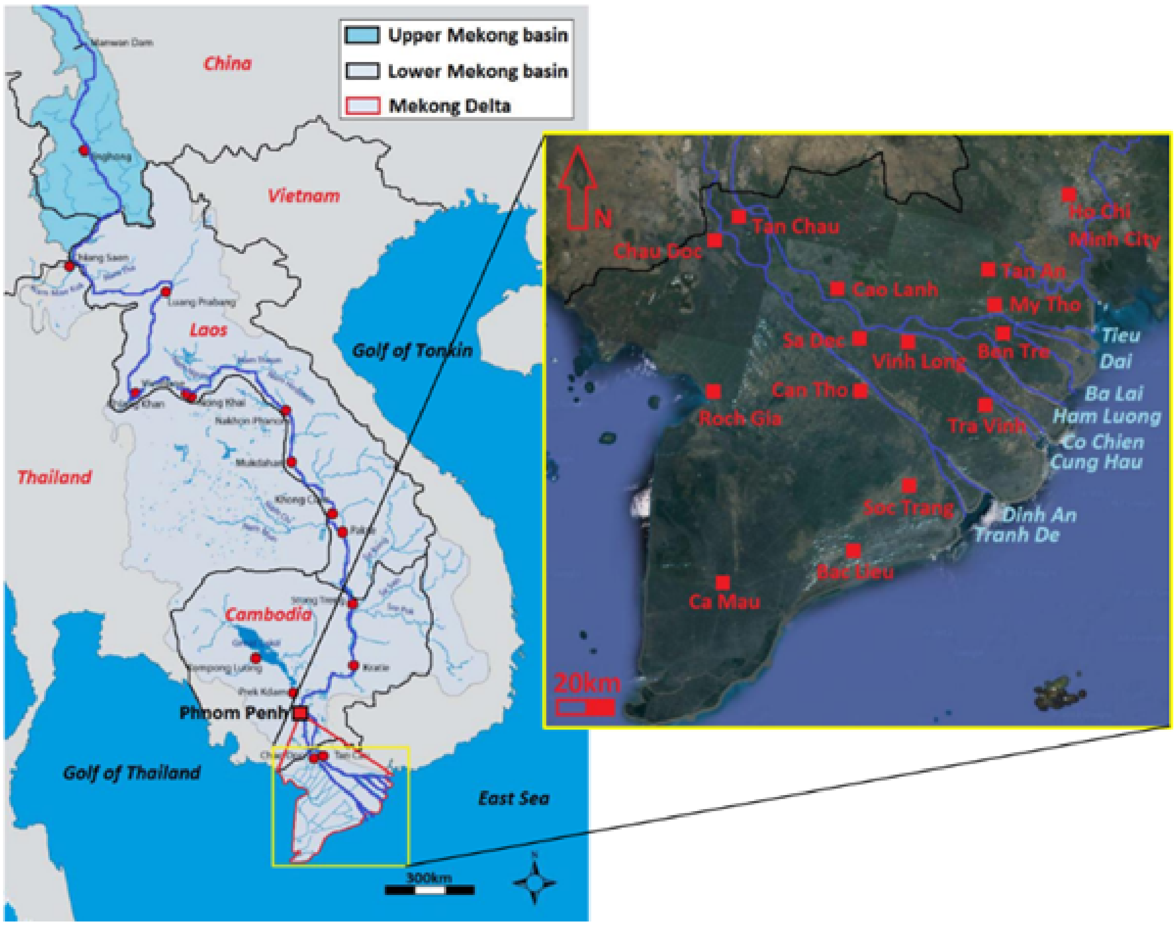
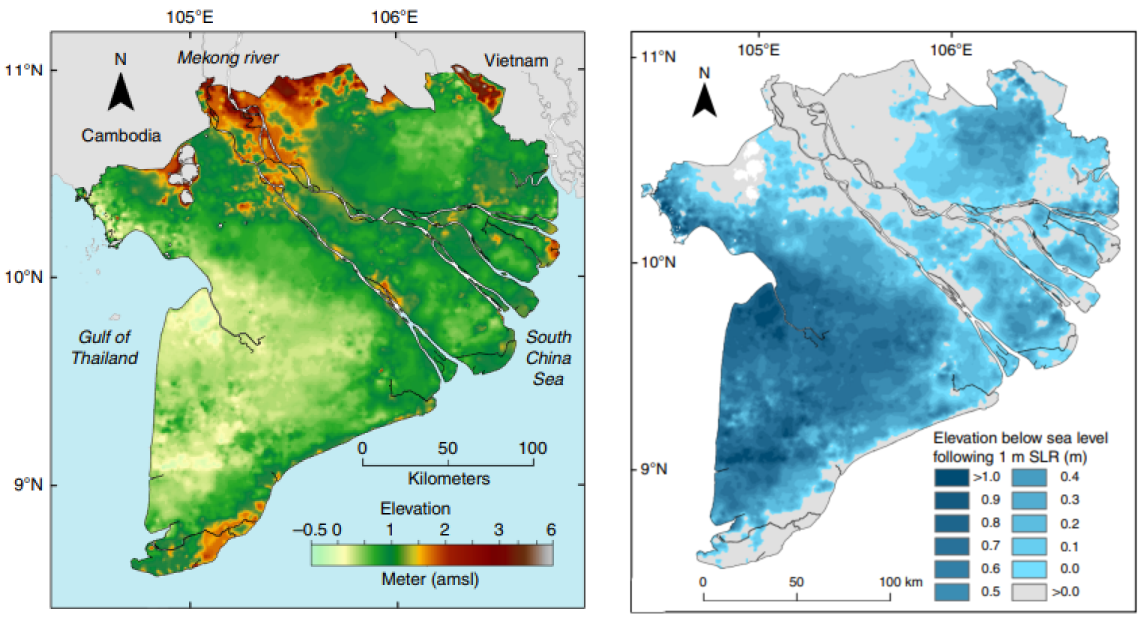


Figure 1.1: MKD with main inhabited areas and basins (MRC, 2011)

1.1 Geography

From My Tho in the east to Chau Đoc and Ha Tien in the northwest, down to Ca Mau at the southernmost tip of Vietnam, the MKD shapes like a triangle of 3.9 million hectares (Veerman, 2013). Upstream of the delta (near Phnom Penh), the Mekong divides into two branches: Bassac (Hau) and Mekong (Tien). The MKD has one of the largest and seemingly lowest elevated delta plains in the world (Syvitski et al., 2009). In 2019, a recently developed digital elevation model sheds a different light on the height of the MKD. The novel elevation model shows that the delta has an extremely low mean elevation of 0.8 m above sea level, dramatically lower than the earlier assumed 2.6 m (Minderhoud et al., 2019).



(a) Elevation map (b) Land below sea level

Figure 1.2: Land elevation MKD (Minderhoud et al., 2019)

Figure 1.2a shows that the MKD has a low elevation level compared to the mean sea level. On top of that the MKD is also relatively flat. The combination of these characteristics makes the delta extremely vulnerable to sea level rise. The lack of elevation also makes it hard to store large bodies of water since it is not possible to place dams to create drainage basins.

1.2 Problem definition

As described in section 1.1 the elevation levels of the area cause the MKD to be prone to inundation. Furthermore, intense agriculture puts a big strain on freshwater resources and has a negative impact on the water quality overall. These factors, in combination with climate change and upstream developments, have an increasingly negative impact on the water resource system of the delta.

These negative impacts follow a trend that is seen in deltas all over the world (Beckley et al., 2007). Most deltas experience the same problems, such as sea-level rise, increasing fluctuations in discharges and the impact of urbanisation. The competitiveness and prosperity of the MKD depend on the efficiency and effectiveness of investments for flood protection, salinity control, water quality and freshwater supply. The main problems in the MKD can be schematised by the flowchart shown in Figure 1.3. In this figure, the blue boxes represent third-party effects, which are not covered in this project. The green boxes represent problems which are addressed in this section.

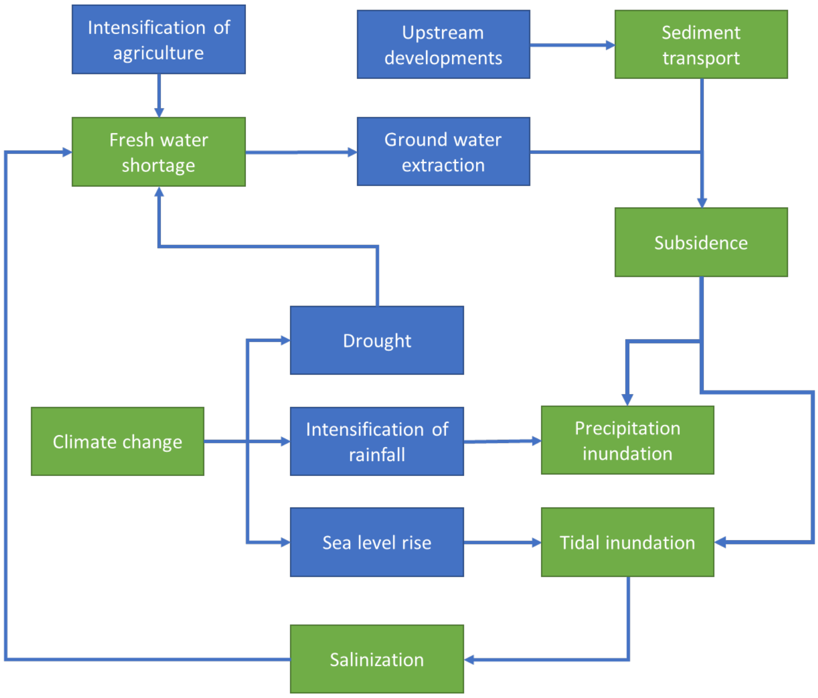


Figure 1.3: Problem definition

1.2.1 Subsidence

The MKD is subsiding with 30 mm/year (Anthony et al., 2015). This is the result of a combination of natural- and human-induced factors. The biggest human-induced causes are groundwater extraction and increased loading of the surface, which also leads to compaction of the soil. Hard structures being built on top of the soil lead to compaction. This compaction then results in the lack of replenishment of new sediments so that the height of the soil can not increase as usual. Normally, the fresh soft sentiment arrives during the wet season and it increases the height of the soil layer. Due to the building of the hard structures, the height can not increase and the excess soil flows away with the river (McGrath, 2019). The increased loading of the surface is mainly caused by large-scale anthropogenic land-use changes that have taken place in the past decade (Minderhoud et al., 2018). A lot of forest area has been converted to agricultural land, mainly used to cultivate rice. This not only increases the loading of the surface but also increases groundwater extraction, which has a negative impact on the water balance. Another main reason for the land-loading increase in urbanisation is a result of the population increase in the area that happened in the past decades (Minderhoud et al., 2018). This accelerated rate of degradation increases coastline regression, flood risk and salinisation of soil and groundwater.

1.2.2 Climate change

The MKD will be one of the first deltas that experience the effects of climate change. As a result of climate change, the sea level rise is expected to be 3.4 mm/year (Beckley et al., 2007). The Hau River is a tidal river and therefore the rising sea level causes problems in the riverine area. Climate change also results in more extreme wet seasons, leading to bigger discharge peaks coming from upstream. The combination of the (local) intensive precipitation and the sea level rise results in inundation problems. Even in the upper delta the river regime is influenced by the sea level (Veerman, 2013). This is depicted in Figure 1.4.

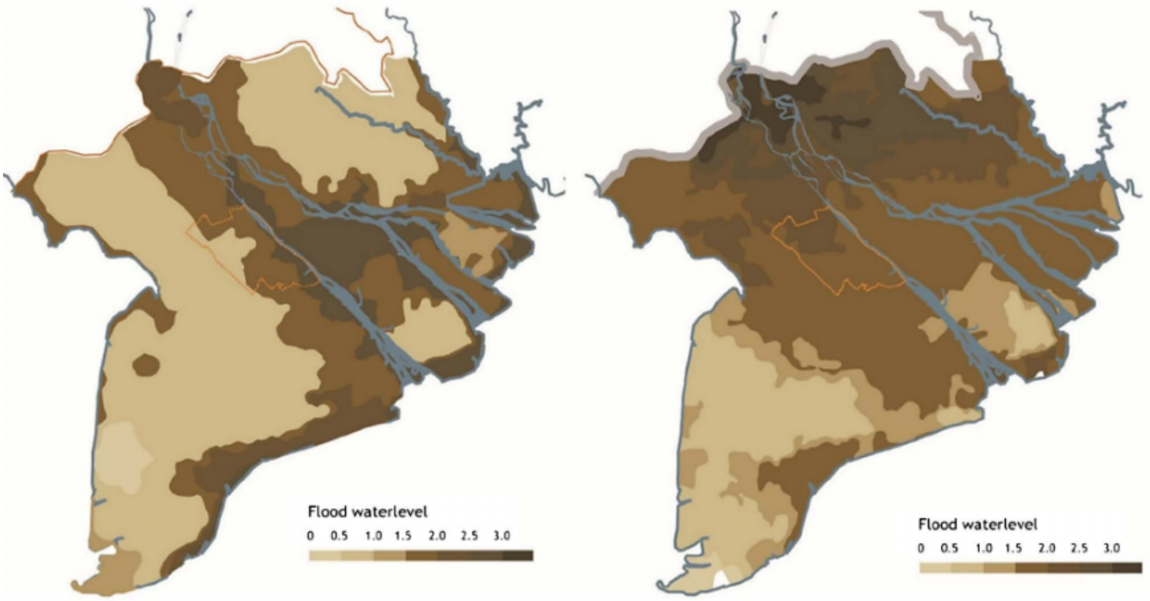


Figure 1.4: Flood map regarding one-meter sea level rise (Siddiqua, 2019)

Reduction of the retention basins and sea level rise eventually increase the water levels in the delta. In combination with the temperature rise and changing precipitation patterns, sea level rise is expected to have a substantial impact on the physical conditions of the MKD. This leads to a range of effects on people's health, livelihood and prosperity. In the flat areas of the delta, the predicted sea level rise can result in large areas of more frequent and even permanently inundated coastal plains. In the city of Can Tho for example, which is located 80 kilometres upstream, some downtown streets are regularly submerged in 0.2-0.6 meters of water (Vo, 2015). Contrary to the effects of sea level rise, the droughts caused by the dry seasons will aggravate. This is caused by the development towards more extreme seasons.

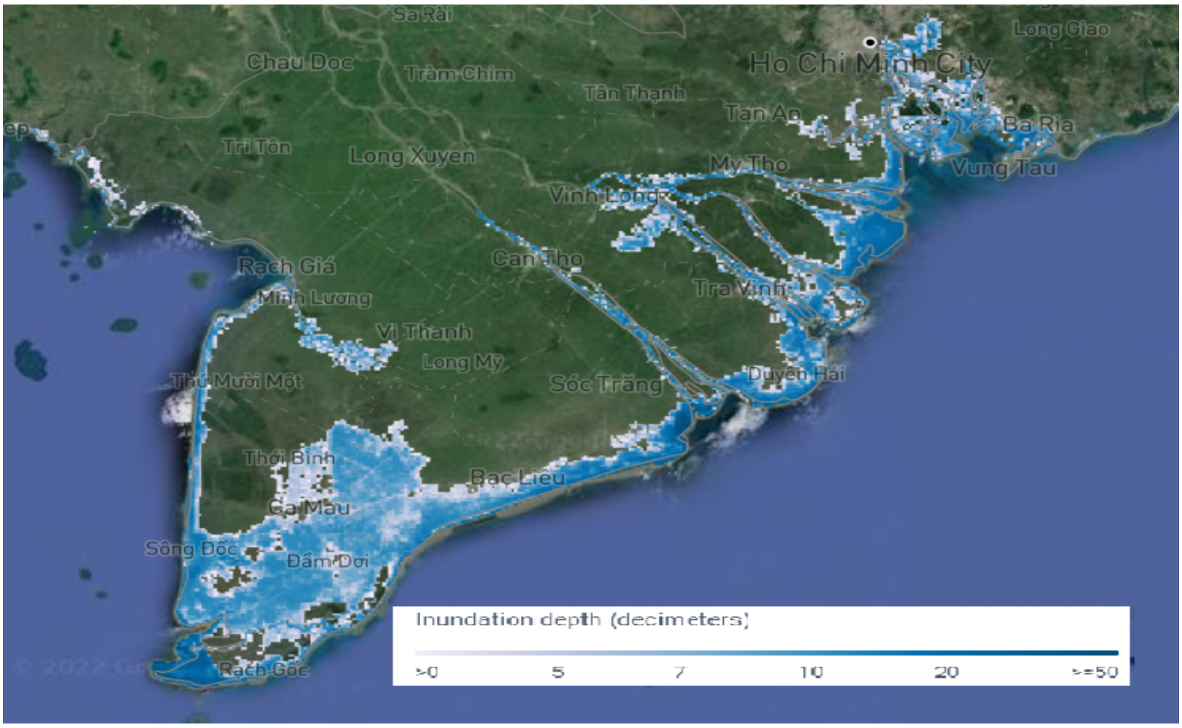
1.2.3 Inundation

Large parts (about 50%) of the delta are seasonally flooded during the wet season, mainly in the Plain of Reeds and the Long Xuyen Quadrangle. These areas are located in the upper delta and are of significant agricultural importance to Vietnam. The inundation affects the lives of more than 2.0 million people (Veerman, 2013). The problem is aggravated due to subsidence and climate change as discussed earlier.

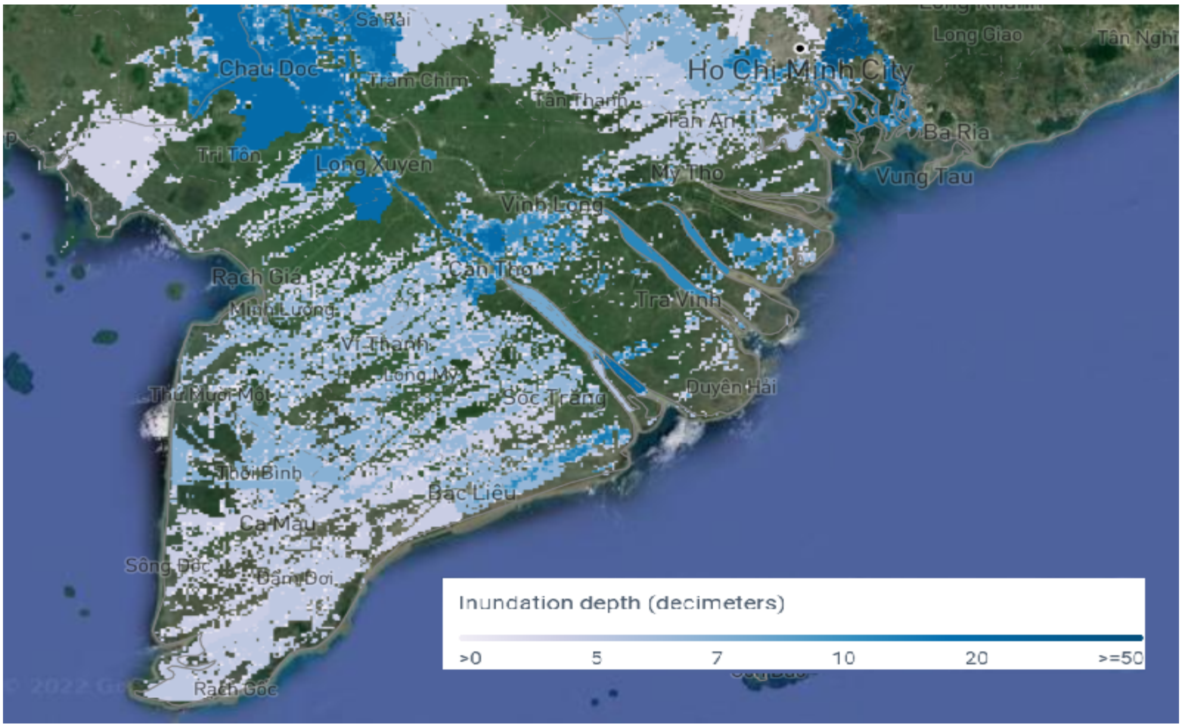
Flooding in an estuary can be divided into two types. It can be the result of high river discharges (riverine) and the result of high tide (coastal). The flooding application of WRI generates flooding maps for both coastal and riverine flooding (for future scenarios see Appendix A). In this application the following parameters were chosen:

- A pessimistic future scenario both for riverine and coastal flooding is used, as it generates an image of the worst-case scenario.
- A return period of 1000 years was used for both types of inundation. This was done to provide a sufficient safety level on predictions.

In Figure 1.6 the projected flooding maps are displayed. The coastal inundation is mostly concentrated on the southwest coast of the delta. River inundation problems are present in the entire delta with the biggest risks of damage to the cities that are adjacent to the river.



(a) Coastal baseline



(b) Riverine baseline

Figure 1.6: Inundation map for both coastal (a) and riverine inundation (b) (WRI, 2020)

1.2.4 Salinisation

The increasing salinity of the river and groundwater is an issue in the MKD. It is predicted that salinisation in the MKD will increase to cause harm to the ecology and the (future) fresh water supply. Low river flow in the dry season causes saltwater intrusion in the coastal regions of the delta, affecting over 1.4 million hectares of land. Furthermore, salinity can harm pipes and structures in rivers. All of the combined problems resulted in an economic loss of 360 million dollars in 2016 in the MKD (Mai et al., 2019).

In the previous years the salt intrusion distance increased by 15 - 25 km in eight estuaries (Mai et al., 2019). Eslami et al. (2021) developed process-based numerical models that take human factors as well as climate change into account and used these models to make a prediction for the next three decades. Those models show a salinity increase of 10 - 27% for the areas that are exposed to anthropogenic factors. The effects of climate change can increase this further by 6 - 19%.

Causes of salt intrusion can be distinguished based on the main driving factors. Firstly, there is a salinisation increase due to human activities. The population is growing along with the agricultural and economical sectors. Secondly, climate change has a great impact on the salinisation in the area. It will lead to relative sea-level rise, bigger storms and changes in precipitation. This is displayed more extensively in Table 1.1.

Main driver	Causes
Increasing human activities	Groundwater over-exploitation Rapid development of aquaculture Uncontrolled drainage canals Operation of hydro-power dams
Climate change	Relative sea-level rise Storm surge Changing temperature and precipitation regimes

Table 1.1: Causes for saltwater intrusion (Xiao et al., 2021)

Groundwater over-exploitation results in salinisation. The huge need for groundwater in the early '90s came from the rapid development of agriculture, aquaculture and industrial purposes (Xiao et al., 2021). Additionally, changing temperatures and precipitation regimes resulted in higher groundwater over-exploitation. High usage of fresh groundwater lowers the hydraulic pressure of the fresh groundwater, changing the balance of fresh and salt groundwater. Saltwater will flow there where fresh water is pumped away, resulting in the salinisation of the groundwater.

Uncontrolled drainage canals can also result in salinisation. These canals drain a lot of groundwater, resulting in a reduction of the water table. As a consequence, the salt water from the sea can propagate further inland. This effect is even more extreme in the dry season when less fresh water is available. The saltwater in the drainage canals is then not flushed away, resulting in a flow of salt water into the ground.

Operational hydropower dams and (illegal) sand mining result in a lack of sedimentation in the Hau River. The decreased supply of sediment from upstream results in the erosion of the estuary. This, in combination with subsidence, allows for salt seawater to flow into the fresh groundwater (Xiao et al., 2021).

Currently, 1.0 million hectares of the MKD experience yearly tidal flooding (Le et al., 2007). Climate change causes the sea level to rise and as subsidence of the area goes on, the relative sea level rise will only become higher. This causes areas in the MKD to flood more easily with salt water. Additionally, smaller storm surges will already result in flooding.

1.2.5 Freshwater control

Water quality and freshwater supply are considered major problems in the MKD. Fresh water is important since large parts of the delta are used for rice cultivation, fruit orchards and vegetable crops. In Can Tho, the main water supply is based on ground-, surface- and rainwater. The main problems that are related to freshwater are the high salinity level (subsection 1.2.4) and the aluminium contamination of this water. Due to a lack of sanitary facilities and (industrial) water pollution, the water quality can cause health issues. In the middle hydro-logical zone of the MKD freshwater shortages are impacted by groundwater extraction (Veerman, 2013). These issues are related to over-exploitation, salt intrusion and urban pollution (Moglia et al., 2011).

During the dry season in Can Tho, the freshwater infrastructure is inadequate for the population size. The water supply system works in the urbanised area using surface water, however, these services only have limited coverage in built-up areas in the city. As such, the water supply network only serves households directly next to roads and larger alleyways. Other locations use other water sources such as local rivers, irrigation canals and wells. The supply is coming from surface water sources which are influenced by upstream changes in the Hau River. In addition, in the more severe dry season, the infiltration is likely to be reduced. This impacts the surface water quality. Due to the higher degree of change conditions (dry and wet soils), the resilience of the underground freshwater infrastructure is also a threat. This relates to the extra stress to which the pipes are exposed (Moglia et al., 2011).

1.2.6 Sediment transport

The transport of sediment helps to sustain a delta profile. Upstream flows distribute sediment over the river bed. When the inflow is smaller than the outflow, a deficit occurs. A profound understanding of sediment transport is crucial to predict erosion and deposition. Furthermore, sediments transported by rivers are the major sources of materials for protecting deltas from the natural processes of subsidence (Binh et al., 2022). Human activities in river deltas all over the world cause substantial decreases in transport sediment loads. These include climate change, construction of dams, mining and urbanization, leading to detrimental effects on landforms, erosion and salt intrusion (Binh et al., 2021; Eslami et al., 2019; Hackney et al., 2020; H. Huu et al., 2021). Various models estimate a 48 to 60% annual sediment load reaching the coast out of the total sediment load at Kratie in Cambodia and predict suspended sediment reductions of 18 to 85% (Binh et al., 2022; N. V. Manh et al., 2014).

Another sediment-related issue in the Mekong River is sand mining. According to the Vietnamese Ministry of Agriculture, more than 80 companies are approved to mine 28 million tons of river sand per year (Long, 2022b). However, actual numbers on sediment volumes are less available as sand is being mined illegally too. Reported statistics of sand mining for all of the Mekong's channels within the delta are 17.77 Mm^3 per year for 2018. It is highly likely that this estimation is too conservative (Jordan et al., 2019).

1.2.7 Division among experts

After having conversations with various experts that are involved in problem-solving in the MKD, it becomes clear that there is little consensus on the identification of which problems to solve and in what way. There seems to be agreement that inundation is the main issue. However, some experts argue that the problems are so severe and the inundation can not be stopped so a new balance should be found in the delta. Others believe that measures still can be taken to turn the situation around. Amongst this last group, there is a discussion about the role of Nature-based Solutions versus hard structures as a measure. The meeting reports that led to these insights can be found in Appendix B.

As an example of an adaptation plan, the Mekong Delta Plan argues that businesses in the lower parts of the MKD should shift their practices to something less dependent on fresh water. At the core of this proposal is a concept of three-step shrimp farming (Veerman, 2013). This industry will not only be less dependent on freshwater but will also generate more profit compared to the current agricultural industry. This increase in profit is vital to make sure the region does not fall behind economically in the future. This is an example of acceptance of salinisation in the lower part of the delta and adapting to the new situation.

It is in everyone's best interest to find adequate solutions quickly. The longer it takes to find proper solutions the harder and more expensive it will be to implement them. With the current rate of climate change, there is not much time to waste. This is why there should be thought ways to bring the opinions of different experts and groups together, to work more efficiently and find better solutions.

1.2.8 Feasibility of investments

The feasibility and attainability of current developments and future master plans are to be examined. The investment climate of the MKD is perceived as less attractive, and neighbouring provinces north and east of Ho Chi Minh City (HCMC) are able to capitalise more from its proximity to the city than the MKD. The MKD is mainly suffering from the following (Renaud & Kuenzer, 2012):

- The vulnerable and flood-prone natural system is a reality. Many investors perceive the delta as risky and prone to flooding and it is, therefore, less attractive for investments;
- Decentralisation of decision-making on public investments. This has contributed to competition between provinces and cities, leading to sub-optimal decisions;
- Insufficient infrastructure and transportation links, leading to high transportation costs;
- A high out-migration of human capital, mostly to HCMC;
- The tight control over "food security" and other institutional barriers constrain farmers to diversify their agricultural production. The institutional mechanisms for more integrated planning are also insufficiently enforced.

The current rice dominance of the economy is hampering human capacity building, as it requires fewer skills and resources compared to other economic sectors such as aquaculture, fruit culture, horticulture and industry. The agricultural restructuring has not taken place and no remarkable changes in farming techniques have been carried out to increase productivity. Also in the process industry, the majority of companies focus on processing raw agricultural products with low-added value (Thien et al., 2020). The existing value chains of rice and aquaculture are constraining the livelihoods of farmers, leaving them with low margins. Currently, the MKD is a processing area where most commodities and input materials (fuel, fertiliser, agrochemicals, equipment) for production are imported (Korbee et al., 2019).

1.3 Stakeholders

Stakeholders who are involved in the MKD can be visualised with a power-interest matrix. In such a matrix the power that a stakeholder has is plotted on the x-axis, while the y-axis displays its level of interest. With these two indicators, four main groups can be distinguished.

The bottom left group with low power and low interest has to be monitored. The bottom right group, with low interest and high power, needs to be kept satisfied. The group with low power and high interest (top left) need to be kept informed. Lastly, the group with high power and high interest (top right) consists of the stakeholders with the most impact on the project (Every, 2020). In Figure 1.7 the power-interest for this project is shown.

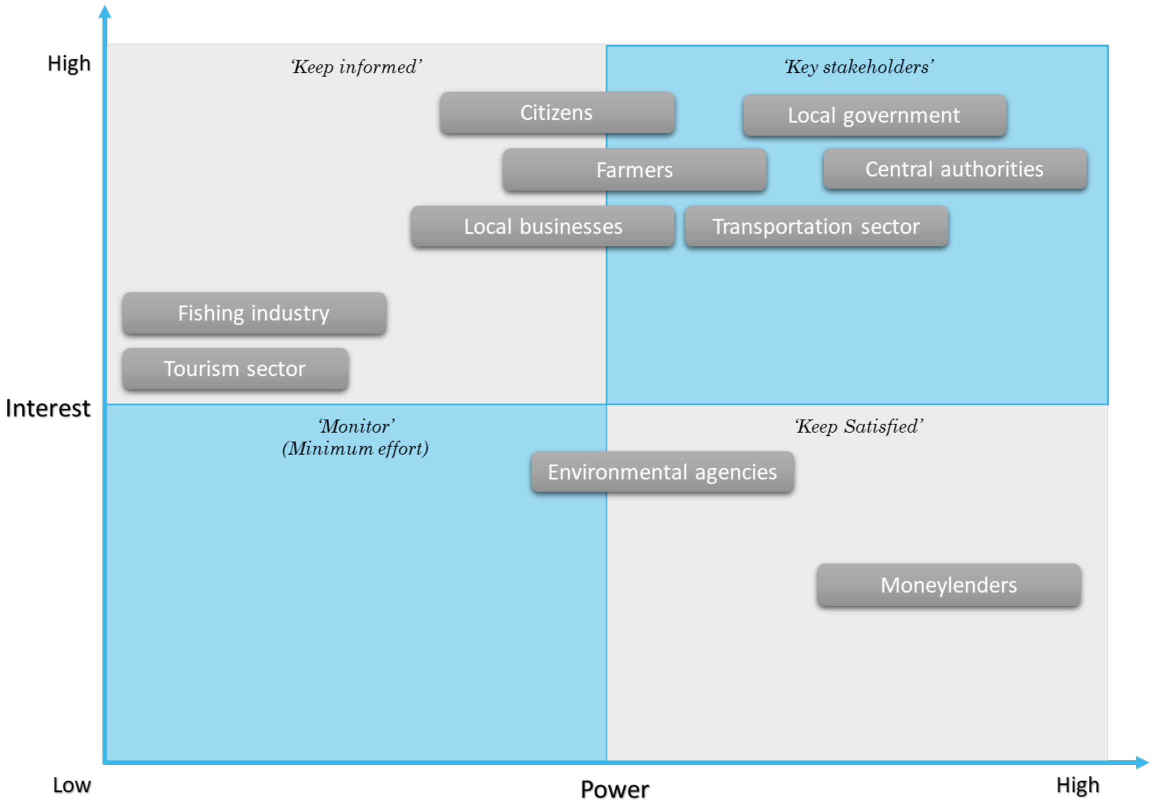


Figure 1.7: Stakeholder analysis

Local authorities

The local authorities consist of three main departments: provincial, district and commune authorities. The provincial authorities include provinces and cities which are directly under the central government (Huy, 2020). Can Tho is one of these five cities (Albrecht et al., 2010). Commune authorities consist of two main bodies: the administrative and the parliament. These two departments are known as the People's Committee and People's Council respectively (Vietnam General Statistics Office, 2006). Within the local authorities, the main services for the public are covered. Examples of this are public transport, infrastructure, water supply, sanitation, waste, etc. These provinces and 'special' cities also have a supervisory role over the budgets and decisions made. This causes lower (district or commune) authorities to defend their place in the province. Local authorities are making decisions and have authority over public services (Albrecht et al., 2010). This gives them high power. The local authorities have a high interest as well to protect the area from the problems mentioned in section 1.2 as this will endanger the people and decrease the attractiveness of the area as a whole.

Central authorities
The authority which has the highest power is the central government because it manages the local authorities and it has therefore also a high interest in the problem. The area is also important from an economical point of view. Moreover, it is the duty of the government to accelerate public investment and guarantee public safety. Therefore it is considered a key stakeholder.

Moneylenders
The World Bank, South Asia Development Bank, etc. have an interest in increasing the overall well-being of the MKD and a return on their investments. By promoting economic development they aim to achieve poverty reduction in the long term. The organizations mainly focus on implementing reforms or projects which also incorporate providing water and protecting the environment. International Monetary Fund (IMF) promotes financial stability and policy advice. This is more focused on short- to medium-term loans, which relates to countries that experience payment difficulties. Collaboration of these two parties is split into four main categories; assessing financial stability, reducing debt burdens, climate change and the 2030 development agenda ("The IMF and The World Bank", 2022). Key parts in the development agenda are (UN General Assembly, 2015):

- Clean water and sanitation,
- Industry innovation and infrastructure,
- Sustainable cities and communities,
- Climate action.

For this study the external moneylenders are depicted as organizations who have a medium to low interest in the final result. However, the expenses they can cover will have a very large influence on the outcome. Therefore for the feasibility of the result, it is aimed to keep them satisfied.

Transportation sector
It is believed that transport infrastructure is key to developing the delta's economic growth (B. Dang, 2022). Adequate infrastructure can be an enormous push factor for private investments in the area. The MKD's comparative disadvantage to other regions in Vietnam is also important when it comes to attractiveness for industrial investments. Poor transport facilities are an important factor for this disadvantage (Veerman, 2013). Therefore the transportation sector has a high interest in the protection of the area. As transportation is determined as the key to further economical benefits the sector is granted a high power in this analysis.

Fishing industry
This industry can be divided into fisheries and fish farms. Most of the industry mainly focuses on brackish water products like shrimp and pangasius. The fish farm industry is an upcoming market that has an interest in brackish water supply for shrimp farms. A full reduction of saltwater intrusion can be a problem for this sub-sector. On the other hand, pangasius fisheries require fresh water. Furthermore, pangasius fishing shows indications of saturation (United Nations Development Programme, 2022). Therefore, a conflict inside the industry is going

on. Although the sector is the main financial contributor to the delta, the power of the fish industry is not great as there is conflict in the sector. On top of that, the existing problems due to sand mining, upstream hydropower dams and salinisation are not being addressed to a great extent at the moment. This indicates that they are not being heard.

Local businesses
Local businesses mainly consist of floating marketers and store owners. The floating marketers utilise the canal network near Can Tho. The market functions as a key hub for trading locally produced goods among the local citizens (T. Trinh, 2018). The fishing industry mainly stimulates the floating market, as one of the most traded products is fish. The market accounts for over 67% of the total industrial production of Can Tho (L. Q. Manh, 2020). Because of these reasons their interest is to keep the fish, their main source of income, of high quality. Conventional store owners mostly want to prevent damage due to floods. To the individual marketeers power is limited as most are just local citizens.

Tourism
The floating market functions as a major tourist attraction (see local businesses). This is related to the geographical location of Can Tho. By preserving the floating markets, tourists will be attracted. This increases the development of tourism which is a key aim of Can Tho (T. Trinh, 2018). In this sense, the tourism sector is dependent on the floating market, which puts both its power and interest below the (floating) marketers. Therefore the tourism industry only needs to be informed about the developments.

Farmers
The area around Can Tho is mainly used for agriculture. There has been a large development in agriculture in the last decades. The influence of farmers on the economic structure of the area has therefore increased. The main agricultural production chains are rice, fruit trees and vegetables (L. Q. Manh, 2020). These products are exported, which makes the MKD a key area within Vietnam (Veerman, 2013). Regarding the decreasing freshwater supply, salt groundwater intrusion and flooding the farmers have a high interest. The power they have is limited but can become more in the coming years as the development goes on.

Citizens
Habitants of the MKD have a high interest in the development and protection of their area (Veerman, 2013). However, their power to influence decision-making is limited. Studies show that citizens have limited knowledge of the government structure when it comes to more complex topics (United Nations Development Programme, 2015). In public decision-making, citizens can participate directly and indirectly. Citizens usually feel that their participation is only used for informing local people about already decided plans. Therefore there is low trust in local participation (A.-W. Dang et al., 2015). Based on the information above, citizen power is therefore estimated as low. At the same time, their interest is high as they experience a lot of negative consequences of hydraulic issues. Like flooding, which causes a lot of damage to their environment and potentially endangers their lives.

Environmental agencies
This stakeholder refers to those agencies that want to preserve the biodiversity of the MKD. Moneylenders cooperate with environmental agencies since they incorporate the sustainability

development goals (“The IMF and The World Bank”, 2022). They adhere to a bio-centrism point of view, where the environment has intrinsic value (Poel, van de & Royakkers, 2011). The interest of the environmental agencies lies in Building with Nature solutions, as that will preserve or even enhance the biodiversity in the MKD. Their power lies in the entanglement with moneylenders. In this study, it is assumed that they have more interest in the protection of the area as this could be a benchmark for solutions to similar deltas all over the world. Although they are entangled with the moneylenders, environmental agencies have smaller power, as they do not decide where the money goes to.

Each stakeholder that is described in the section above has a specific interest in this project. In Table 1.2 the interests of these stakeholders, the main research question is summarized.

Stakeholder	**Interest**
Local authorities	A delta which is safe, habitable and healthy for its citizens
Central authorities	A delta which is safe, habitable and of economic value for the country
Moneylenders	Poverty reduction and preservation of the delta with sustainable solutions
Transportation sector	Fast and reliable transportation facilities
Fishing industry	Freshwater facilities and open water connections
Local businesses	Calm water and high market function
Tourism	Attractive and safe environments
Farmers	Fertile soils
Citizens	Safe and healthy living conditions
Environmental agencies	High livability and biodiversity

Table 1.2: Stakeholder interests

1.4 Scope

Due to the short research time, it was decided to limit the scope of this project to a smaller part of the MKD: the Hau River estuary. The two main problems in this region are inundation and salinisation. As salinisation is aggravated by the inundation of salt water, the first problem can be reduced by solving the latter. In the Hau River estuary, riverine flooding is considered the driving factor for inundation. Therefore, the hydraulic problem that is focused on in this study is riverine flooding.

As discussed earlier, many more problems occur in the Hau River estuary but finding solutions for these problems is out of the scope of this report.

1.5 Research question

While efforts are being made in mitigating the inundation problems the MKD is still experiencing flooding. The problem is of a magnitude that requires a drastic change in the way the inundation problems are handled. This leads to the following research question:

Which integrated solutions reduce riverine inundation problems in the Hau River estuary while also considering socio-economical aspects?

The answer to this question will be found using a goal and a set of objectives that can be found in the next section.

1.6 Goal and objectives

The long-oriented goal of the central authorities is to make plans towards a safe, prosperous and sustainable delta. The goal of this report is to present integrated solutions for the Hau River estuary that provide guidance to the central authorities in decision-making. The following objectives have been formulated to support the achievement of this goal:

- Indicate the problems that are of significance in the Hau River estuary
- Describe the current and future situation in the Hau River estuary
- Find reference projects and their ways of coping with similar hydraulic problems
- Propose multiple solutions that solve hydraulic problems in the Hau River estuary
- Validate the influence of the solutions with models
- Review proposed solutions based on socio-economical consequences
- Assess the effectiveness of proposed solutions

1.7 Report structure

In this report, firstly the methodology is described. Within this chapter, the approach for solving the goal and objectives is elaborated. Following this approach, the system of the Hau River estuary is explained in terms of hydraulic characteristics in chapter 3. This chapter also contains a link to reference projects and their solutions. In chapter 4 the models that are used are defined. Subsequently, the socio-economical and transportation factors are described. Complemented by an overview of the future developments in the MKD these are the contents of chapter 5. Hereafter, solutions are proposed in chapter 6. The design is determined, the effectiveness against flooding is assessed and the socio-economical consequences of the solutions are described. In chapter 7 an attempt is made to rate the proposed solutions and a roadmap for future development in the Hau River estuary is presented. Hereafter, a discussion about the report is made. Followed by a conclusion with recommendations in the last chapter.

2 | Methodology

The MKD is facing some difficult problems in the future. This study focuses on one of these problems, namely riverine flooding. The scope of the study area was reduced to the Hau River estuary.

The goal of this report is to present integrated solutions for the Hau River estuary that provide guidance to the central authorities in decision-making.

2.1 Approach

At first, a literature study was performed to get familiar with the research area and to obtain a better understanding of its problems. Reading other studies and reports helps to form a more broad image and view of the research topic. Furthermore, it serves to set boundaries and constraints on the research area. The literature study was complemented by interviewing various people in the Hau river estuary. After getting more familiar with the research area and its problems, the research question, objectives and goals could be formulated more precisely. Ultimately, answering the research question, fulfilling the predefined objectives and reaching the research goal led to the proposal of four different solutions. These are a discharge sluice, wetlands, a bypass channel and lastly a protection and adaptation proposal. The first three of these solutions consist of a hard engineering structure while the fourth solution takes a different approach. Some basic models were used to perform proof of concepts and determine required model dimensions. However, most of the analyses were done qualitatively. The reason for this is that the used models don't have the necessary accuracy and complexity to be leading in the analyses. The assumptions, design decisions and other specifics will be dealt with in chapter 6, which is dedicated to solution proposals.

2.2 Data collection

The introduction mostly relies on online available data. For the rest of the study, most data used was provided by the project supervisors, since it appeared challenging to find reliable and consistent data on the MKD. The data includes bathymetry of the Hau River, the influence of the tides and water levels and discharges from various stations ("SIWRR dataset", 2011). This year is considered as fit for designing for heavy floods (Xuan, 2021). Data from 2016 and 2017 were also studied. However, these years were less intense in terms of flooding. Therefore it was decided to stick to the somewhat older data from 2011.

Bathymetry data was processed via Geographical Information Systems (GIS). A representative profile was chosen based on the bathymetry data which represents the larger part of the Hau River.

Discharge data of the system was then used to examine the way water flows in the system. Peak moments where discharge is at its maximum were identified and the data was used to gain insight into seasonal influences on the system. The data was also used to identify whether flooding is caused by rainfall or tidal influence and to where the tide has an influence on the discharge and water level in the river.

2.3 Determining dimensions of solutions

After examining the hydraulics of the estuary four solutions were proposed. Three of these included the construction of some sort of hydraulic structure. In order to determine the dimensions of these structures, some calculations and assumptions have been made. It was investigated at what water level the city of Can Tho floods and a design discharge downstream of the city was defined.

These inputs were then used to design the hydraulic structures in the solutions. The downstream design discharge was used to determine the size of the bypass. A bypass reduction model was used to compute the discharge in the bypass and the resulting discharge downstream. The design discharge in the bypass was then found by iteration.

Calculating the required area of the wetlands demanded an identification of a peak discharge that should be drained. A location for the wetlands, which cover a significantly great area, was then found.

2.4 Assessing the effectiveness of solutions

The proposed solutions, in their particular dimensions, were tested on the basis of models. A simple model was set up to simulate the Hau River without any measures. Then these were used to assess the effectiveness of the proposed solutions, mainly by their ability to reduce the water level near Can Tho. It was intended to make use of more complicated models to investigate the effects of solutions more extensively. The Southern Institute of Water Resources Research (SIWRR) was willing to provide simulations of the proposed solutions in their one-dimensional model of the entire MKD. However, due to circumstances these models were eventually not used.

A zero-dimensional model was set up that simulates the in and outflow in the Hau River as a reservoir, caused by tidal and river discharge. It was used to determine the water levels in the city and validated by real data in Can Tho. Ultimately, the zero-dimensional model was used to assess the effectiveness of the discharge sluice. This model was suitable to assess this solution, as it copes well with the alternating situations of an opening and closing barrier.

Above described model was not deemed fit for testing the wetland and bypass solutions. As these solutions are both designed to reduce discharge. The amount of reduction is dependent on the water level at the outlet. This requires calculating the water level at multiple locations, namely the outlet and near Can Tho. This last location was used to compare the results of different solutions. The zero-dimensional model can only calculate a water level for the entire reservoir it simulates, generating only one output. Therefore, a Delft3D model was set up for the Hau River. This model was verified with measured data and then used to assess the effectiveness of both the wetland and bypass solution. Delft3D is not suited to model the discharge sluice in, as it can not easily deal with the changing grid that is required to simulate an opening and closing barrier.

The fourth solution did not require any hydraulic modelling. This proposal mainly intends to keep the situation the same. Its objective is to adapt land use and way of life to a new ecological and geographical balance, accepting the new natural equilibrium.

It was acknowledged that the water level-reducing abilities could be best compared by simulating each solution in the same model. However, the zero-dimensional model was not fit for the simulation of wetlands and the bypass channel. On the other hand, the Delft3D model was less suitable to simulate the discharge sluice.

2.5 Socio-Economics

The resulting study aims to be integral, which is why the social economics of the area and the consequences of proposed solutions on them, were described. The research was carried out on economic activities, demographics, land use and transportation. The main complication that is caused by inundation is limited means of transport (Thanh, 2022). Therefore, an emphasis on transport was made in chapter 5 and the reviewing of proposed solutions.

The transportation system was modelled with the four-step model (Rosenbaum & Koenig, 1997). For this model population and land use, data was used as an input, complemented by transportation data, such as trips per person and road network characteristics. The model was used to determine transportation opportunities of the solutions with regard to travel time and/or connectivity.

2.6 Survey

An integral approach for a project on this scale benefits from the opinions of the local community. It is especially relevant to understand the problems that affect people's lives the most and in which solutions they believe. Twelve main attributes were defined to examine this. A questionnaire was then set up and carried out in order to obtain this information. Participants were asked to rank the attributes with a pairwise comparison. These results were displayed and assessed with Analytical Hierarchy Process (AHP). This is a pairwise comparison-based method to determine the relative importance of the relevant attributes. It was aimed to obtain responses which reflect the society. Incorrectly completed questionnaires where it was unclear which answer was given have been excluded.

2.7 Assessment

By assessing the solutions insight is gained into the order of feasibility of the solutions. The assessment is based on the models which have been discussed and additional information about the solution. The assessment method was used in the multi-criteria analysis, which also contains the effectiveness of a solution. By compiling a set of criteria which are deemed important the individual scores are obtained. Since the criteria are not equally important, their relative weights have been determined based on a best-worst method approach. Via a value function, the relative weights and performances of the solutions are scored. This causes a final score which indicates the ranking of solutions.

3 | Hydraulics of the Hau River estuary

The study area of this project is the Hau River estuary, which is a side branch of the Mekong. It is a highly dynamic estuary because of the high fluctuating discharges, tidal differences and seasonal variety in precipitation. Next to this river the largest city of the MKD, Can Tho, is located.

In this chapter the hydraulic characteristics of the Hau River are described. Data was provided by Thuyloi University and measured at the measuring stations displayed in Figure 3.1. The hydrology stations in this figure (Tan Chau, Chau Doc, Vam Nao, My Thuan and Can Tho) had hourly data on the water level in the river with respect to the mean sea level measured at the Hon Dau tide gauge, along with discharge data for the years 2010 and 2011.

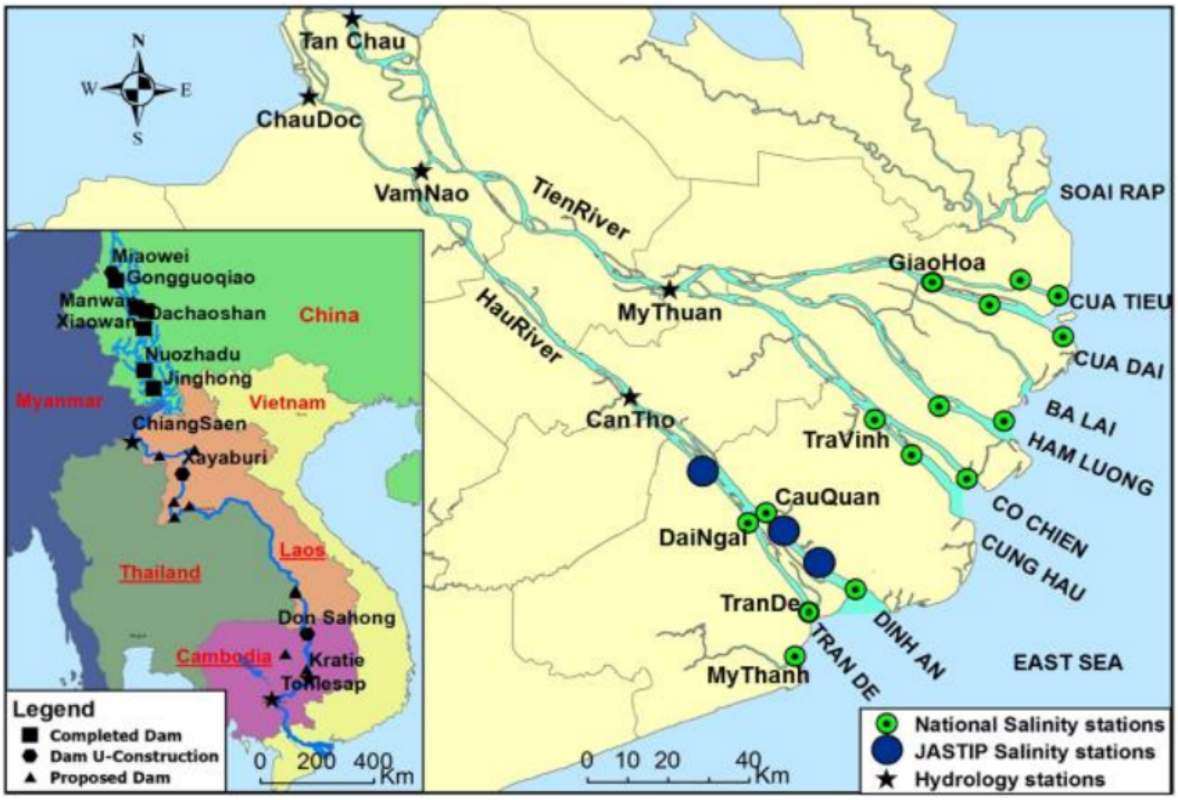


Figure 3.1: Measuring stations in the MKD (MAI et al., 2018)

3.1 Bathymetry

The bathymetry of the Hau River was determined with GIS. An upstream cross-section near Can Tho is displayed in Figure 3.2. The width of the river at this point is 1,760 m. The deepest point in the river is 18.49 m and the mean water depth is 10.70 m. This follows from the bathymetry data ("SIWRR dataset", 2011). At both riverbanks, the elevation is approximately 2.0 meters above mean sea level (Vinh Pham, 2017).

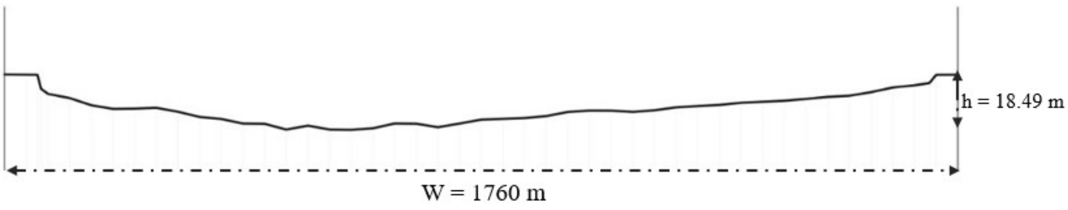


Figure 3.2: Bathymetry Hau River

3.2 Discharge

Figure 3.3 illustrates the discharges measured at the five stations from Figure 3.1. The hourly discharge data is averaged over a day. The inflow in the dry season is not problematic in terms of flooding. The highest discharges are recorded at the Tan Chau measurement station. A part of this volume flows into the Hau River through Vam Nao. It can be concluded that the main inflow in the Hau River in the wet season near Can Tho comes from Vam Nao. The contribution of Chau Doc to the discharge at Can Tho is limited.

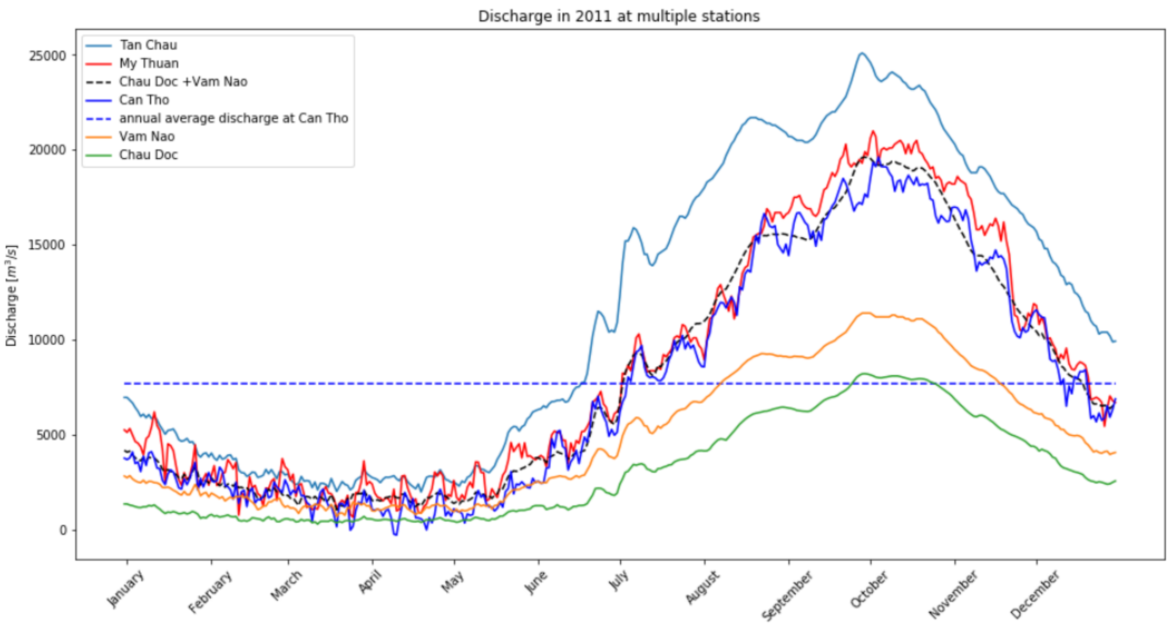


Figure 3.3: Discharge at all measuring stations

A horizontal plot of the mean discharge in the Hau River near Can Tho reveals that 7,677 m^3/s is the annual mean discharge ("SIWRR dataset", 2011).

3.3 Precipitation

Southern Vietnam has a wet season which lasts from May till November. This is clearly visible in Figure 3.4. In the other months, nearly no precipitation is measured. This results in a drought problem in the dry season and an inundation problem in the wet season.

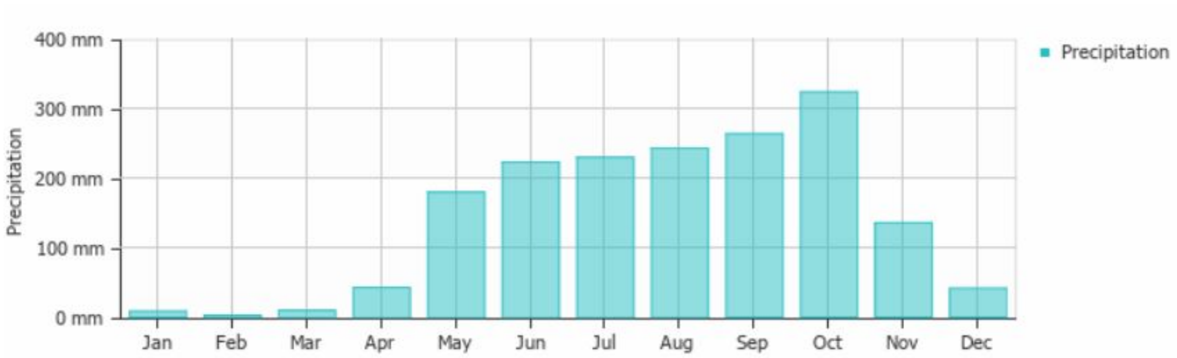


Figure 3.4: Precipitation Can Tho (Weather and Climate, 2022)

When combined discharge upstream of Can Tho (Chau Doc and Tan Chau) is compared with combined discharge at Can Tho and My Thuan, the influence of the precipitation can be clearly observed. In this graph, the discharge in Tan Chau and Chau Doc measuring stations are summed. The same was done for the discharge at Can Tho and My Thuan. The former is upstream, and the latter is downstream (see Figure 3.1). The sum of discharges should be the same if no water is added or subtracted in the area between these measuring stations. During the dry season, this statement holds. Figure 3.5 indicates that there are additional discharges of up to 9,000 m^3/s during the wet season. These additional discharges are mainly the result of high precipitation in these months.

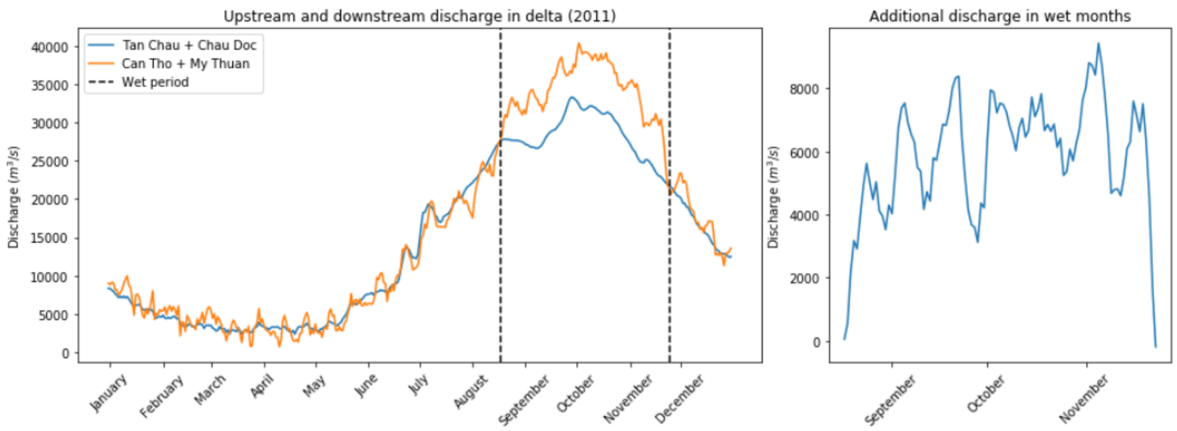


Figure 3.5: Discharge upstream and downstream

3.4 Tide

The tide around the MKD can be described as mixed but mainly diurnal. This means that the coast experience one high and one low tide a day but it also experiences semi-diurnal components that give another relatively smaller low and high tide during the day, see Figure 3.6. The city Vung Tau has the highest astronomical tide of 3.9 m and the lowest astronomical tide of 0.1 m (Tide-forecast, 2022). Since this city is relatively close to the end of the Hau River, one can safely say that these conditions are also valid at the end of the Hau River, the estuary. Available data shows the influence of the tide on the water level.

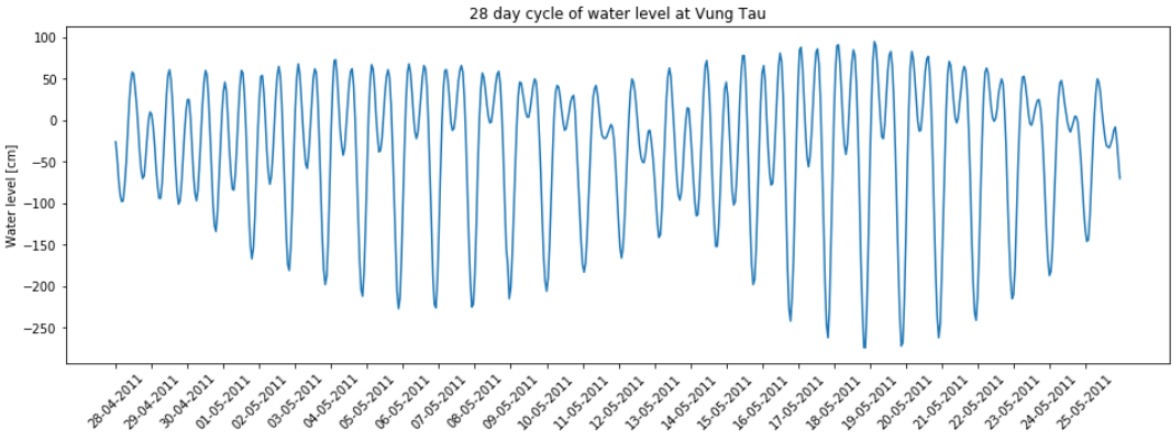


Figure 3.6: Tidal variation in Vung Tau (Tide-forecast, 2022)

From Figure 3.7 and Figure 3.8 it becomes obvious that a higher tide at sea also causes a higher water level in Can Tho. Also, the diurnal components are shown to be faded out and a semi-diurnal tide is present in Can Tho. A negative discharge shows this tidal influence and indicates water from the sea flowing inland. For negative discharges, the water level in Can Tho increases, whereas higher positive discharges are observed together with lower water levels. The water level in Can Tho is tide-dominated, as it still drops in the wet season when the river discharge decreases, indicating low tide (Figure 3.8).

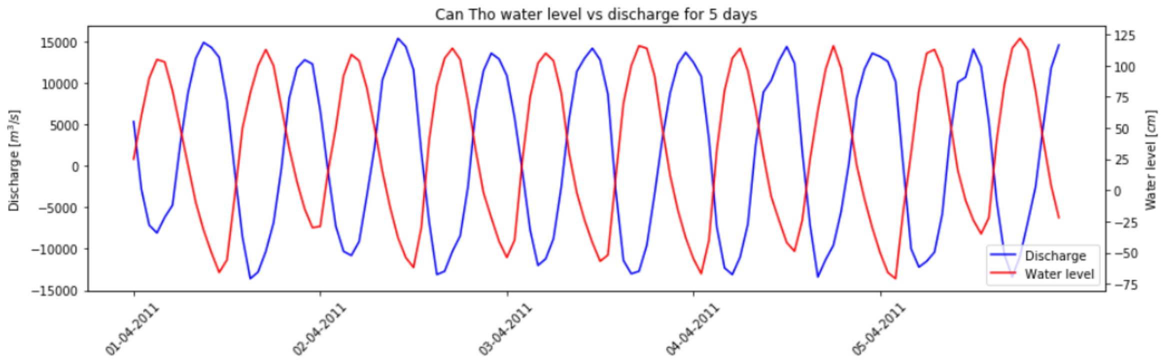


Figure 3.7: Hourly discharge and water level at Can Tho in the dry season

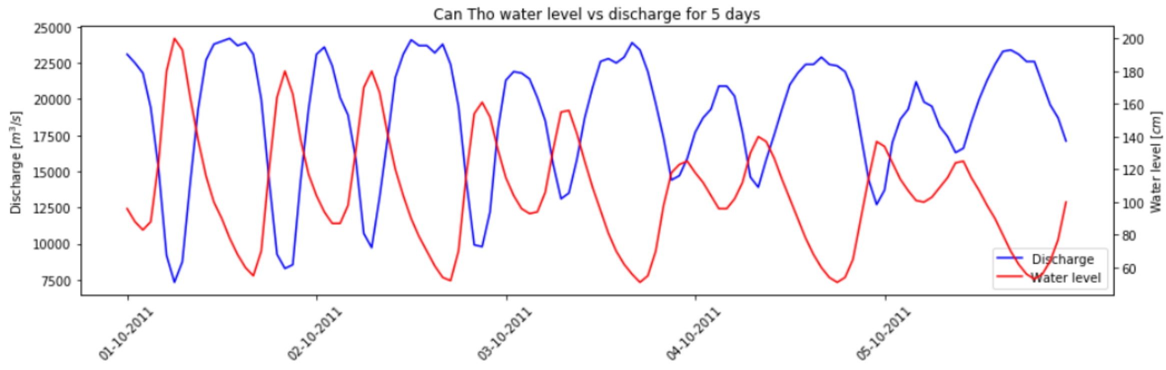


Figure 3.8: Hourly discharge and water level at Can Tho in October

The tidal influence on the water level is still observed in Chau Doc, which is 190 km inland. Here the effects are smaller and the inverse ratio between water level and discharge is only noticed from December to August. From September to November the inverse ratio is not there anymore (Figure 3.9).

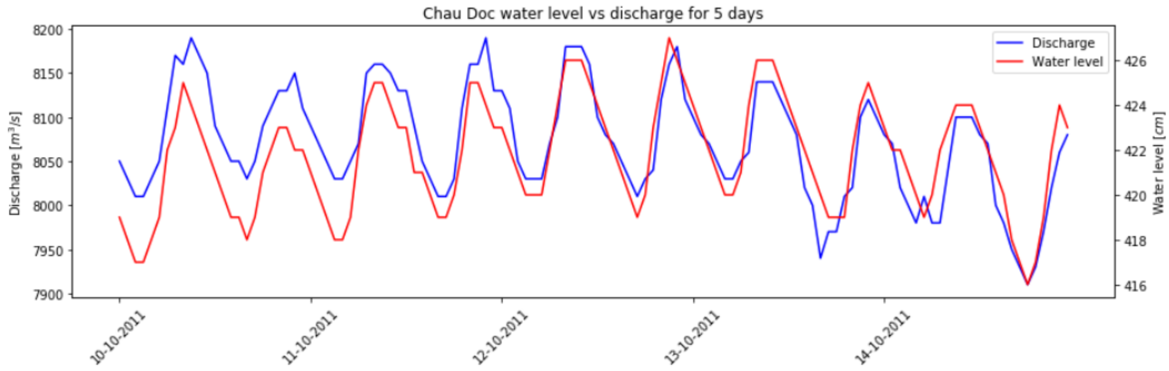


Figure 3.9: Hourly discharge and water level at Chau Doc in October

When the discharge and water level in Can Tho are plotted for a year, the influence of the moon cycle can be observed. This is displayed in Figure 3.10, where the hourly data were averaged for each day. Averaging per day also takes away the daily influence of the tide, as the daily averages don't show any negative values. One can see the sinusoidal shape with tops and downs twice a month, representing the influence of the spring and neap tides.

The high discharges observed in the wet season regularly cause flooding in Can Tho. A daily mean discharge of 10,000 m^3/s or lower seems to cause acceptable water levels near the city.

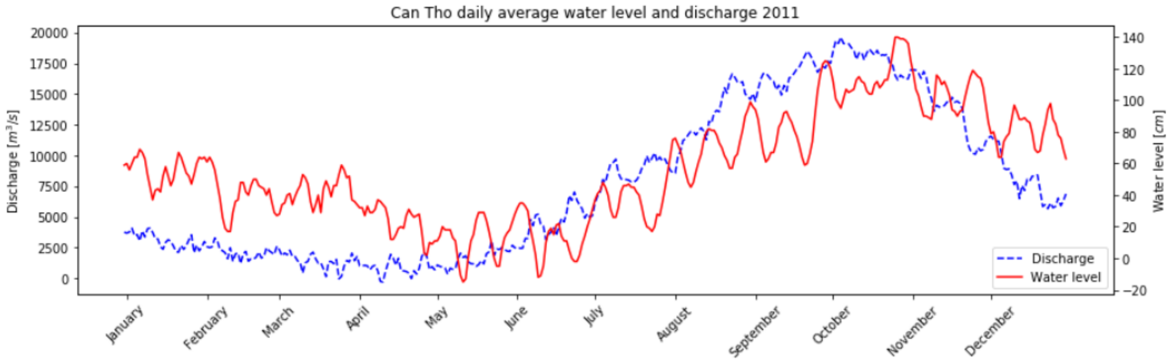


Figure 3.10: Daily discharge and water level at Can Tho (“SIWRR dataset”, 2011)

3.5 Wave climate

To determine the significant wave heights, data from offshore wave conditions must be analysed. As there is not much data available in the area, the data from (Huan & Nhan, 2006) is used. In Table 3.1 the significant wave heights (H_s) from the northeast direction with their corresponding wave period (T_p) for different return periods are shown.

Return period [years]	H_s [m]	T_p [s]
1	3.5	8.1
10	4.5	8.7
25	5.5	9.2
50	6.4	9.5
100	7.2	9.7

Table 3.1: Characteristics dominant waves in the MKD (Huan & Nhan, 2006)

3.6 Storm surge

Storm data is used to calculate the set-up at the coast. The data has 51 storms from 1952 to 2020. From the last 31 storms, the wind speed is measured every six hours. The maximum wind speeds per storm are analysed to calculate the maximum upset for every storm. To simplify the following assumptions are made:

- The maximum fetch length is determined at 250 km. As this is the length that a storm has influence for a big storm (Batke et al., 2014).
- The water depth is taken from Navionics at 250 km from the coast. This is taken as 50 meters.

The following storm surges are calculated:

	Wind set up [m]
Average storm	1.45
Maximum	3.75

Table 3.2: Storm surges based on 31 years of storms

This maximum wind set-up will result in a high risk of flooding at the coast. The flood damage statistics from the Department of Water Resources of Can Tho were compared to the storm data (Vinh Pham, 2017). The storms did not cause flood damage in the city of Can Tho. section A.2 includes the data and calculations for the storm surge at the coast.

3.7 Flood risk

The flood application of WRI (2020) generates flood maps for both coastal flooding and riverine flooding, but this time more specified on the Hau River estuary (for future scenarios see section A.1). From Figure 3.11 one can see that coastal flooding is and will become more of a problem in the south of the MKD and will not be in the scope of this project. The Hau River region is very prone to riverine flooding and this will increase due to human factors and climate change in the coming years (see subsection 1.2.3). From 1975 to 2010 the maximum water level in Can Tho experiences an increasing trend from 1.5 meters to 2.0 meters. Furthermore, this year a maximum of 2.21 meters was reached which is close to the record of 2.25 meters in 2019 (Cuu Long, 2022). This trend still progresses. Approximately the whole of Can Tho will flood when the water level in the Hau River increases by 2.0 meters (Vinh Pham, 2017). Therefore, throughout this project, 2.0 meters is used as the threshold for flooding.

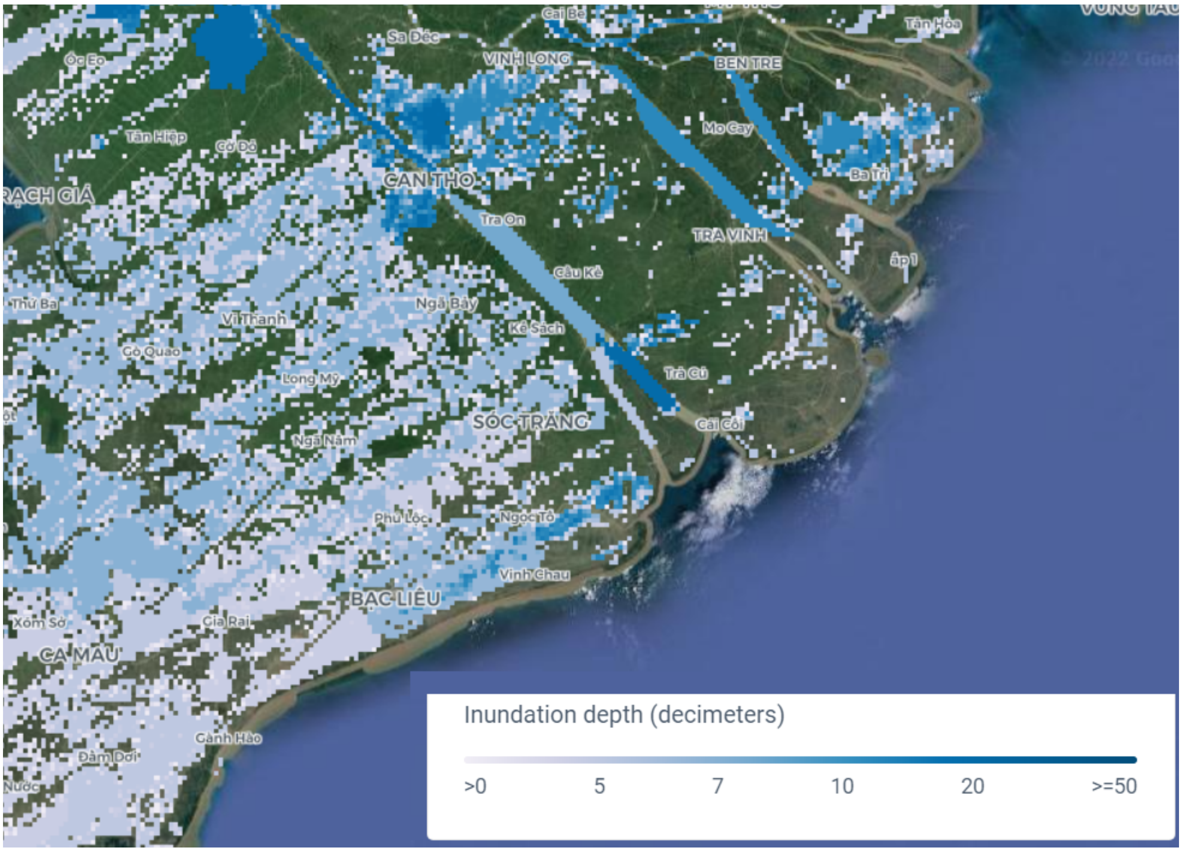


Figure 3.11: Flood map for riverine flooding (WRI, 2020)

3.8 Salinisation

Salinisation is a problem that started to appear more recently in Can Tho. At the beginning of the year 2020, a measuring device measured a salinity of 3.5% during a combination of high tide and a monsoon. This caused salt intrusion up to 95 km upstream. (Cuu, 2020). As seen in Table 3.3 this will result in problems for drinking water, irrigation and life stock.

Salinity Status	**Salinity [%]**	**Use**
Fresh	< 0.05	Drinking and all irrigation
Marginal	0.05 - 0.1	Most irrigation, adverse effects on ecosystems become apparent
Brackish	0.1 - 0.2	Irrigation certain crops only; useful for most stock
Saline	0.2 - 1.0	Useful for most livestock
Highly Saline	1.0 - 3.5	Very saline groundwater, limited use for certain livestock
Brine	> 3.5	Seawater; some mining and industrial uses exist

Table 3.3: Salinity classifications (Horiba, 2016)

This event broke the salt intrusion record of 2016. The high correlation between climate change and these extreme forms of intrusion will therefore occur more often in the coming years. As seen in the prediction model of Eslami et al. (2021) (Figure 3.12) the salt intrusion line will eventually extend in extreme conditions to Can Tho.

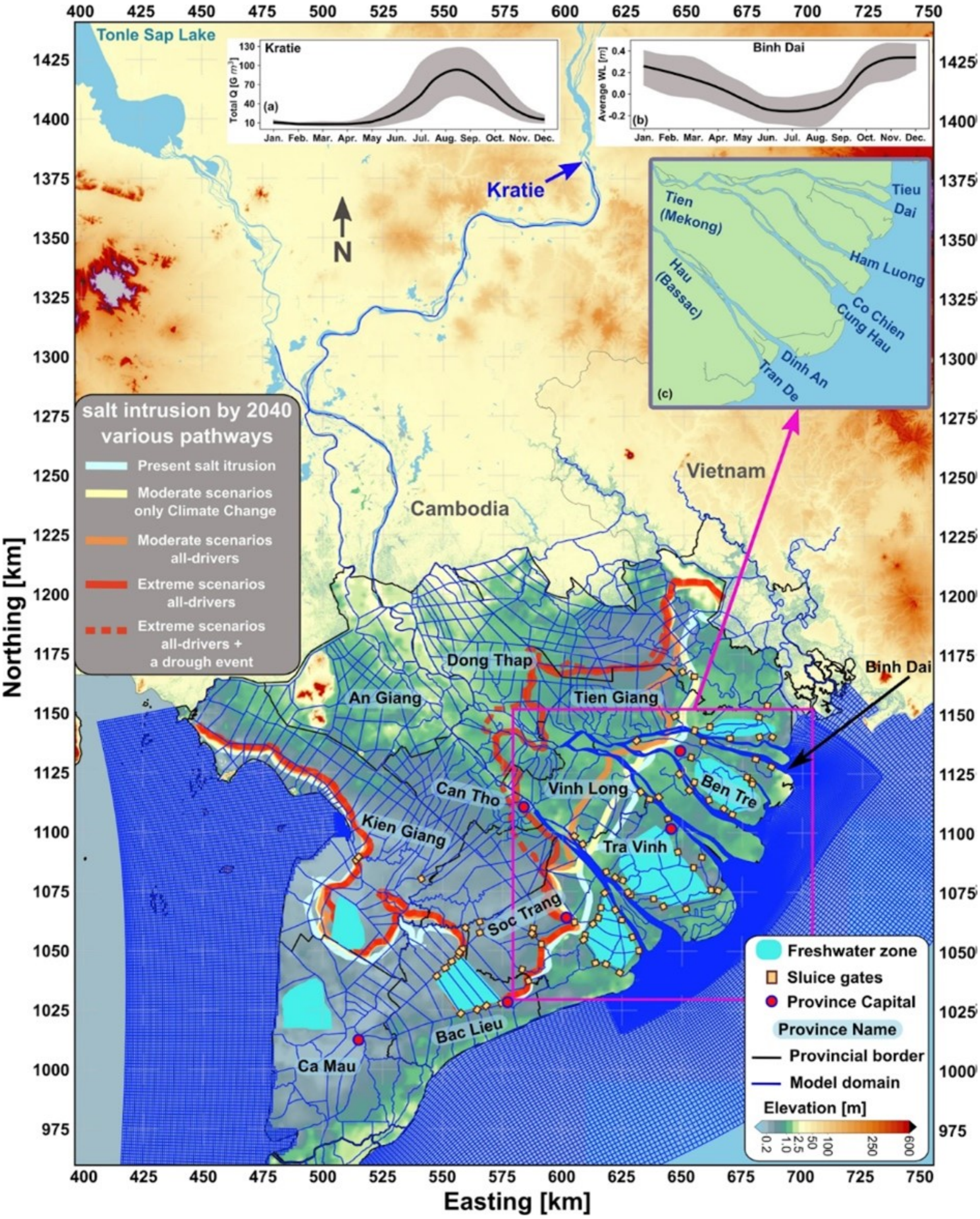


Figure 3.12: Salinity in the MKD (Eslami et al., 2021)

4 | Models

To get a better understanding of the impact of the proposed solutions various models were made. Due to the limited time and resources a lot of assumptions had to be made. It was chosen not to set up complex models to make accurate predictions in the future but to use these models to proof that the concepts and ideas have an impact in the desired direction. The following models were used:

- Zero-dimensional discharge sluice
- Delft3D
- Transport model

In this section each of these models will be discussed more thoroughly. In this way, the use of these models will be justified.

4.1 Zero-dimensional model

A zero-dimensional model of the Hau River as a basin was set up, based on the conservation of mass in the basin and the equation of motion (see below). The model takes tidal water levels at sea (Vung Tau) as an input and compares this with the present water level in the basin. In order to run the model, it is required that a start water level in the basin is chosen. Other inputs are the size of the basin, the area of the opening and the river discharge. This last parameter is hourly measured as the volume of water that flows upstream or downstream. This causes the river discharge to oscillate around 0 (see section 3.4). The river discharge is averaged per day to compensate for these tidal effects.

$$Q = A\sqrt{2g\Delta h} \tag{4.1}$$

$$\sum Q = S\frac{dh}{dt} \tag{4.2}$$

4.1.1 System parameters and boundary conditions

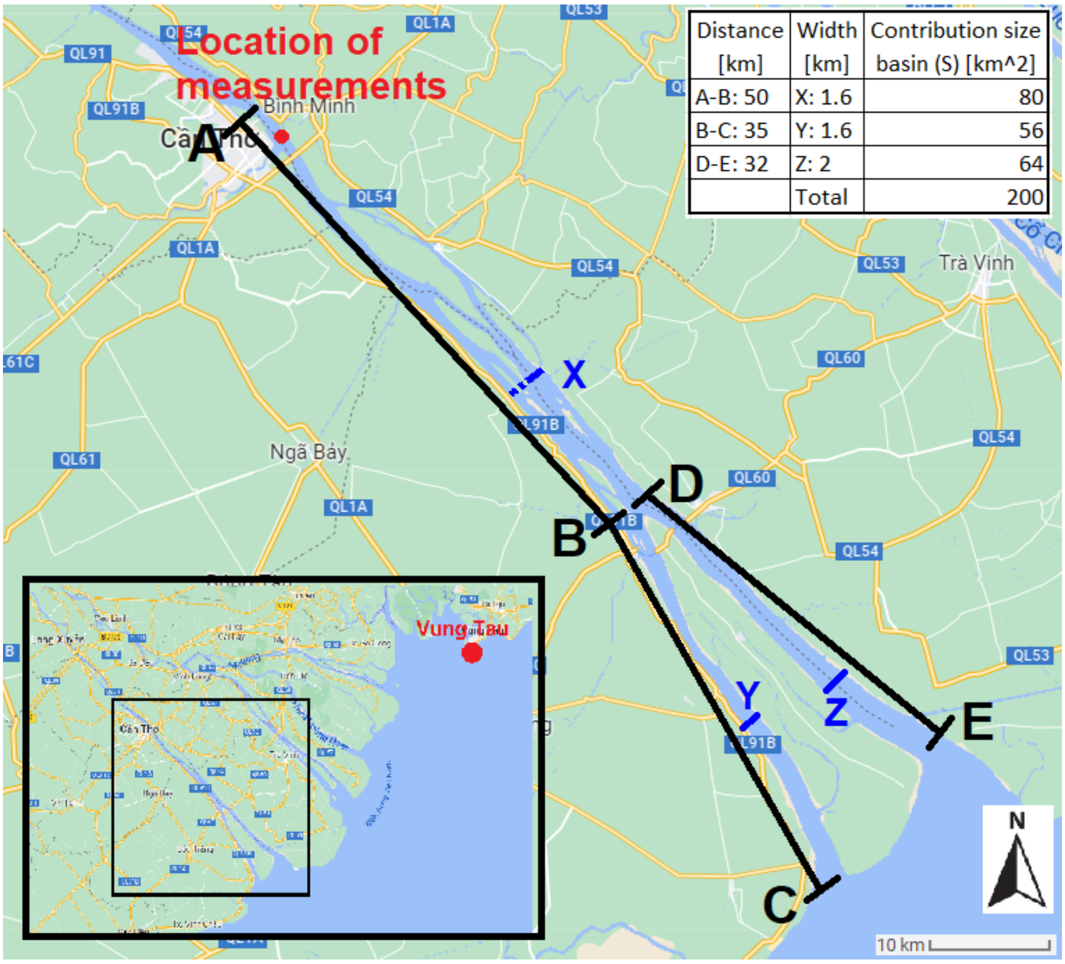


Figure 4.1: Model dimensions

This model is used to calculate the water level at Can Tho, using the Hau River as a basin, stretching from the estuary to Can Tho. After a coarse analysis via GIS, the basin size was estimated to be 200 km^2. The width of the river was also found with Google Maps. For dimensions of the reservoir, see Figure 4.1. Furthermore, the lower boundary for the water level was set at -18.49 meters, as this is the bottom of the river from the normative cross-section. The discharge input in the model was taken as the daily average discharge for each day.

Basin size S $[km^2]$	200
Width B [km]	3.6
Tidal level [cm]	Water levels measured at Vung Tau
River discharge $[m^3/s]$	Average daily discharge measured at Can Tho
Tidal discharge $[m^3/s]$	Calculated by model

Table 4.1: Model parameters

As Can Tho is located 80 km inland, the water level is on average higher than at sea. Figure 4.2 illustrates this effect. It examined the influence of river discharges on the difference between the sea and the Can Tho water level. As the gap appears to grow during the wet season, a relation between the discharge and difference was expected.

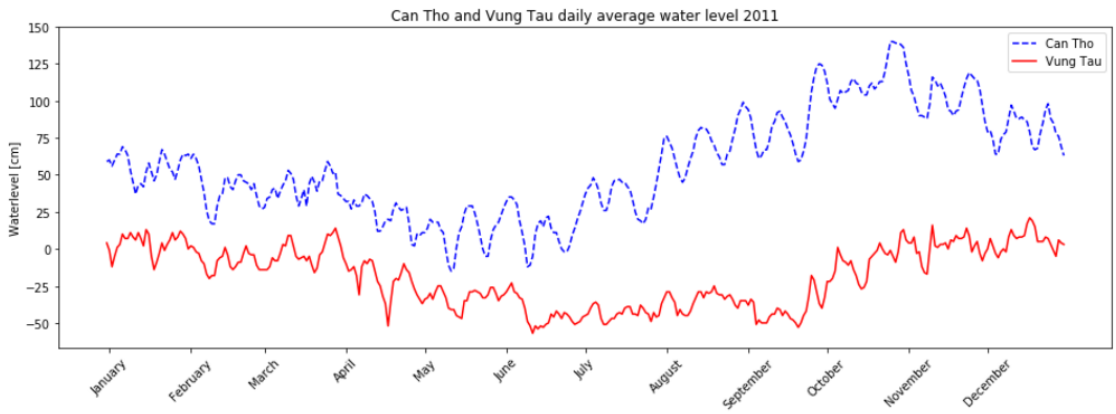


Figure 4.2: Water level gap between Can Tho and Vung Tau

The daily water levels in Vung Tau were subtracted from those in Can Tho to find the difference. For each difference, a daily discharge in Can Tho is known. These were plotted in Figure 4.3. The trend shows that linear regression can be used to describe the effects of discharge on the water level difference. Parabolic fitting was tried as well, but this resulted in an approximately straight line too. Higher polynomials showed signs of overfitting, which is why linear regression was chosen. The result of this linear regression was used in the calculation of water levels in Can Tho, by adding a constant dependent on the daily discharge. It is accepted that there is an uncertainty bandwidth in this constant.

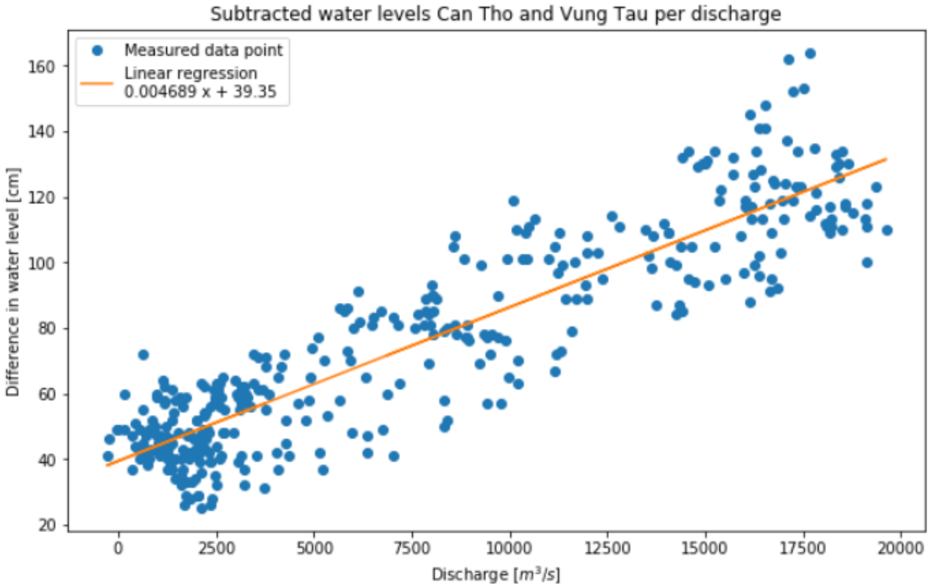


Figure 4.3: Linear regression for discharge and differences

4.1.2 Model validation

The model was optically validated by plotting the calculated water level at Can Tho and the measured water level at Can Tho in the same graph, as can be seen in Figure 4.4. It is observed that the prediction of the water level follows the same curve as the measured data. There is a certain deviation in the calculation for lower water levels. However, the (highest) peaks of the water levels are accurate. Since these peaks are normative for inundation and design, the models' performance is sufficient. It was chosen to plot a whole month to show the models coping with the moon cycle and spring tide. Furthermore, December was chosen because it is a month with average water levels.

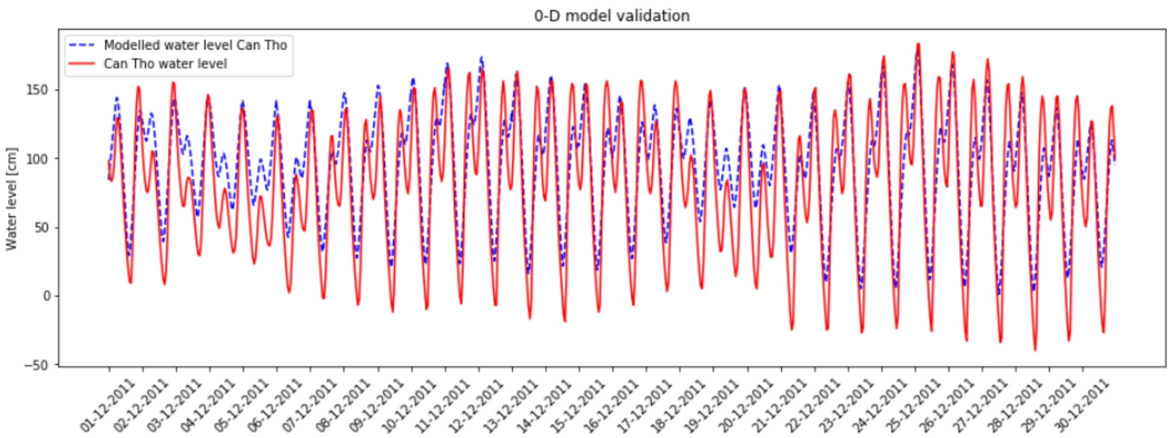


Figure 4.4: Calculated water levels in Can Tho for December

For the prediction of October, the same trend is observed. The highest peaks are calculated accurately. This month is especially relevant, as it is the wettest month in the year, causing the highest water levels in the city. A quantitative analysis of the model's performance is shown in Table 4.2. From this table, it can be concluded that the performance of the model in the dryer months is not great. However, the peaks in the wet season are predicted with useful accuracy. It is noted that the model should mainly serve as an indication. This particular part of October was chosen to display (Figure 4.5), as it is a normative period with water levels higher than 2.0 meters with respect to Hon Dau.

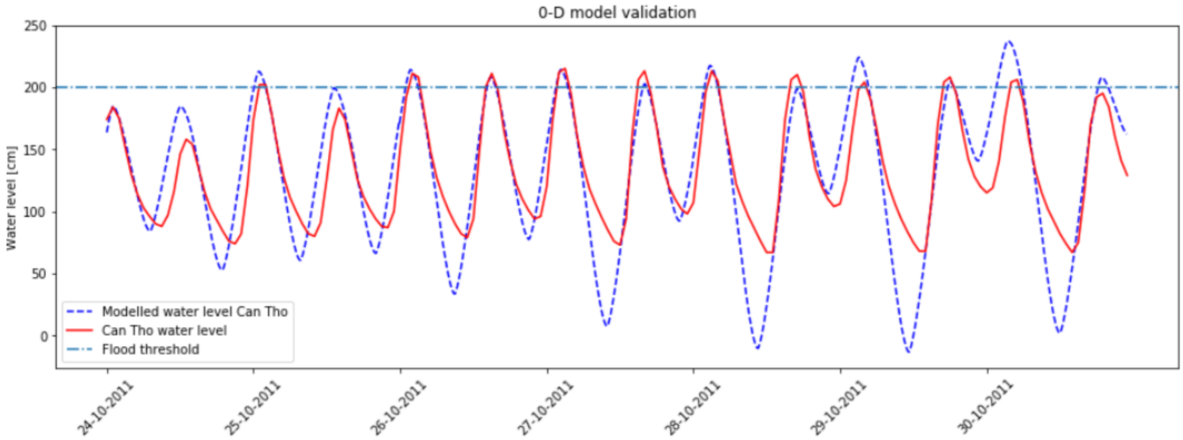


Figure 4.5: Calculated water levels in Can Tho for a part of October

Period	**Error percentage full prediction [%]**	**Error percentage daily peak prediction [%]**
Part of October (Figure 4.5)	5.26	17.0
December (Figure 4.4)	4.48	30.0
January - June	18.9	88.6
July - December	12.7	30.0
October - December	12.7	30.0

Table 4.2: Quantitative analysis of zero-dimensional model performance

4.1.3 Adjustment to simulate discharge sluice

The zero-dimensional model described in section 4.1 was adjusted to model the structure. A crucial change in the model is that the tidal discharge from the sea was blocked. When the sea has a higher water level than the water level in the basin, the model sets the inflow from the sea to zero, simulating the discharge sluice. Figure 4.6 displays the scheme for the discharge sluice.

Figure 4.6: Zero-dimensional model discharge sluice schematic

In Figure 4.7 the effect of a regular discharge sluice can be observed. It shows the water level at sea (directly next to one side of the sluice) and the level in the reservoir (directly next to the other side of the sluice). It is observed that at every crossing of the two lines (indicating an equal water level left and right of the sluice) the barrier opens or closes. In simulations of the water level in Can Tho, this effect will not be so clear, as the modelled water level is not directly next to the structure. In Figure 4.7 it can be seen that the discharge sluice has a significant influence on the water level.

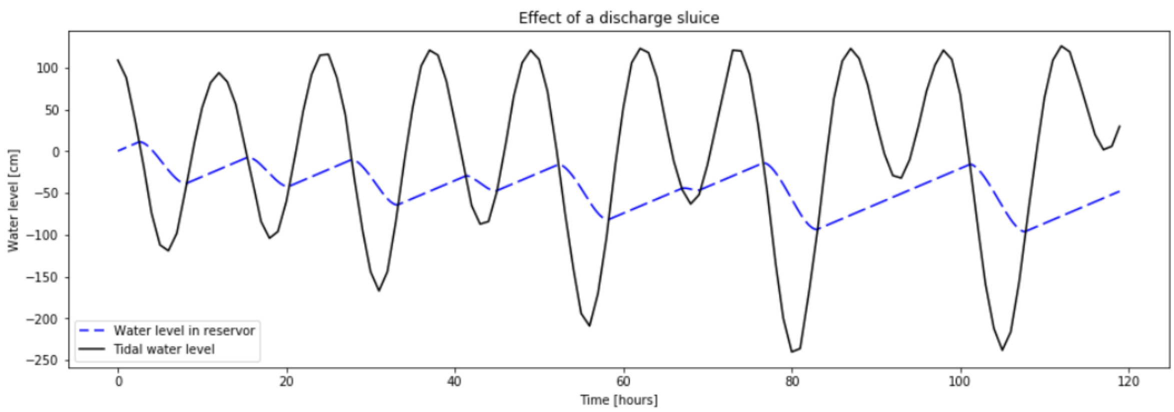


Figure 4.7: General scheme of the effect of a discharge sluice

4.2 Delft3D model

A conceptual Delft3D model was made to validate the impact of the different solutions. Delft3D is a process-based area numerical model, which can simulate basic processes of for example hydrodynamics, sediment transport, morphology and water quality for fluvial, estuarine and coastal environments. For this model the shallow water equations (4.3) and the general formula for the astronomical tide (4.4) are used:

$$
\begin{aligned}
&\frac{\partial h}{\partial t} + \frac{\partial}{\partial x}((H+h)u) + \frac{\partial}{\partial y}((H+h)v) = 0, \\
&\frac{\partial u}{\partial x} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial h}{\partial x} - ku + v(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}), \\
&\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu == g\frac{\partial h}{y} - kv + v(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2})
\end{aligned}
\tag{4.3}
$$

$$
H(t) = A_0 + \sum_{i=1}^{k} A_i F_i cos(\omega_i t + (V_0 + u)_i - G_i) \tag{4.4}
$$

4.2.1 Set up model

The following steps were taken to set up this model.

1. A grid of the observed area was created. The Hau River estuary has a length of 115 km long inland. The estuary can be schematized as fairly straight. Therefore the grid is made 115 km long and 58 km wide to represent the whole area. The length of the grid cells in the x-direction is constant with $\Delta x = 655$ m. The width of the river in the grid is 2.0 km and this part is locally refined in the width direction of the river to get more accuracy of the processes in the river itself. Therefore, Δy is not constant over the length of the total grid. The output of the model mostly consists of water levels over time. Therefore a coarser grid is applied instead of a finer grid which is required when velocities are observed.

2. The depth of the grid is determined with respect to the average bathymetry of the Hau River (see section 3.1). This resulted in a wide river bed with a maximum depth of 18.49 m. This maximum depth will be linearly interpolated to ground level over the width of the river starting 400 meters from the banks. As the threshold of flooding is 2.0 meters of water level elevation, the dry parts (also the banks) get this 2.0 meters as initial depth. An overview of the grid and depth is shown in Figure 4.8. The observation point in Can Tho is shown as a red dot in the figure.

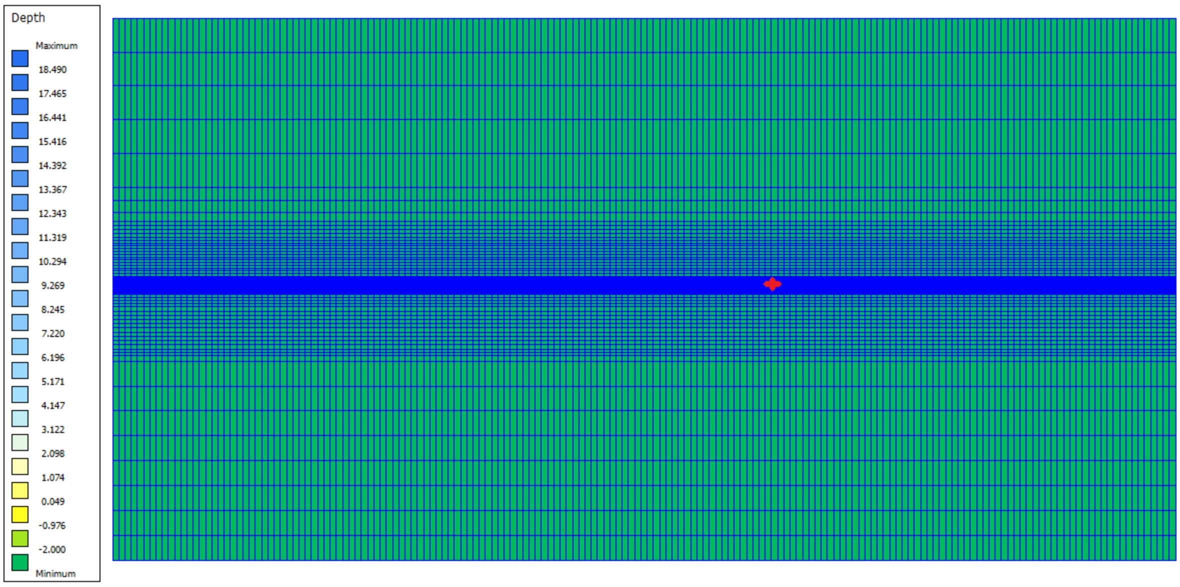


Figure 4.8: Grid and depth profile of the Delft3D model

3. The FLOW software was configured. The following parameters were assumed:

   - Time frame: Start date 06- 01-2023 00:00:00 - 10-01-2023 00:00:00 with $\Delta t = 60$ s. Those dates are chosen because a spring tide, which results in the highest water levels, is experienced in this time frame.
   - The initial water level is set at 0.00 meters as this is assumed as a fair start for the model.
   - Two boundaries have to be imposed to mimic the real-life situation. On the left side, a river inflow is simulated with a total discharge boundary and a time-dependent forcing. First, a normal flow of 5500 m^3/s is simulated for one day. This is done to stabilise the model. At the 7^{th} of January the flow is stepwise increased in time until the maximum of 16,000 m^3/s is reached. This peak discharge will be present continuously over the next three days, simulating a peak discharge in the wet season. In reality, the river discharge fluctuates but in this model, the peak is assumed as constant to observe an extreme scenario. On the right side, the tidal cycle is added as a boundary. The water level is forced with different astronomical tidal constituents. The tide in Vung Tau is taken into account for these constituents (see Table 4.3).

Name	**Amplitude [m]**	**Phase [deg]**
M_2	0.79	35.8
S_2	0.31	80.9
O_1	0.45	262.5
K_1	0.60	312.2

Table 4.3: Tidal constituents in Vung Tau (Trinh et al., 2015)

4.2.2 Baseline output

The output that will be used is primarily the water level in the middle of the river at Can Tho. Regarding Figure 4.9, it is shown that the flooding threshold is reached when the discharge increases to its maximum value in combination with a high tide occurrence. In such a period the city of Can Tho would experience a flood, which will be the basis of the outcome of the model runs.

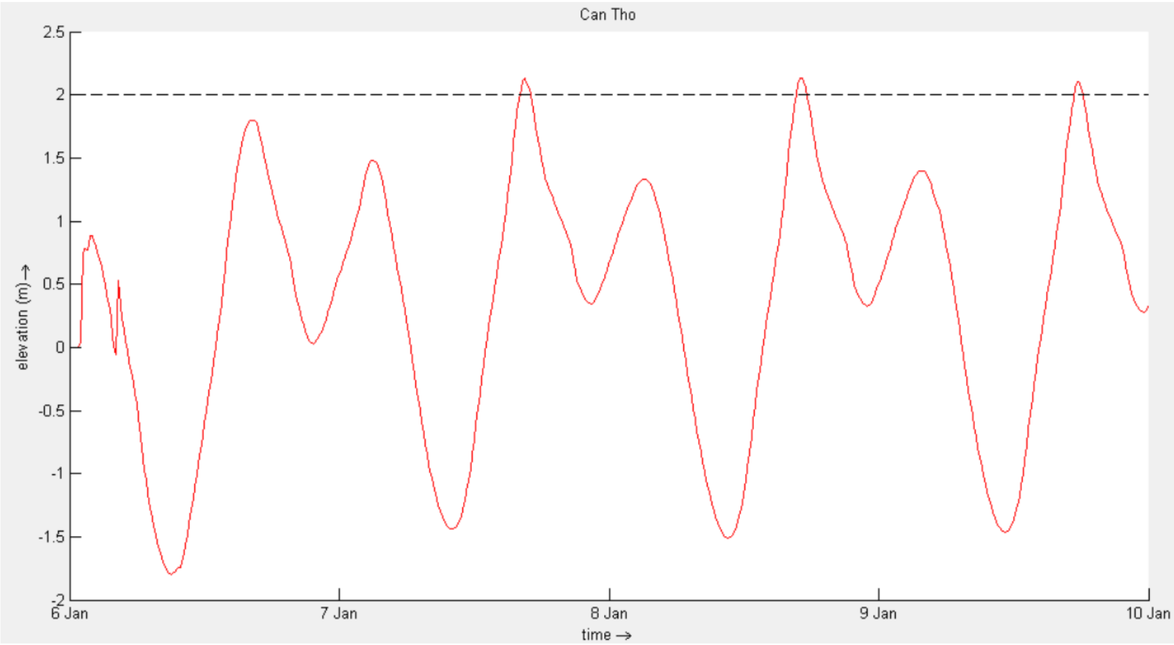


Figure 4.9: The water level at Can Tho relative to the flood threshold of 2.0 meters

4.2.3 Validation and remarks

The model is a simple conceptual design to obtain some insight into water level reduction and therefore has its limits. It cannot be validated profoundly as it is a basic design and limited data is available. For example islands, local widening and local narrowing are neglected, resulting in geometric properties of the model that will not match the whole estuary. Furthermore, the elevation level of the ground is assumed to be 2.0 meters everywhere, while in the real situation, this is not the case. The only validations that could be checked are the tidal variation at the sea boundary and the discharge at the Can Tho station. Furthermore, the discharge was assumed with a consistent maximum value, which will over-predict the flooding.

To validate the model two things are observed. First, the input of the tidal constituents is checked with the data in Figure 3.6. This is shown in Figure 4.10. It is chosen to use the data for four days with spring tide occurring. The Delft3D model shows higher water level increases. This means that the model could overpredict the flood occurring.

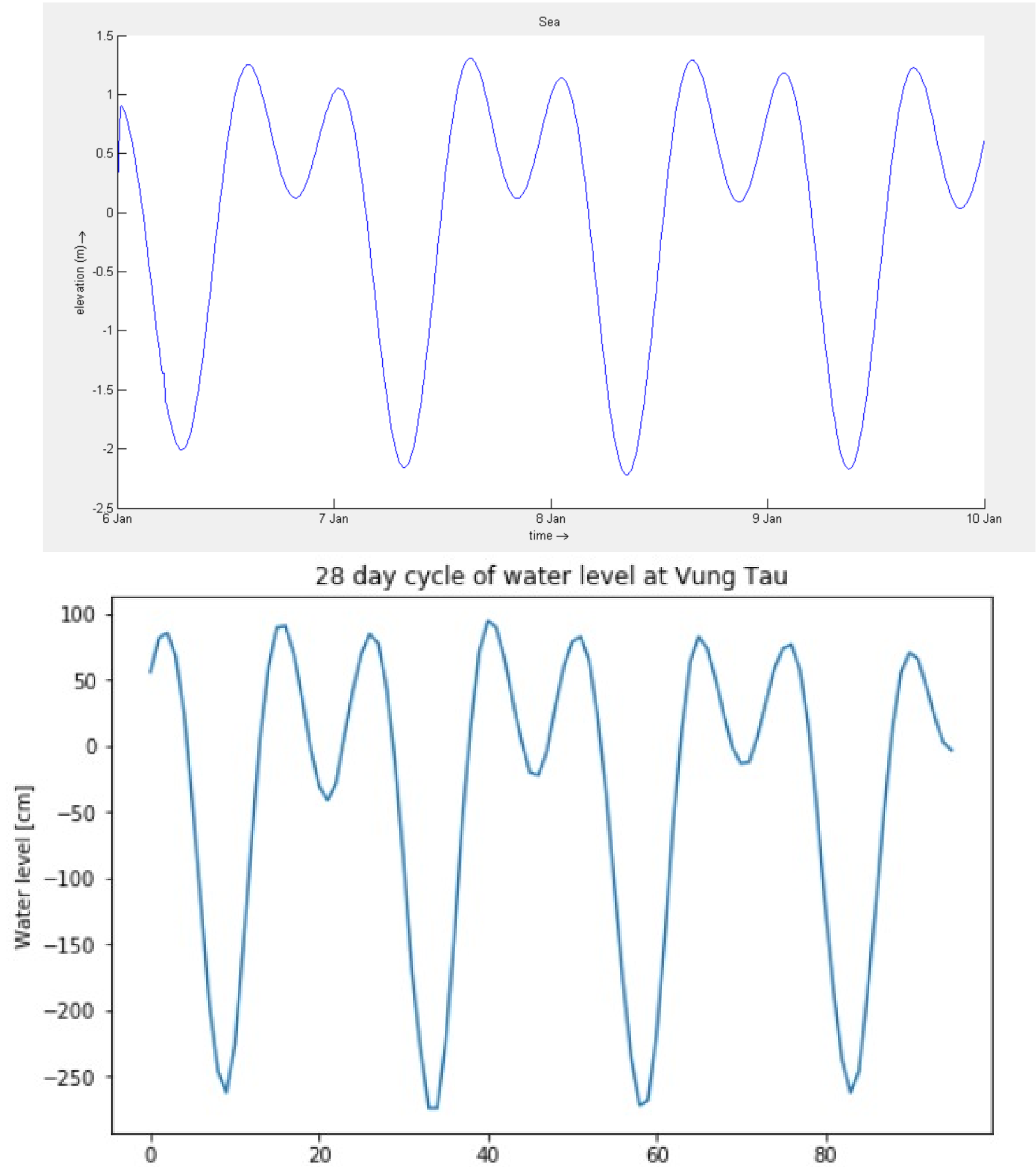


Figure 4.10: Validation tidal output Delft3D with measured data

The other validation that is done is the validation of the relative discharge in Can Tho over time. Four days are taken into account out of Figure 3.10 for a period in the wet season with high river discharges. The model shows in Figure 4.11 that the amplitude of the model is higher and differs in shape. An explanation of the higher discharges can be the constant river discharge in the model which is not the case in reality. The negative discharges can be explained because of the higher tidal variation as seen in Figure 4.10. The difference gives an overestimation, which can be seen as design safety and takes into account future scenarios.

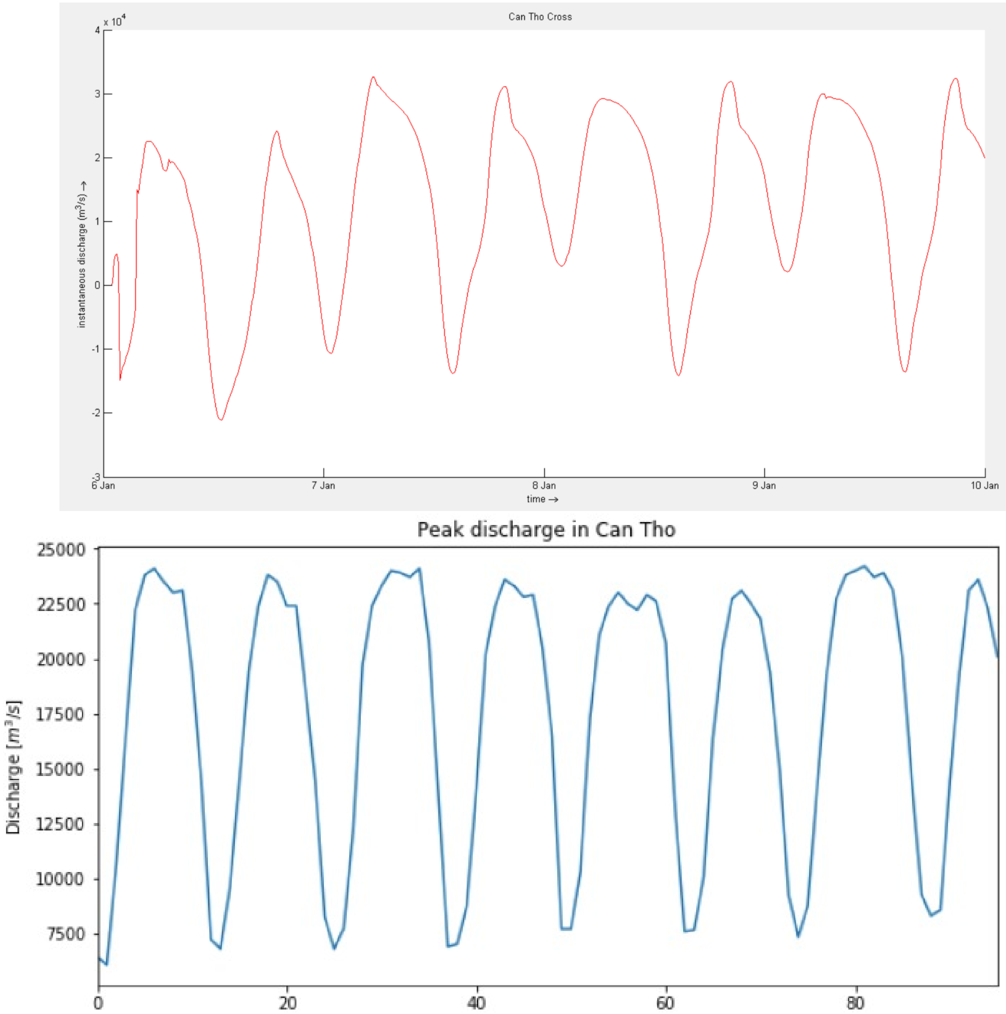


Figure 4.11: Validation discharge output Delft3D with measured data

4.3 Transport model

The four-step model is used to model road transportation in the MKD. This model consists of four key steps: trip generation, trip distribution, modal split and traffic assignment. This is summarized in Figure 4.12. The first step uses zonal and socioeconomic data to determine the attraction of a location. Then a double-constrained gravity model is used to compute the Origin-Destination (O-D) matrix in step two. The modal split distributes the trips over different means of transport. Finally, the traffic assignment can be determined, taking into account the number of trips, O-D matrix, available network and modal split. Dividing traffic over the network is done in the last step with an All-or-Nothing assignment. In this assignment method, the fastest route algorithm is used for all traffic to get from origin to destination. This thus does not take capacity constraints and congestion into account.

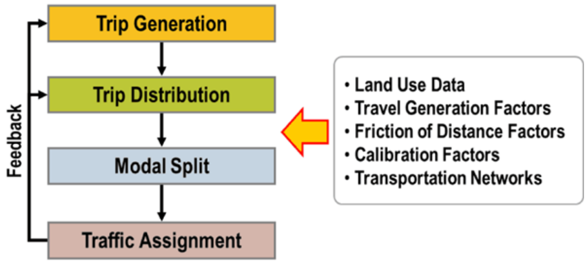


Figure 4.12: Four-step model (Rosenbaum & Koenig, 1997)

4.3.1 Input data for transport model

The network which is set up is shown in Figure 4.13. Key urbanized areas and provinces of the MKD are indicated. The lines between the nodes are simplified highway connections. Three different road types (Provincial-, National highways and expressways) have been distinguished. Provincial roads have the static characteristics of a 30 km/h free speed and a capacity of 1,200 veh/h/lane. On the national highways, the free speed is 50 km/h with a total capacity of 1,800 veh/h/lane. Expressways have an average free speed of 80 km/h and the capacity is 2,500 veh/h/lane. These values are determined in the sense, that it complies with realistic travel times.

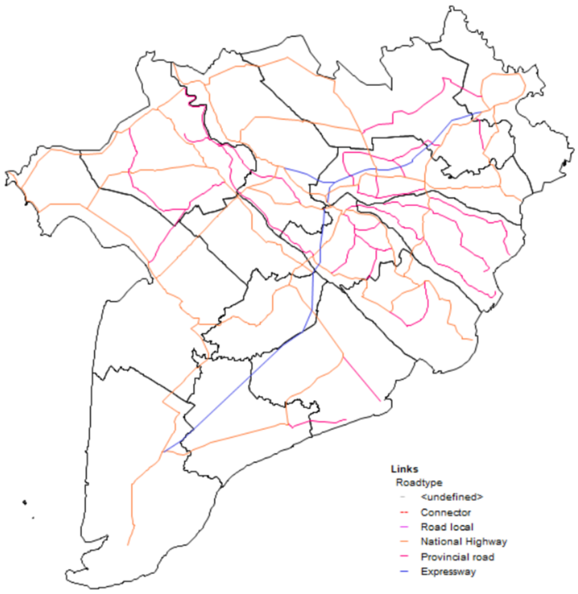


Figure 4.13: The transportation network in the base scenario

Within this study, the focus lies on agricultural businesses and urban areas. Population data and national indexes of traffic in urban areas are used to calculate production. The underemployment rate was used to calculate the attraction of the cities, while the calculation of the attraction of rural areas is based on the total area of agricultural land. When the number of trips from each location is known, these trips are distributed over the other destinations.
The production and attraction of each city were calculated with demographic information.

Data regarding the number of citizens comes from the national statistics office and united nations world population prospects (Knoema, 2021; United Nations, 2022). The statistical yearbook of Vietnam provided data on agricultural land. For the other jobs in urban areas, an underemployment ratio of 3.95% is used (GSO, 2021).

An average number of trips of 1.56 per person per day was used (Won & Kim, 2017). By multiplying these trips per day by 10% the commute during morning peak hours is computed (CROW, 2012). The production is then the average number of trips multiplied by the number of citizens. For HCMC 25% of the population is assumed to travel to the MKD on a regular basis. With the development of the port in Soc Trang, additional attraction is created. Similar-sized ports created a total of 200,000 extra jobs (Oluokun, 2022). The total characteristics of each significant area are shown in Appendix G.

The modal split is of significant importance. Many people in Vietnam use motorbikes to commute. From studies, it has been shown that only 1% use the car compared to 74% of motorbikes (D. N. Huu & Ngoc, 2021). The result of the calculated production and attraction can be seen in Figure 4.14.

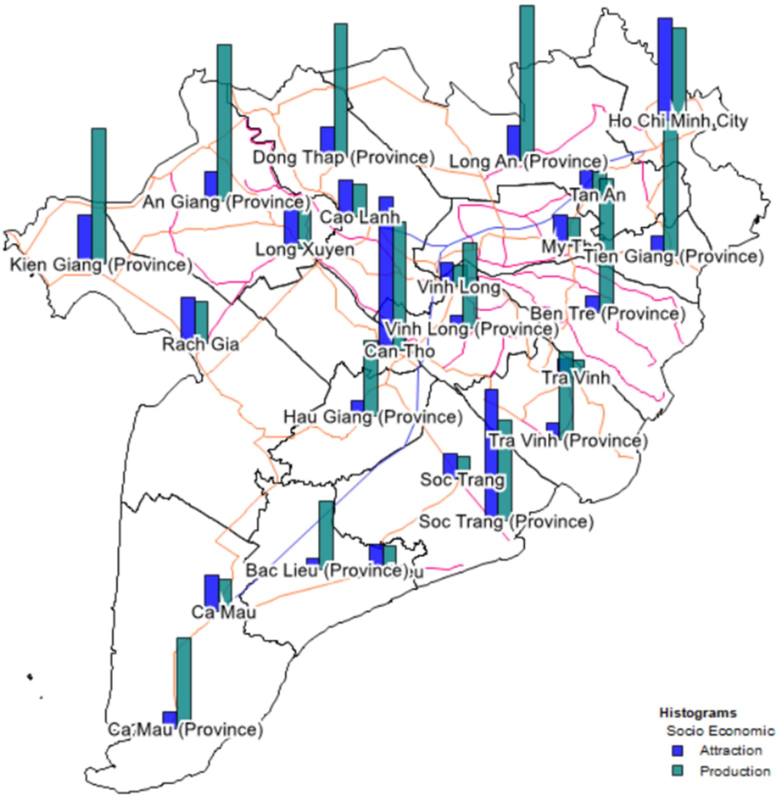


Figure 4.14: Production and Attraction per area

The production and attraction are combined with the skim matrix, which contains the shortest travel time between two destinations, to determine the origin-destination (OD) matrix. The calculation was performed by the top-lognormal distribution. This method is chosen because the willingness to use a specific mode can be easily incorporated into the transportation model.

$$f(t_{ij}) = \alpha \cdot \exp\left(\beta \cdot ln^2\left(\frac{t_{ij}}{\gamma}\right)\right) \tag{4.5}$$

Within this function c_{ij} represents travel costs from zone i to j. The other parameters which are used: $\alpha = 0.35$, $\beta = -0.3$ and $\gamma = 5$ (Ortúzar & Willumsen, 2011). Since a high outlook is used, it is assumed that the trips follow the trend of GDP growth. Therefore a growth factor of 4% is used.

4.3.2 Traffic load base scenario

From the OD Matrix, an All-or-Nothing (AON) assignment is used. This method relies on the Dijkstra shortest path algorithm (Dijkstra, 1959). In this algorithm, the shortest path is found between two nodes. From a starting node, S the shortest path is computed to all other nodes based on the travel times. Combining this with the OD matrix, the loads on the network are determined. A downside of this method is that in AON congestion effects on the roads are not taken into account. Furthermore, road users consider the same attributes of routes and weigh these equally. Since the aim of this model is to indicate the differences between network-related solutions, this method is chosen. From the network in the base year, the V/C ratios on the network are shown in Figure 4.15.

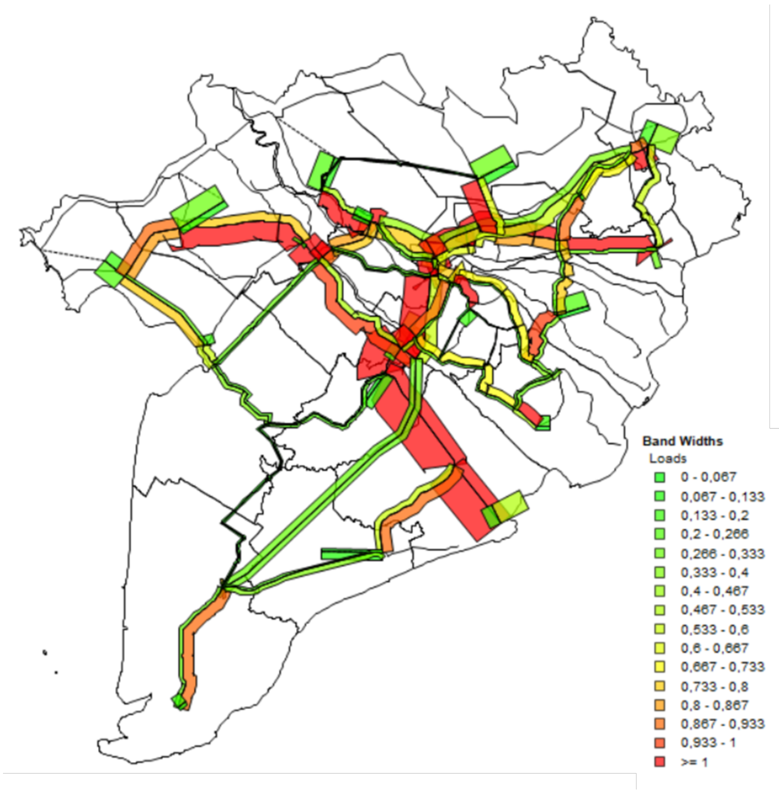


Figure 4.15: Network load base scenario

5 | Socioeconomics & transportation

This chapter emphasizes the MKD as a whole, instead of only the Hau River estuary, which is done inchapter 3. In order to understand the socioeconomics and transportation in the area it is required to study the bigger picture. At the beginning of this chapter, the economic activities are outlined. These activities serve to understand the demographics and land usage of the MKD more clearly. Subsequently, the demographics and land use are described. Then the transportation in the MKD is described, followed by the future development of the delta and the survey results. The chapter is concluded with findings from studying reference projects.

Considering Figure 5.1one can understand that the city of Can Tho developed heavily in the last decades. This development aggravates the problems which the MKD faces (see section 1.2) since they pose a threat to an increasing number of people.

(a) 1985 (b) 2000

(c) 2010 (d) 2020

Figure 5.1: Development of Can Tho over the last 35 years

5.1 Economic activities

The main economic activities within the MKD relate to agricultural activities. These activities find their origin in the rich natural and human resources which are vital for agricultural policy. In the 1990-2000 period, many farmers shifted from growing one crop of long-growth duration traditional rice per year to two or even three crops of high-yielding rice varieties per year (rice intensification). Currently, the MKD is characterised by its agro-based economy; serving the nation as its rice bowl (and the cornerstone of national food security policy) as well as the primary provider of food-based export revenue. The most important gateway (HCMC) is just outside of the MKD. The delta accounts for half of the nation's rice production and contributes to Vietnam's place among the top three rice exporters (Food and Agriculture organization of the United Nations, 2011). The income in the MKD per capita in 2008 was estimated to be around 140 million VND (5,500 euro) on average (We Are Water, 2021). In the Netherlands, the income per capita in 2008 was estimated at 39,400 euro (Nikki van Toorn (CBS, 2021), which is approximately seven times than the MKD.

5.2 Demographics

The complete MKD has a population of 17.3 million people. In Figure 5.2the demographical characteristics of the MKD are shown. The provinces adjacent to the Hau River estuary are also presented in the figure. The left y-axis is a scale for the population density and the right y-axis scales the total population. The density of population in the MKD is 424 people/km^2, which classifies the MKD as densely populated. In 2012 about 25% was urbanised compared to the national average of 32%, leaving about 75% of the population rural (Veerman, 2013). From 2015 to 2020 the Can Tho area had the second largest growing population in the world, with a growth rate of about 6% per year (Thien et al., 2020). In the last years, the population growth is declining and this decrease is projected to continue in the next years, see Figure 5.3 on the next page.

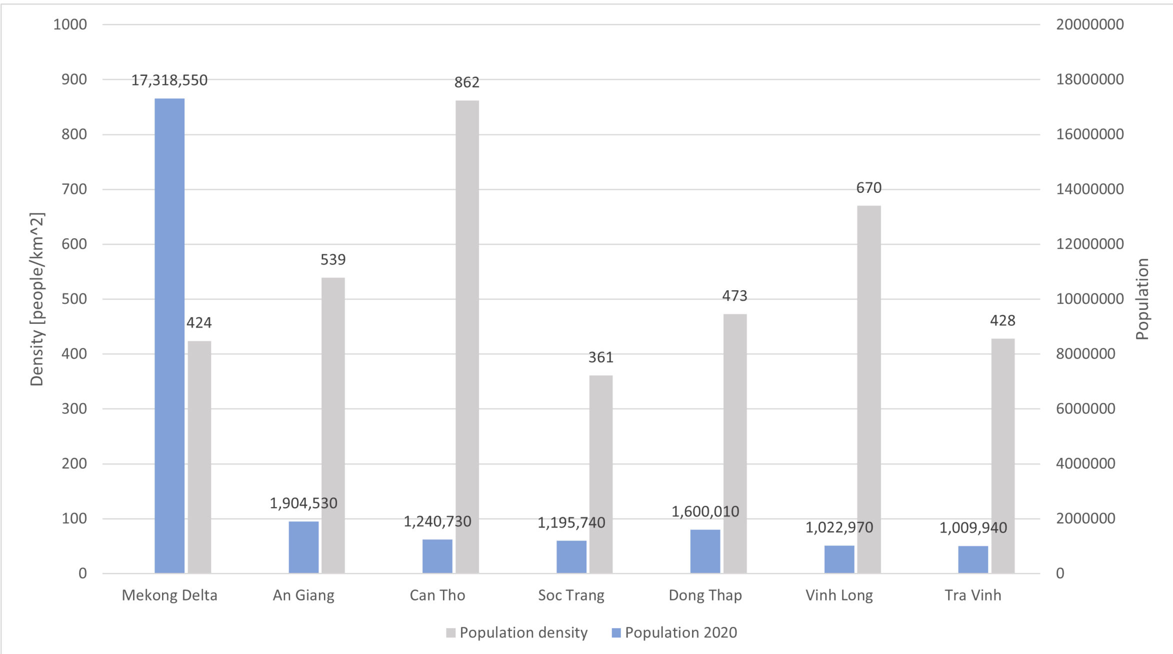


Figure 5.2: Demographics in the MKD (Knoema, 2021)

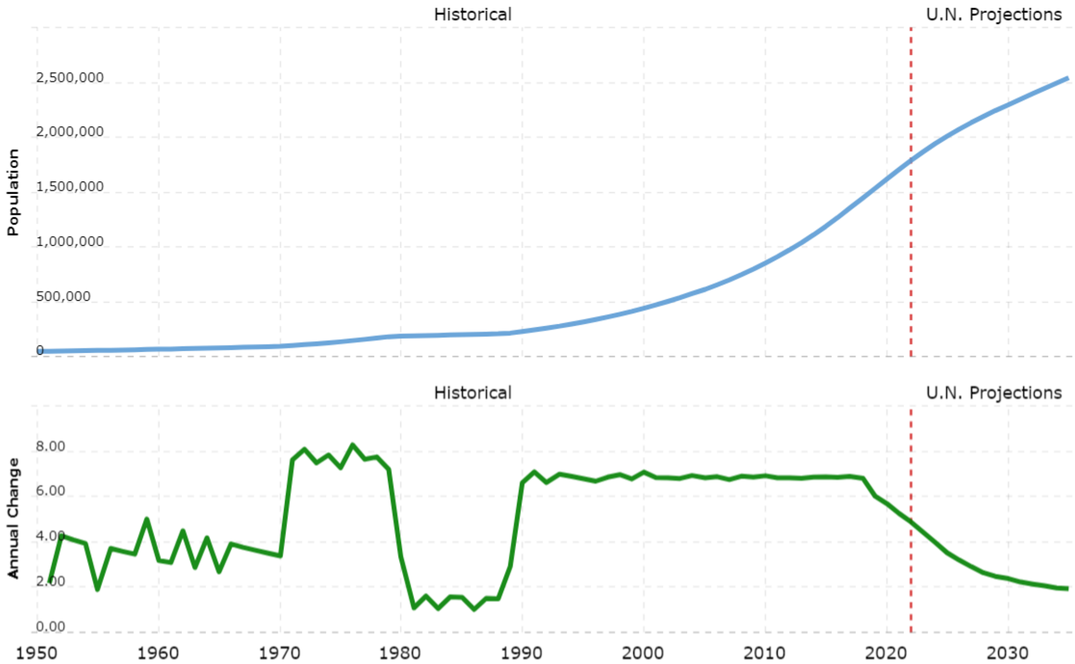


Figure 5.3: The population trend of Can Tho (MacroTrends, 2022)

5.3 Land use

With regard to the difficult conditions, the delta has highly fertile soils and loads of fresh water which enables highly productive agriculture and fishery. Most land parts are used for rice cultivation, shrimp farms, fruit orchards and vegetable crops. In Figure 5.4 it can be seen that the area is dominated by agricultural activities. In the coastal area, mainly aquaculture and a combination of shrimp and rice farms can be distinguished. Closer to the border with Cambodia double rice crops dominate the agricultural activity. In the middle area, there are mainly triple rice farms, fruit orchards and cash crops (Seijger et al., 2019).

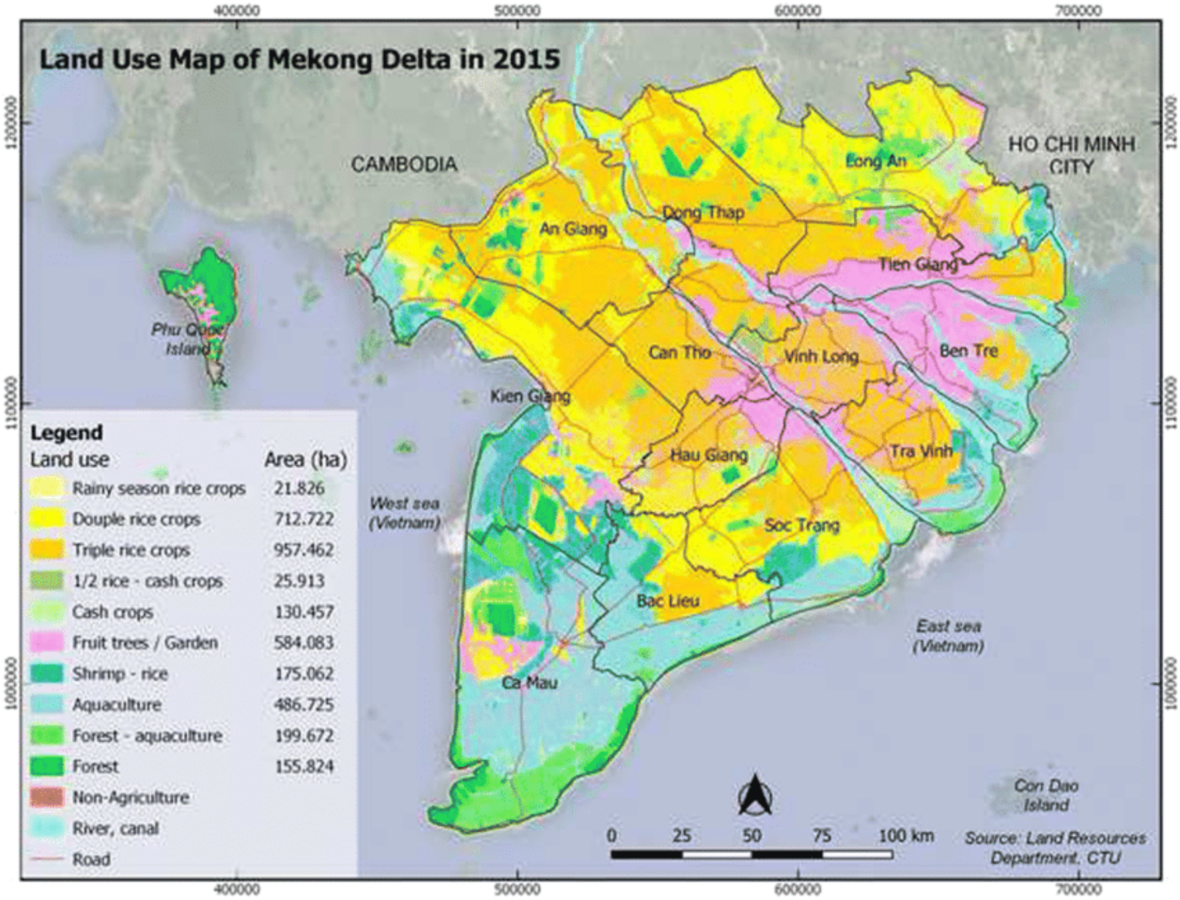


Figure 5.4: Land use in the MKD (Seijger et al., 2019)

5.4 Transportation

This section describes the transport system in the MKD. The current state of the road traffic system in the delta is much weaker compared to other regions in Vietnam, which constrains the commercialisation of the agri-food-industrial business. Especially the inter-provincial roads have insufficient capacity to serve the economic development (Veerman, 2013). The delta has a potentially very advantageous waterways network, which is not sufficiently utilised and is in serious degradation, resulting in soaring transportation costs, which hampers investments. A large port system for the direct export of agricultural products is missing. Local provinces for rice and catfish processing such as An Giang, Dong Thap, and Kien Giang are insufficiently connected (The World Bank, 2020). Current master plans anticipate huge investments in the roads and waterway network, with emphasis on upgrading and constructing an expressway from HCMC to Ca Mau. It is key to examine realistic future traffic forecasts (different scenarios) and identify which network/corridors would need priority to facilitate the desired long-term vision. The networks and general characteristics of water and road transportation are discussed in this chapter. In autorefapp:transportdetails additional information about water, rail and air transportation is given.

5.4.1 Water transportation

The current network for water transportation contains the main Hau River and sub-canals to the agricultural area. The structure of this network is shown inFigure 5.5. In this figure, a difference is made between the main, primary and secondary rivers. The MKD plays an important role in the international supply chain. Manufacturers in for example Phnom Penh (Cambodia) use the waterways in the MKD to ship goods. Presently, the Ministry of Transportation is carrying out the Mekong Waterways Project. In this study, the aim is to revitalise the canal network in the MKD. This is expected to enhance the shipping capacity throughout the delta, which will increase economic growth (Mekong River Commission, 2015).

Ships bound for international waters use one of the two branches of the Hau River (Hem & Asai, 2015). On the northern branch, there is enough depth for vessels to pass, while on the southern branch, the channel does not comply with depth constraints for sea-going ships. At the Can Tho port, investments have been made to increase the throughput to 2.5 million Dead Weight Tonnage (DWT) per year (Mekong River Commission, 2015). The maximum vessel size for which the port will be designed is 20,000 DWT (JICA, 2010). Complying with this bulk size, ships can have a length of 157.9 meters and a width of 23.2 meters. These ships also have a depth of 12,5 meters and a total height of 45 meters. Lastly, there is a minimum clearance of 10.0 meters on the river (Deltamarine, 2015; KMKA co., 2022). Regarding the Soc Trang port, plans have been developed to create a new seaport. The aim is a total throughput of 55 million DWT in 2050 (Vietnam News, 2019).

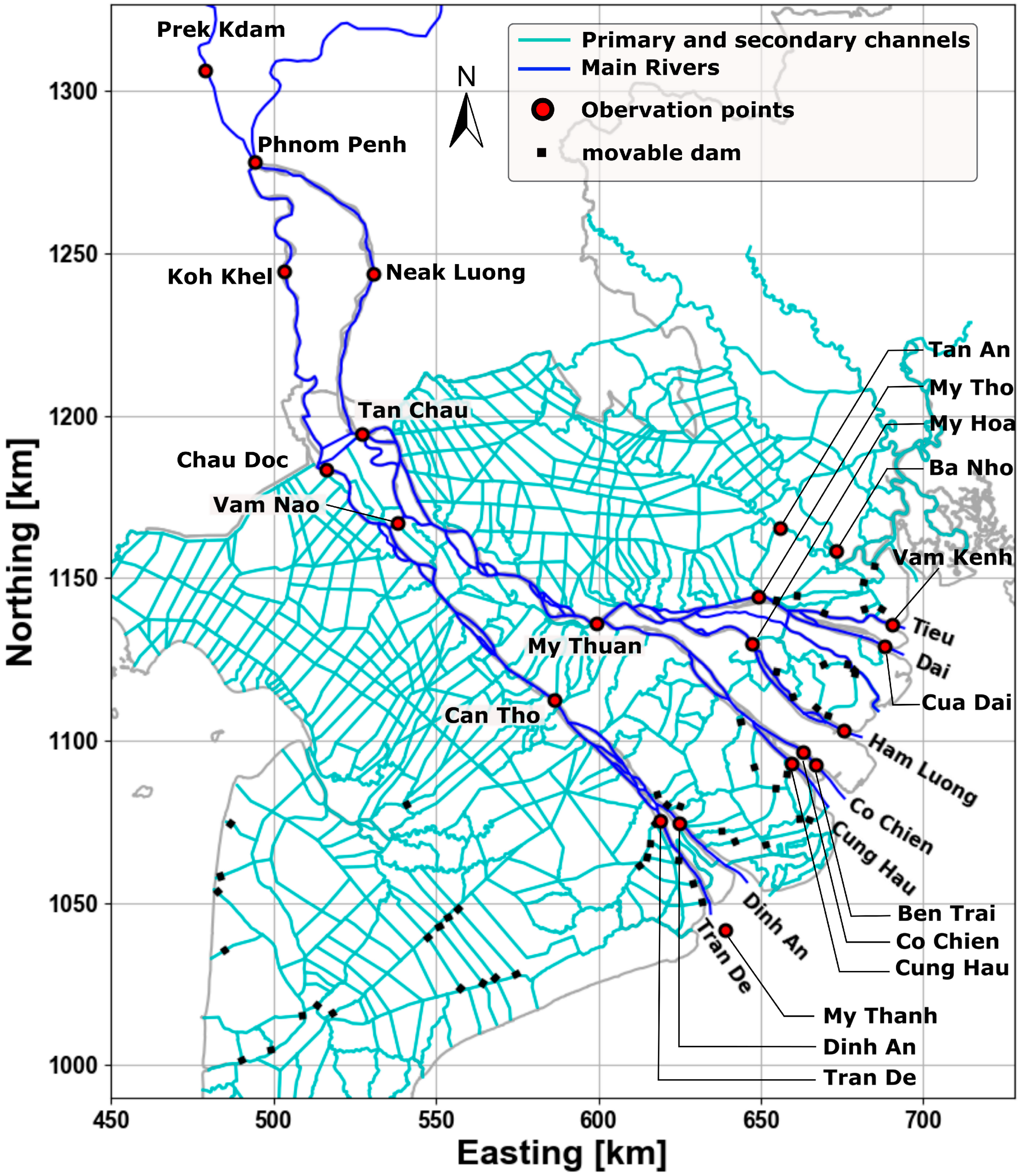


Figure 5.5: Canal Network MKD (Evers & Benedikter, 2009)

5.4.2 Road transport

Transport infrastructure in Can Tho is predominantly dependent on roads (85% of manufactured goods are transported through roads), rendering the transport sector vulnerable to disruptions caused by seasonal flooding. The city has proactively assessed transport investments based on flood risks. The link between transport and urban land-use planning is not fully taken into consideration (Forni & Nguyen, 2016). Around Can Tho, there are currently six national highways present as can be seen inFigure 5.6. There are also eleven provincial routes and over 383 km of district roads (Can Tho City Statistics Department, 2014).

Figure 5.6: Highway Network MKD (Ministry of Transport, 2021; OpenDevelopment Mekong, 2015)

Improving the efficiency of road freight transportation is crucial to support the industrialization and modernization of the Vietnamese economy as well as to increase the economic returns from investments. Increased accessibility and connectivity as a result of new and improved transport infrastructure are also likely to increase land values and investment opportunities along transport corridors. This is value-creation that the local government can accomplish using a variety of mechanisms and convert into public revenue (Forni & Nguyen, 2016). The government, therefore, has directed the Ministry of Transport to invest in the construction of expressways in the MKD region. This has resulted in the construction of the My Thuan - Can Tho expressway (including the- second My Thuan bridge) and the completion of the Can Tho – Ca Mau highway. A graph analysis was performed after simplifying this network. In this performance, Betweenness centrality is used as a parameter to measure the connectivity of the nodes in the network (Hansen et al., 2020). In total, the network consists of 20 nodes and 29 links. This results in a Betweenness centrality of 0.224 following equationEquation 5.1. In this equation, $\sigma_{jk}(i)$ is the number of shortest paths between nodes j and k that traverse through node i.

$$b_i = \sum_{j \neq i \neq k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \tag{5.1}$$

The road transport network was modelled and displayed in Figure 5.7. In this figure, the high outlook (as described in Table 5.1) for 2050 is used. By using this scenario, the 'worst' case is elaborated. The figure shows the Volume/Capacity Ratio (VCR) of the links in the network in colour. The more the colour of the link resembles red, the more the road capacity is reached. The width represents the absolute load on each link in vehicles per hour. From this figure, it can be noted that the development of the port of Soc Trang has a significant influence on the network. The corridor between Can Tho and HCMC is also operating at capacity. A more in-depth explanation of the model is given in Appendix G.

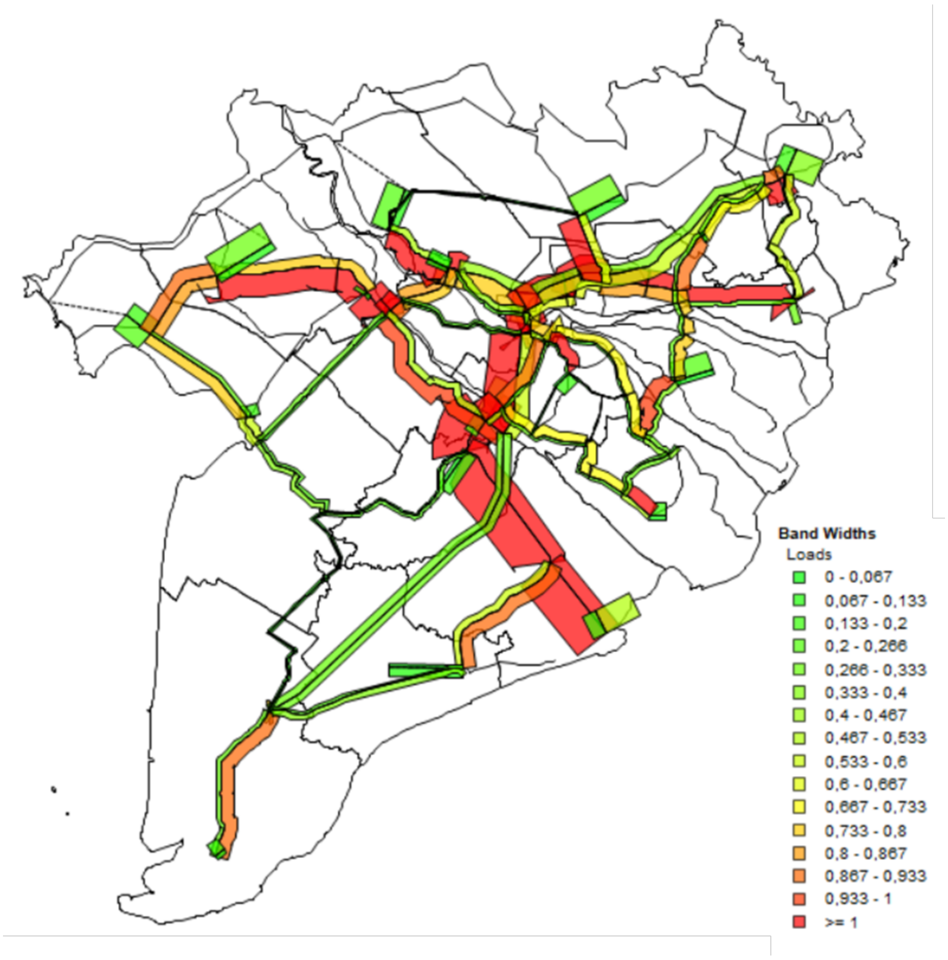


Figure 5.7: Network load base scenario

5.5 Future development

The population of the MKD can increase from the current 17.3 million to 30 million in the year 2050. This is dependent on the way that the area develops socioeconomically, as can be seen in Table 5.1. A key factor of development is climate change. Its effects on the development of the Hau River estuary are described in subsection 1.2.2.

	Moderate outlook			**High outlook**		
	2025	2050	2100	2025	2050	2100
Population [Million]	18	15	7 - 8	20	30	40
Urbanisation [%]	28	30	<40	36	45	>60
GDP Growth [%]	2 - 3	<2	-	- 6	>4	-
Industrial sector GDP share [%]	20 - 25	<30	-	35 - 40	>40	-

Table 5.1: Characteristics of different socioeconomic outlooks in the MKD (Veerman, 2013)

With the rich natural resources of the MKD, the primary focus of the region's economy is on the agricultural sector. In recent years, however, the region has seen more development opportunities, such as becoming a balanced multi-sector economy with sufficient urbanisation and industrialisation. Although there are clear socioeconomic development objectives and policies for the region, approved by the Prime Minister, actual developments are moving in a different direction. One of the intentions promoted by the Vietnamese government is "high tech agriculture" (Veerman, 2013). Regarding land use in the area, different studies have indicated that there will be a shift in agricultural activity. A decline in triple rice agriculture is expected. This land is expected to be used for other agricultural activities such as aquaculture and fruit orchards.

One scenario which has been deemed realistic by The Water People is that the MKD develops into a regional hub for high-value agriculture and agro-food products for export and domestic markets. This means that non-agro-food industrial and tertiary sector activities, except for related services and industries such as logistics, machinery and equipment are directed outside the delta. This enables economic development and GDP growth based on the region's agricultural advantages. This scenario represents a specialised economic growth model that deviates from the national average, but more closely reflects and builds upon the present agro-based economic structure and climate of the delta. Apart from concerted investments and policies to create an enabling economic climate for specialised agro-industrialised processing and export, this economic model will also require a turnaround of the agro-based production sectors. The latter, either in aquaculture, fruits or commodities, will need to transform into modern, commercially oriented, production systems focused on high product quality that meets international and middle-class urban consumer standards. A continuation of declining rural population pressures and resource consolidation – as presently emerging in some areas of the delta – may thus form a favourable socioeconomic environment to achieve this. This is especially true if and when a growing agro-industrialised sector will be able to absorb a production-based labour force that is non-agricultural and growing steadily. Also, this Agro-Business Industrialisation scenario depends highly on effective spatial planning and well-concerted investments in agro-industry, production and transport. Disappointing growth rates and trends may result in a “slipping-back” of this economic trajectory into a Food Production scenario. An overview of the development scenario is shown in Figure 5.8.

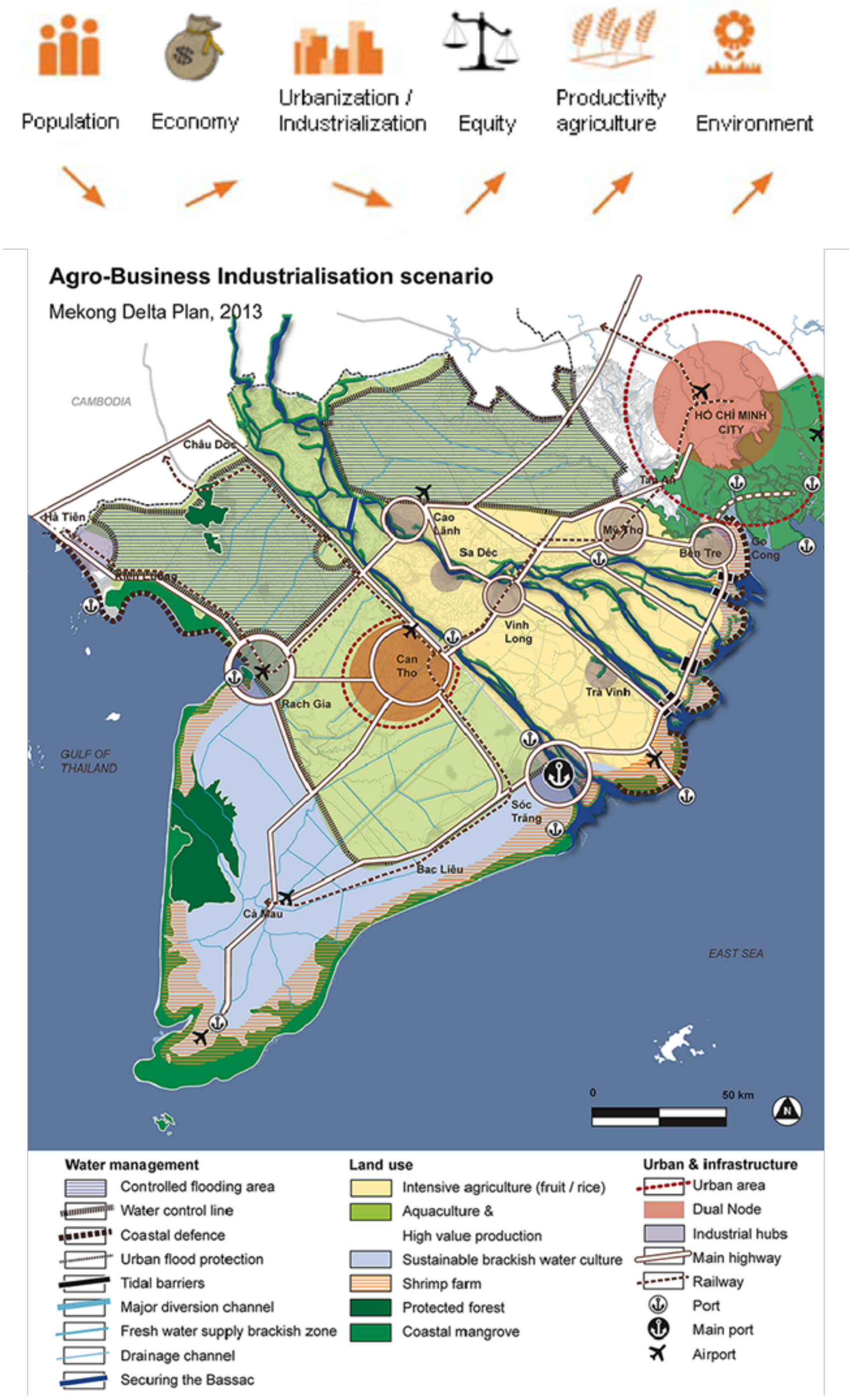


Figure 5.8: Future development MKD (Veerman, 2013)

5.6 Survey results

In the study area, the city of Can Tho, a survey was carried out to examine the problems that affect people's lives the most. Identified topics are environmental aspects, the well-being of citizens, economic prosperity and societal benefits. Their relevant importance, based on the results of the survey, is indicated in the pie graph in Figure 5.9.

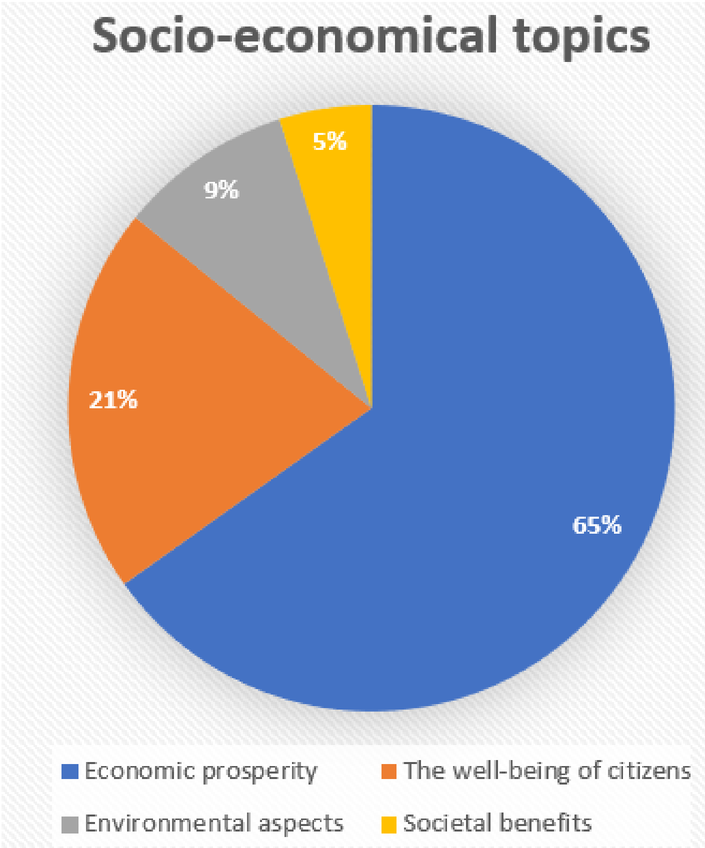


Figure 5.9: The relative importance of identified topics

It is obvious that economic prosperity is assessed as the most important. In this topic, improving transportation facilities, industrial economic development and sustainable agricultural production were distinguished as attributes. A more specific distribution of the identified problems people care about is found in Figure 5.10on the next page. Some weight is added to the average score of the well-being of citizens by sustainable agricultural production. It is remarkable that flooding only takes the sixth place on this list. Furthermore, the importance of environmental aspects consists almost entirely of the contribution of air pollution as a problem, which is assessed as the most important one.

The results of the survey require some comments. The sample size ($N = 16$) is small. This compromises the legitimacy of the outcome. Furthermore, some of the participants assessed one attribute way more important than others, causing a big spread in the assessments. This statement is supported by Figure 5.11 found on the next page. A wide box plot indicates a broader disagreement on the importance of an attribute.

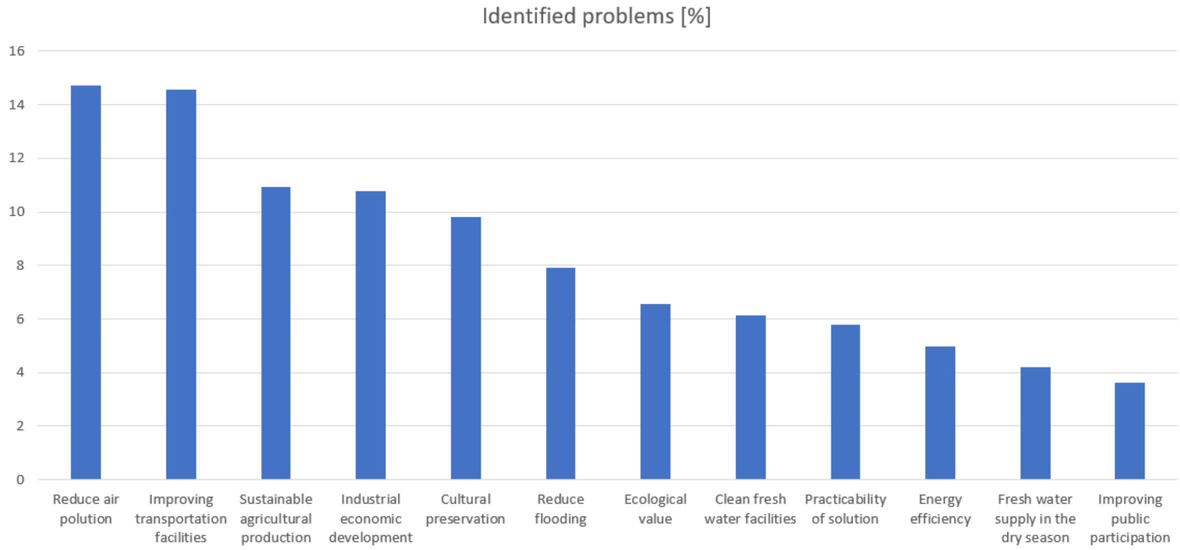


Figure 5.10: The relative importance of identified specific attributes

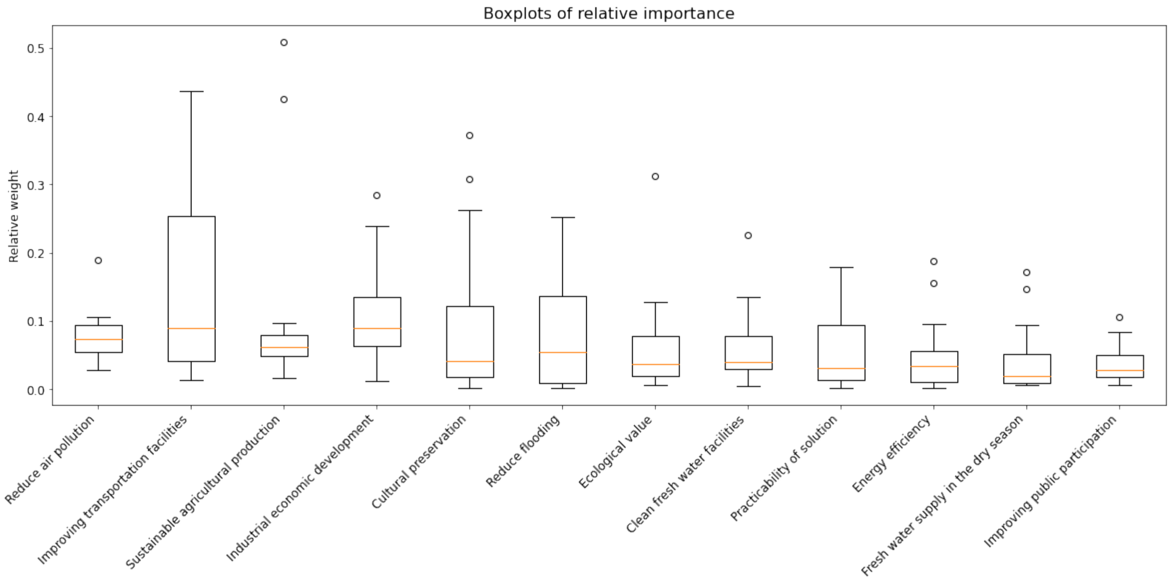


Figure 5.11: Boxplot

5.7 Lessons out of reference projects

From a comparison with the Red River (RR) in the Northern part of Vietnam, it is learned that the country is already familiar with hydraulic structures. Irrigation systems bypasses and dams are part of the water management of the RR delta. Although there is some experience present in the construction and operation of these hydraulic structures, maintenance is not always sufficient. This can be a result of misplaced priorities, a shortage of money, poor management, a weak monitoring system etc.

Both riverine and coastal flooding form a threat to the RR delta. Therefore, an extensive flood protection system has been built. However, most of the levees are of age and were built with cheap materials and without the right knowledge. This has led to unstable and degraded levees. They often suffer from damages like piping, under-seepage and forms of instability like sliding or local collapsing during periods of high discharge. The river levees were considered more important than sea levees throughout the past and are therefore in better shape. Other findings on the RR delta can be found in Appendix D

Another example of construction and maintenance complication was found during a field trip to the Bac Hung Hai irrigation system in the RR delta. A sluice system (constructed in 1958) was observed where an embankment was built on only one side of the river. The other embankment was supposed to be constructed later when the funding would be available. More than 60 years later, the other embankment is still to be constructed. At a different location, a sluice was visited that was three years old. The structure already showed signs of deterioration. Concrete decay and failure of rubber seals caused water to leak through the structure. An extensive report of this field trip is available in section C.1.

The above-described situations indicate future complications that are to be expected after the implementation of any proposed solution. A structure that requires high maintenance is more likely to perform worse over time. This also applies to complex structures.

6 | Proposed solutions

As stated before the problems that the MKD faces are severe and diverse. As the delta is in danger and a highly studied area, lots of potential solutions are considered in the last few years. In this chapter, four solutions are proposed that are most relevant to the goals of this report. These solutions are inspired by the reference projects in the RR and some of the Building with Nature concepts that are imposed in the Netherlands. The comparison with the RR delta was not too helpful, as some of the solutions make use of the elevated land in the northern part of the country. As there is little to no elevation in the MKD, these best practices can hardly be implemented in the MKD.

In advance, it can already be stated that no single solution can be considered the undisputed best. A proposal can, for instance, perform well on flood prevention, but not do anything to reduce salinity. The solutions should be considered as stand-alone measures to keep the report in contemplative way.

In the following sections, the four proposed solutions are described one by one. For each solution, the nature of the concept is described, after which a preliminary design is presented. Then, if necessary, hydraulic models are used to assess the effectiveness of the proposed solution. The fourth proposal does not need hydraulic modelling, as it intends to keep the situation the same. For each solution, the impact on the transport system is examined. This is then used to examine the social and economical influence. An overview with advantages and disadvantages completes each section.

It was planned to test the proposed solutions with the one-dimensional models of SIWRR, of which also Royal Haskoning DHV makes use. Due to a late cancellation on their end, this was not executed (see Appendix H). The effectiveness of solutions was assessed using a zero-dimensional model and Delft3D.

6.1 Solution 1: Discharge sluice

The discharge in the Hau River can be regulated with the realization of a discharge sluice. The tide inundation, as well as the salinisation problem, can be reduced. During a flood, the saline water can be kept outside of the river by closing the discharge sluice. During low tide, the sluice can be opened because the discharge of the river will be bigger than the tidal discharge resulting in an outflow of water into the sea.

6.1.1 Proposed design

The Hau River around Can Tho is approximately 1,870 m wide. This is relatively wide for a discharge sluice. There are 3 proposed locations to place the sluices, see Figure 6.1. The locations of the sluice will be rated on the span, navigational depth and transport possibilities. The first option is a single structure which spans the Hau River. There are several locations in the river that have a little island to reduce the span. This way the span for location 1 is approximately 2.0 km. A combination location 2 & 3 demands two sluices to be built. This will result in two spans of 1.70 km and 1.87 km. The last location is near the coastal area where it would also be necessary to build two sluices. These two sluices will result in two spans which will be 1.86 km and 2.72 km. To determine the location where the sluice will be assessed, the pros and cons of every location are listed in Table 6.1.

Figure 6.1: Location discharge sluice

Location	Pros	Cons
1	- Easy to connect to existing road network via future expressway - Single sluice system might be easier to operate	- Close to Can Tho which results in a small river basin for water storage - Levees needed along the river banks all the way downstream - Does not decrease salt intrusion downstream
2 & 3	- Relatively short spans increase feasibility - Easy to connect to existing road network	- System with two sluices might be more complicated to operate - Close to Can Tho which results in small river basin for water storage - Levees needed along the river banks all the way downstream - Does not decrease salt intrusion downstream
4 & 5	- Might connect the planned harbour to the road system - No levees needed to protect the river banks - Furthest away from Can Tho results in the biggest basin	- Relatively large spans reduce the feasibility - Relatively large spans might be more complex to operate

Table 6.1: Pros and cons for discharge sluice location

With a multipurpose use of the discharge sluice the surrounding area will benefit more. After consideration of the pros and cons, as discussed in Table 6.1, location 1 is considered not worth to investigate further. The ability to build a road over the sluices to connect the existing roadwork from Can Tho to HCMC, or directly to the harbour planned on the end of the estuary, is considered more feasible than location 1, which does not have a lot more benefits than having a shorter span. In other words: it seems worth it to invest a bit more for more potential in the future. Location 2 & 3 also has the possibility to act as a place to cross the river for the existing roads. The basin size is defined as the river area available from the discharge sluice to the city of Can Tho. For location 2 & 3 the basin size is smaller compared to location 4 & 5 but it will still provide enough storage. Measures have to be taken to deal with the tidal inundation downstream. To conclude one can say that only location 1 can be seen as not feasible. Location 2 & 3 and location 4 & 5 can both be seen as possible locations where the discharge sluices can be built.

6.1.2 Salinisation

During ebb, there is more fresh water from the river flowing into the sea than salt water from the sea into the river. The highest concentration of salt in the saline water is at the bottom (van Prooien, 2022). This salt water has a higher density compared to the freshwater. The dense saline water will therefore want to move beneath the less dense fresh water into the river. When the freshwater flows over this saline water, a circulation pattern occurs, moving the water with a high salt concentration into the river (Figure 6.2). This should be kept in mind when designing the discharge sluice. One can think of a small barrier at the bottom of the river to prevent this from happening. This small barrier can then also be used as a foundation for the gate of the discharge sluice.

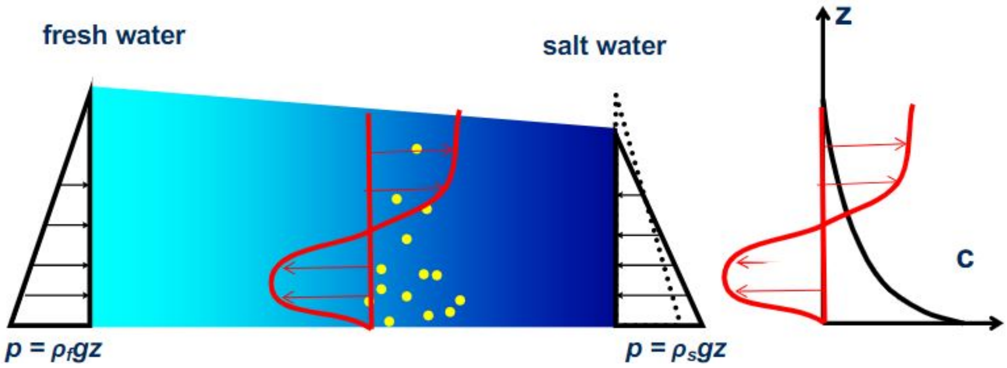


Figure 6.2: Salt water intrusion during ebb (van Prooien, 2022)

6.1.3 Effect of the discharge sluice on the water level

In the city of Can Tho flooding is caused by the combination of high tide from the sea and large discharges from upstream due to heavy rainfall. When the upstream discharge meets the high tide the water level rises drastically. During the wet season, the upstream discharge gets too big and causes flooding.

The discharge sluice drastically lowers the water level. However, with extreme discharges, the basin still floods. The plotted water levels in the figure occur in the wet season in October when the water level is high and flooding is realistic. Can Tho will flood when the water level reaches a value higher than 200 cm (Thanh, 2022).

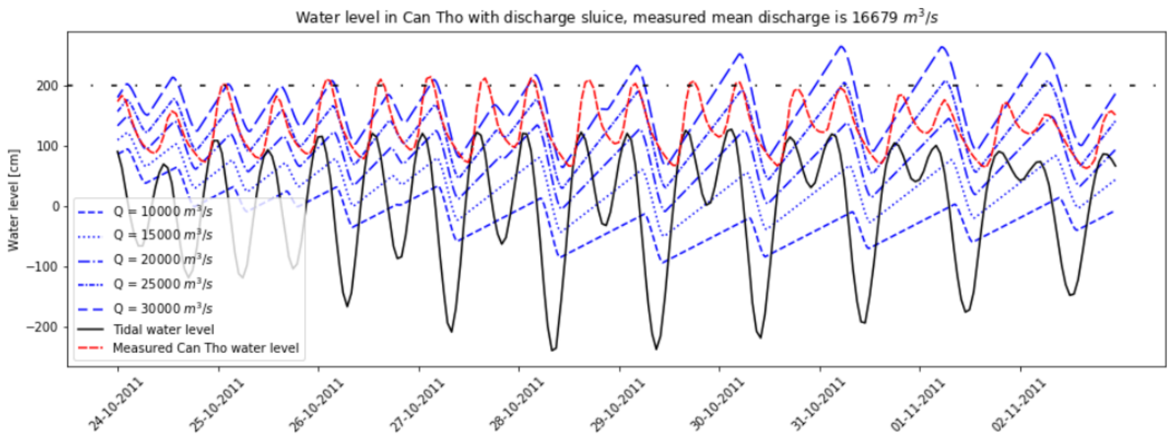


Figure 6.3: Change in water level for different discharges, S = 80 km^2

The effect of constructing sluices at location 2 & 3 is illustrated by Figure 6.3. The reservoir size here is taken as 80 km^2. There is still a significant controlling and reducing effect on the water level in Can Tho, but it does not have the same impact as a sluice at location 4 & 5, which is illustrated in Figure 6.4.

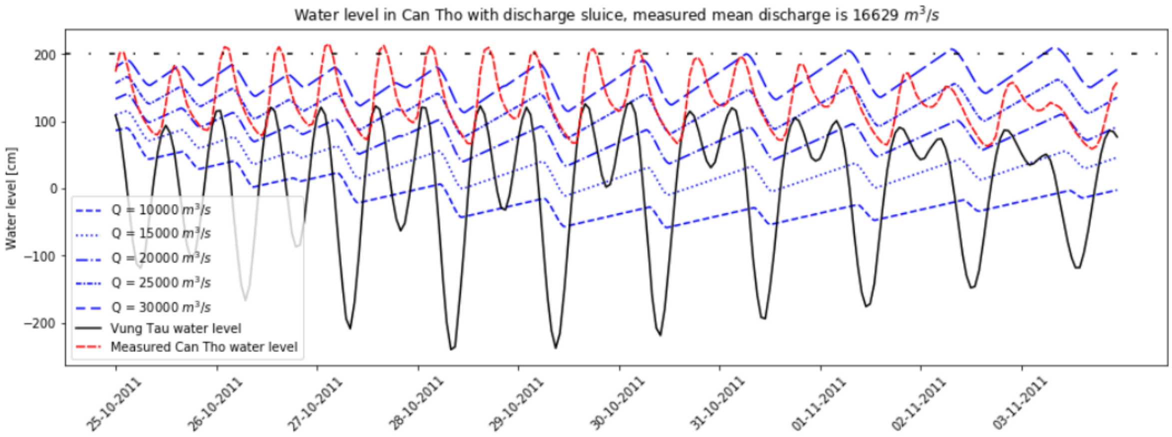


Figure 6.4: Change in water level for different discharges, S = 200 km^2

6.1.4 Structural feasibility

During the construction of the discharge sluice, some major complications are to be expected. The project will match dimensions with some of the biggest existing water retaining structures. Furthermore, the sluice is required to open and close in a relatively short time span, to limit hindrance to water transport.

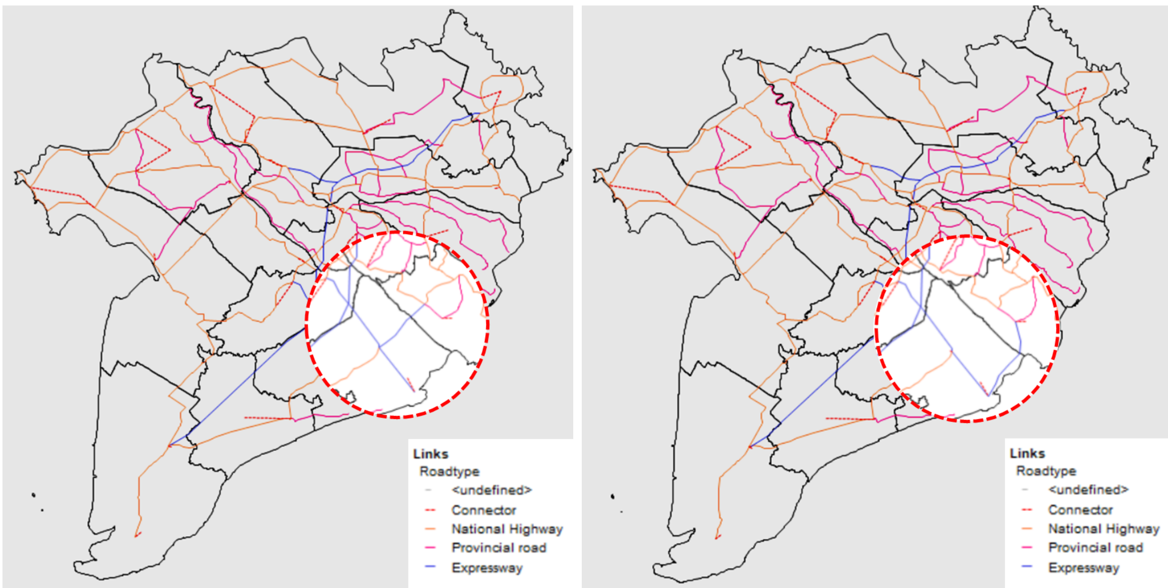
A similar project in the Netherlands, which is called de Oosterscheldekering, has been built in 1986. Its function is different, as it is constructed to serve as a storm surge barrier (Rijkswaterstaat, 2022). However, it can be used as a reference project, since the dimensions are in the same order of magnitude. Its construction time spans over 26 years, in which 5.0 kilometres were dammed and of 4.0 kilometres the opening can be controlled. The biggest lock doors in the Oosterscheldekering are up to 42 meters wide and 12 meters tall and weigh 480 tons. These doors can be lifted vertically and close of the sea arm in 75 minutes. A quicker closing would result in too intense waves in the Oosterschelde (Steenepoorte, 2016).

The opening system of the sluice doors in the Hau River can be executed in two ways. They can open horizontally by rotating around the pillars, which requires a rolling system on the bottom of the river. This system has two doors between every set of pillars, allowing for a length per door which is half the span. The other option is a vertical opening sluice door, that is lifted up during opening and lowered down to the bottom of the river during closing. This system requires a strong lifting installation. The latter can cause complications, as the limited power of lifting motors for substantially lighter sluice doors already forms a problem in Vietnam. This was observed during a field trip to Cong Cau Xe Moi discharge sluice (see Appendix C). Therefore, in preliminary design calculations, the horizontal opening system is applied.

The maximum observed tidal variation was 3.71 meter ("SIWRR dataset", 2011). As the discharge sluice won't be closed at the lowest water level of the sea and the discharge of the river will increase the water level on the land-side of the barrier, a difference of 3.71 meters is not to be expected on either side of the barrier. In order to illustrate the order of magnitude of the loads on the structure caused by a difference in water level, Δh = 3.0 meter will be used in calculations. A span of 30 meters between two pillars is chosen, to provide passage for the largest ships size, which are 23.2 meters wide subsection 5.4.1. The static water load will result in moments of 123 MNm on the pillars and horizontal forces of 14.85 MN. It requires substantial pillars to carry these loads. The doors themselves will have a weight of approximately 300 tons. See Appendix I for calculations and details.

6.1.5 Transport

With the discharge sluice built on location 2 & 3, a road can be constructed on top of the sluice. This gives a better connection between Soc Trang and Tra Vinh who are currently only connected by a ferry. This new link allows for better access to the port of Soc Trang (Figure 6.5a). On location 4 & 5, the river crossing is directly connected to the port of Soc Trang, as shown in Figure 6.5b. The new river crossing over the Hau River will be designed as an expressway. This fits in with the development goals which have been proposed for 2050 within the Mekong Delta Plan. In this plan, also expressways opt between the border of Cambodia and the coastline of the MKD (Veerman, 2013). Between the port of Soc Trang and the city of Soc Trang, the existing provincial road will thus be upgraded towards an expressway with three lanes in each direction. At the discharge sluice, the expressway will contain two lanes in each direction. Between Soc Trang and Can Tho, additional investments will cause an extra boost in accessibility. This existing national highway will be upgraded into a two-lane expressway. The changes in the network for both locations are shown in the red circle in Figure 6.5. With the addition of a new link, the Betweenness centrality of the network is also adapted. By following Equation 5.1, the connectivity of the network is increased to 0.238.



(a) Location 2 & 3

(b) Location 4 & 5

Figure 6.5: Transportation model discharge sluice solution

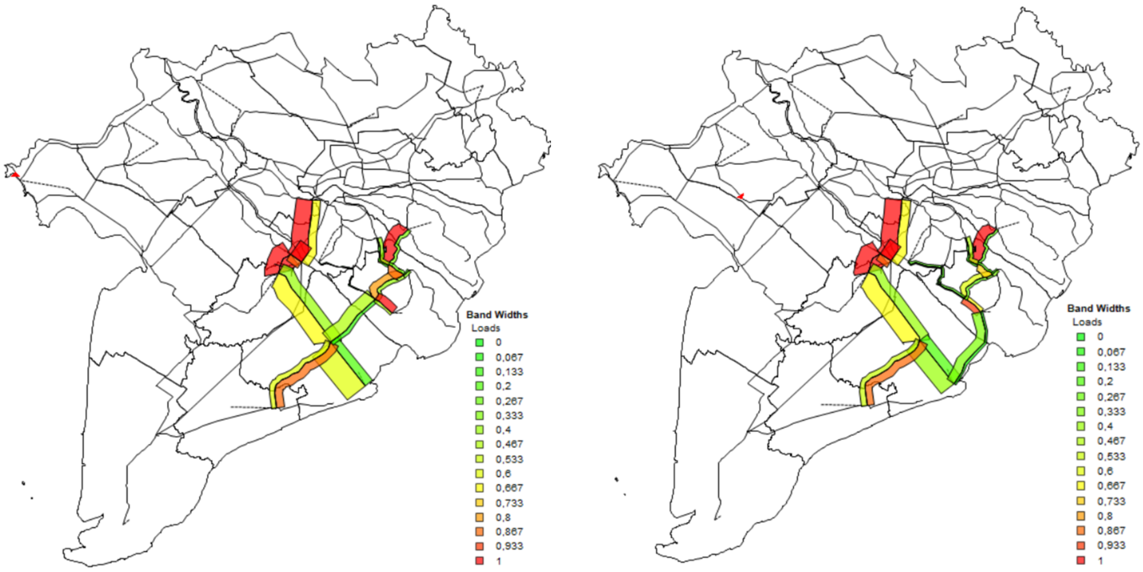
With the addition of links in the model the travel times between each origin and destination are changed. On location 2 & 3, the travel times between the Soc Trang province and

Tra Vinh/Ben Tre provinces will be reduced by approximately two hours. Also, the overall accessibility of Soc Trang will be improved by 1,350 hours. This means that the sum of the travel time from every destination to Soc Trang and vice versa is lowered. Regarding location 4 & 5, the travel time between the port of Soc Trang and Tra Vinh province is reduced by more than three hours. The total travel time to Soc Trang and the other way around is reduced by 1,550 hours. The sum of travel time savings on the complete network is higher by adding a link on location 4 & 5 (6,110 hours vs. 6,580 hours). It has to be noted however that this relates to free speed only. Congestion and road capacity effects are not taken into account. In Appendix G the complete skim matrices of the alternative locations are shown.

In Figure 6.6 the trips are distributed over the network. The representative links are highlighted with bandwidth plots. The width indicates the total load on the link and the colour indicates the VCR. Based on the two models, the load at Can Tho is comparable with both alternative locations. The load at the Can Tho bridge to HCMC remains unchanged compared to the base scenario. The remaining network stays approximately the same regarding load and VCR for both alternative locations. In addition, at the port of Soc Trang and Tra Vinh province, traffic is split over two links. As a result, the road on the links on both sides of the Hau River has less load at locations 4 & 5 compared to locations 2 & 3.

Due to the cross-river connection at locations 4 & 5, there are more origins and destinations that save time compared to locations 2 & 3. However, the average time savings per origin and destination are higher at locations 2 & 3. This means that, if there is a time saving with an origin and destination combination, the time saving is on average higher with a cross-river connection at location 2 & 3. This makes a connection at location 2 & 3 for specific destinations more attractive.

The location in the network makes it also more attractive to use location 2 & 3. This is reflected on the link between Tra Vinh province and Can Tho, which is located north of and parallel to the Hau River. This link is not used when a cross-river connection at locations 2 & 3 is established. When a cross-river connection is made at locations 4 & 5, greater use is made of this road parallel to the Hau River.



(a) Location 2 & 3 (b) Location 4 & 5

Figure 6.6: Network load for discharge sluice solution

6.1.6 Socio-economics

With the realisation of a discharge sluice project, there are socially economical effects that will arise. In this subsection, these effects are discussed.

The river banks of the Hau River are not well protected. During high tide parts next to the river banks are continuously exposed to flooding. Experiencing this can give an anxious feeling as the living conditions are becoming uncertain. The community will probably feel more safe when they see a hard structure, like a discharge sluice, because it has a strong and robust look.

The construction of a sluice of this size would be a very large and long-term project. The duration of a discharge sluice construction could be around 10 years, comparable to the construction time of the Oosterscheldekering (Rijkswaterstaat, 2023). This will increase job opportunities for the inhabitants or even could attract workers from neighbouring regions, which will increase the economical possibilities.

The building of the discharge sluice will decrease the salinity stress over freshwater. The water that people extract from the river and ground is in almost every case not treated (World Resources Institute, 2022). Although the pollution of the river will still be a great problem (subsection 1.2.5), the water upstream of the river will be fresh enough and could get used again for irrigation purposes.

By investing in the road transportation system, travel times are shortened. Especially in the Soc Trang port area, this can be of great value. By having lower travel times, it becomes more attractive for vessels to make use of this port. Which then can cause an increase in employment opportunities. With these opportunities comes economic prosperity in the surroundings. People who live in the area can benefit from this economic prosperity. Higher economic prosperity also attracts more residents to live in the MKD. Since the MKD is the main rice exporter of Vietnam and its surroundings, the wider region can benefit from better accessibility around the port.

The resilience of the road network will increase with the addition of a new river crossing. Therefore, the reliability of travel times will increase. When taking climate change into account in road construction, this can also mean that travel times will remain stable during extreme flooding. This induces people to feel safer in the area. Therefore, it is less expected that inhabitants will move elsewhere (e.g. HCMC).

There are also some downsides to building a discharge sluice. The biodiversity can deteriorate because the sea water is not able to enter the system upstream of the sluice. This will decrease the biodiversity in the area with brackish water which is a habitat for specific species. In addition, the fish cannot migrate when the tide becomes flooded. A fish migration river could be a solution to this issue.

Another difficulty that the discharge sluice will induce is the transportation through the gate. The delta experiences flooding twice a day, so the sluice has to be closed two times per day. Closure of the gate will obviously reduce the transport capacity. Furthermore, the discharge sluice will contract the flow, resulting in higher flow velocities of the river. This increase in flow velocity will make it more difficult for vessels travelling upstream when the sluice is opened during ebb. The higher resistance requires (primarily for small vessels) more power and therefore more fuel. A lock can be constructed to remain the transportation possibilities, but this can possibly result in a queue. The waiting time has to be monitored severely.

6.1.7 Overview

The discharge sluice can regulate the discharge in the Hau River. It will open during low tide and close during ebb tide. In this way, the discharge sluice can tackle two big problems: salinisation and inundation. This discharge sluice will work best when it is built close to the sea. A road can be built on top of the discharge sluice. In this way, the transport network will also benefit from the discharge sluice. The limiting mobility of ships, decrease in biodiversity and high costs are the downsides of this project. In Table 6.2 the pros and cons for the discharge sluice are listed.

Pros	**Cons**
Protects against tidal inundation	Limiting mobility for ships
Discharge regulation	Expensive
Salinisation decrease	Maintenance
Connection between banks of estuary	Biodiversity decrease
People feel safe, seeing a hard structure	

Table 6.2: Pros and cons of discharge sluice solution

6.2 Solution 2: Wetlands combined with a double levee system and buffer zones

A wetland is a natural part of land connected to the riverbank. The area is subjected to allowable flooding until reaching a levee. Creating a wetland is in the "room for the river" principle as shown in Figure 6.7. This is a reference project in the Netherlands, creating more space for the river in times of high discharges with the additional advantage of restoring natural habitat for various types of species and creating recreational areas (Ministerie van Infrastructuur en Waterstaat, 2022).

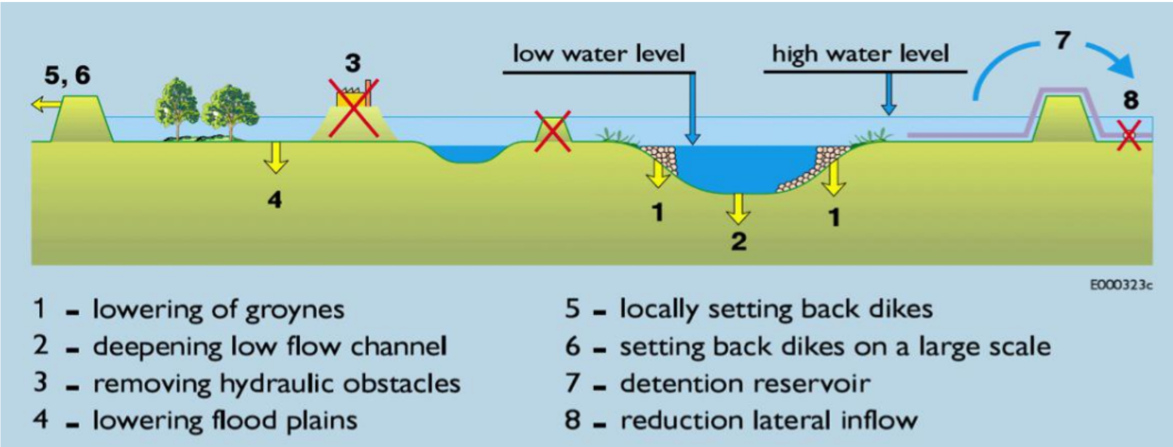


Figure 6.7: Room for the River measures (Silva et al., 2001)

A wetland is mostly implemented in an integrated foreshore or in a double levee system. An integrated foreshore is a wetland that interacts with the flooding of the river. The double levee system differs in a way that there is less allowable flooding at the foreshore. The first levee can have a relatively high flood risk but the second one behind the buffer land has to protect the inhabited areas. These wetlands can reduce the height of the first levee when they are built at the sides of the Hau River. Another way to reduce water problems is the use of a buffer zone. This can be done by creating parks or lowering squares. The wetland and double levee system can easily be used in combination with buffer zones inside the city. This is further described in subsection 6.2.1 (Ecoshape, 2020).

6.2.1 Increase flooding capacity

By creating a wetland the wet area of the river increases when the capacity of the river is exceeded. In this way, controlled flooding is created. All the water that is stored in the flood planes cannot flood Can Tho. The mild slope and the vegetation will reduce the run-up to the levee. This vegetation also has a positive effect on the strength of the levee. The macro-stability of the levee will increase because the foreshore will act as a stabilisation due to the mass. In addition, it will also increase the seepage length (Ecoshape, 2020).

Combining the wetlands outside the city with a solution for inside the city is preferable. With inner city solutions, a runoff of precipitation into the river is prevented. Since adding precipitation increases the discharge level in the Hau River this combination is preferred.

Considering high precipitation rates in October, as seen in section 3.3, the irrigation of this water has to be stored. At this moment the pavement area in Can Tho is growing (Forni & Nguyen, 2016), which causes the precipitation to flow into the river. Creating (natural) buffer zones in the city that will store water will prevent this water from flowing into the river during storms. This creation of buffer zones can be done by constructing parks as this will reduce the runoff by 45 % (Buyung & Ghani, 2017). Another option that will increase the storage capacity is lowering squares and plazas as has been done in Rotterdam, see Figure 6.8. The lowered plazas can become a storage area when the city's drainage system has reached its limits. Afterwards, the water can be drained when there is the capacity for it.

Figure 6.8: "Waterplein" in Rotterdam, the Netherlands

6.2.2 Fresh water supply

The water that is collected in the wetlands can be used as fresh water. In the case of a double levee system, during the wet season from May to October, the peak discharge and precipitation can be stored in the wetlands for the dry period (see section 3.2 and section 3.3). There is no new freshwater storage needed in this period as the freshwater supply is high enough. The water in the wetlands is filtered and pollutants are trapped (Ecoshape, 2020). The collected fresh water reduces the lack of fresh groundwater. The freshwater collection will result in less saltwater intrusion of the groundwater because this freshwater will fill up the extracted groundwater. Currently, during an inundation event the water in Can Tho will mostly flow back to the river and will be unusable for irrigation processes. The buffer zones in the city can reduce the water that flows back to the river. Moreover, if an irrigation system is built that uses that water as freshwater, the city would replenish its freshwater supply.

6.2.3 Increasing biodiversity

With the fast agricultural development of the area, a lot of natural habitats were lost. Human expansion is the main reason for the deteriorating biodiversity. A wetland is a bio-diverse habitat. By creating wetlands, the natural forces will stimulate regrowth and some bio-diverse habitat can be given back to nature. The wetlands could provide a breeding and feeding ground for example birds or fish. Half of the bird species (124) are namely dependent on the wetlands (Campbell, 2012). Furthermore, it could function as a natural corridor between the wet river environment and the agricultural environment on the landward side. This recreated bio-diverse habitat can also attract more nature tourism, causing economical opportunities in the cities.

By applying this solution a Building with Nature concept will be used. This means that human development integrates a sustainable and strong solution using natural processes (de Vriend et al., 2014). In that way, the human settlements can benefit from natural protection and nature can develop in its own way. Building with Nature is an iterative process as the development of the natural structure has to be intensively monitored to see if the projected design is met.

6.2.4 Proposed design

The main objective of the wetland solution is to reduce the peak discharge in the Hau River. Figure 6.9 displays the highest peak discharges of the year, which last for about six hours. Note that a low discharge actually results in a high water level due to tidal influence (see section 3.4). To ensure a sufficient capacity for current and future scenarios, a peak discharge reduction of 12,000 m^3/s for six hours is used in further calculations, which may seem high. The present water column that will flow into the wetland will partially infiltrate into the groundwater. Excess water can be drained into irrigation canals. After a period of six hours, the next high water level will occur, while it is likely that not all water is drained yet. To overcome this problem, the high peak discharge reduction of 12,000 m^3/s is used. The total required volume capacity of the wetlands is calculated by assuming that the peak discharge should be drained for a peak lasting six hours. This results in a required storage capacity of approximately 260 million m^3.

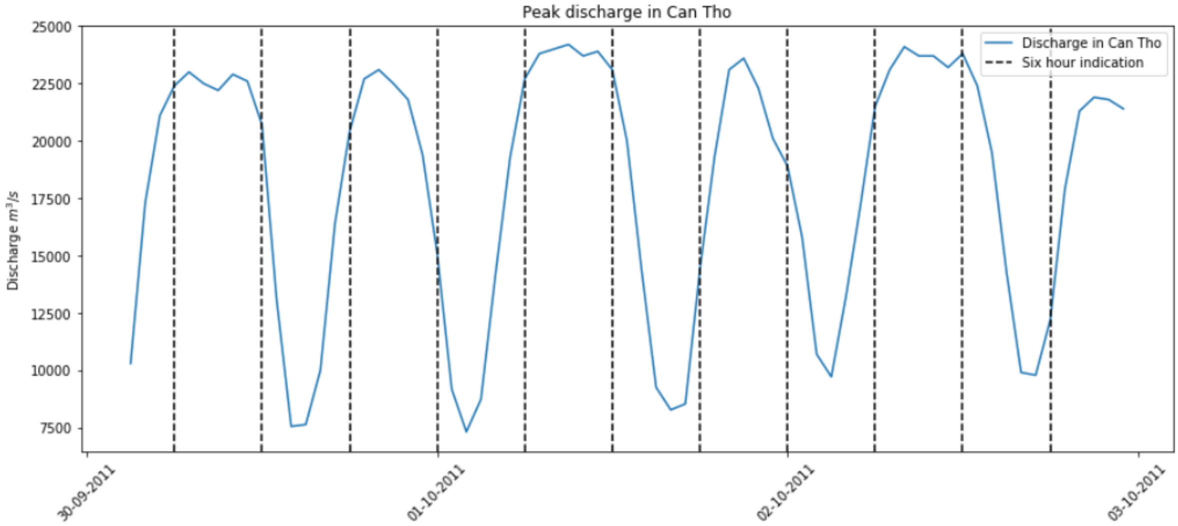


Figure 6.9: Peak discharge Can Tho

$$V_{wetlands} = Q_{surplus} \cdot T_{peak}$$
$$V_{wetlands} = 12,000 \cdot 3600 \cdot 6 = 259,200,000 \quad m^3$$

Based on the literature, the proposed wetland is designed with an average depth of 1.2 meters (Virginia DCR Stormwater Design Specification, 2013). By dividing the storage capacity by the average depth the total required land area A_{total} is obtained.

$$A_{total} = \frac{259,200,000}{1,2} = 216,000,000 \quad m^2$$

This wetland, with an area of 216 km^2, should be built at the sides of the Hau River upstream of Long Xuyen and Can Tho. The selected areas are displayed in Figure 6.10.

The three wetland areas are shown in more detail in Figure 6.12 and Figure 6.13. Note that some positive factors such as soil absorption, and some negative factors such as local rainfall and flora and fauna in the wetlands, are neglected. These positive and negative factors might balance each other to a certain limit. To make sure that all the water can be stored, the total area is rounded off at 220 km^2, which is divided over three areas. Wetland 1 has a surface area of 105 km^2, wetland 2 of 70 km^2 and wetland 3 of 45 km^2.

Figure 6.10: Total area wetland

The area of the first wetland is 105 km^2 with an average depth of 1.2 m. The total storage capacity is:

$$V_{wetland1} = 105,000,000 \cdot 1.2 = 126,000,000 \quad m^3$$

The maximum average discharge that flows into the wetland is then this volume divided by the 6-hour duration.

$$Q_{wetland1} = \frac{126,000,000}{3600 \cdot 6} = 5,833 \quad m^3/s$$

This is the maximum discharge that can flow into this first wetland. The same method can be used for the second and third wetlands with an area of 70 km^2 and 45 km^2 respectively (for a schematisation see Appendix J).

$$V_{wetland2} = 70,000,000 \cdot 1.2 = 84,000,000 \quad m^3$$
$$Q_{wetland2} = \frac{84,000,000}{3600 \cdot 6} = 3,889 \quad m^3/s$$
$$V_{wetland3} = 45,000,000 \cdot 1.2 = 54,000,000 \quad m^3$$
$$Q_{wetland3} = \frac{54,000,000}{3600 \cdot 6} = 2,500 \quad m^3/s$$

With the acute discharge reductions accomplished by the wetlands, the discharge at Can Tho will be reduced to a value below 10,000 m^3/s (see Figure 6.11).

$$Q_{CanTho} = 22,000 - (5,833 + 3,889 + 2,500) = 9,778 \quad m^3/s$$

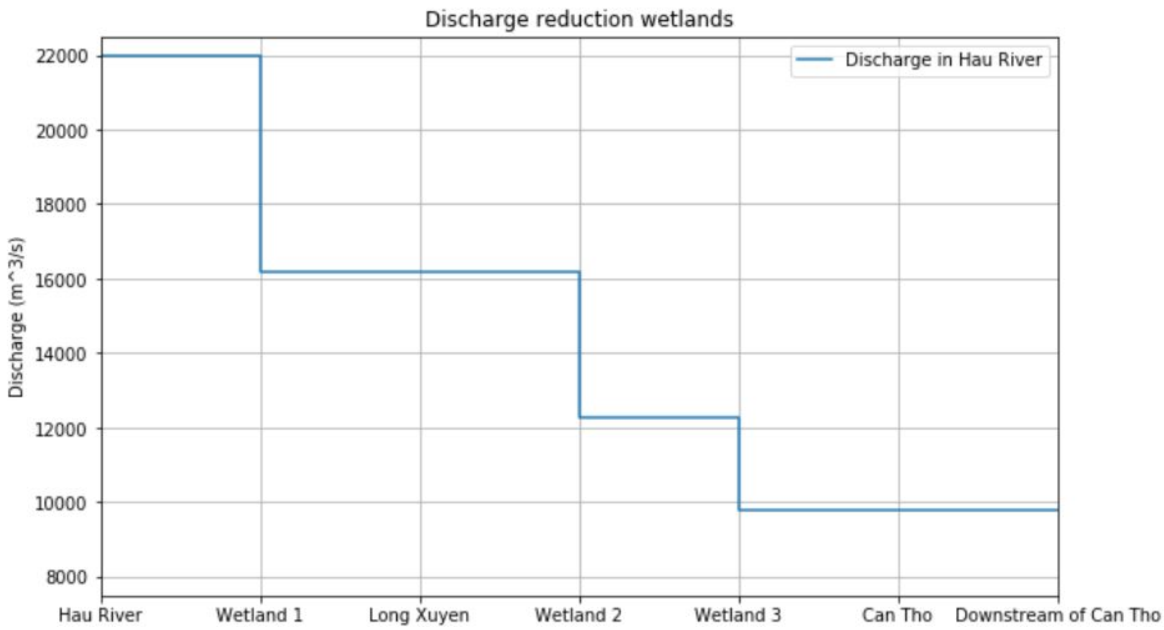


Figure 6.11: Discharge reduction wetlands

Location justification

Designating an area of this size as a wetland brings some complications. As the area is supposed to flood regularly, well-considered decisions have been made on its location(s). Key factors to take into account are the relocation of people, the presence of valuable assets, and possible damage to transporting network.

As described in subsection 5.4.2 there are plans to construct new road links to increase the connectivity of the MKD. Additionally, a national highway of significance is located between Can Tho and Long Xuyen. This should be taken into account when selecting the specific locations for the wetland areas.

The wetland in the north is located close to the beginning of the Hau River (where the Mekong River joins the Basacc River, see Figure 6.12). It is enclosed between the Long Xuyen Quadrangle and the Plain of Reeds so that both these important areas will not get affected by the wetlands. This big wetland area can store approximately 50% of the total discharge surplus. The area is located upstream of Long Xuyen so that the discharge in the Hau River in the wet season near the city is significantly reduced. The realization of the wetland has a consequence that some people in the area have to be relocated. The area is chosen such that the existing provincial roads are not harmed.

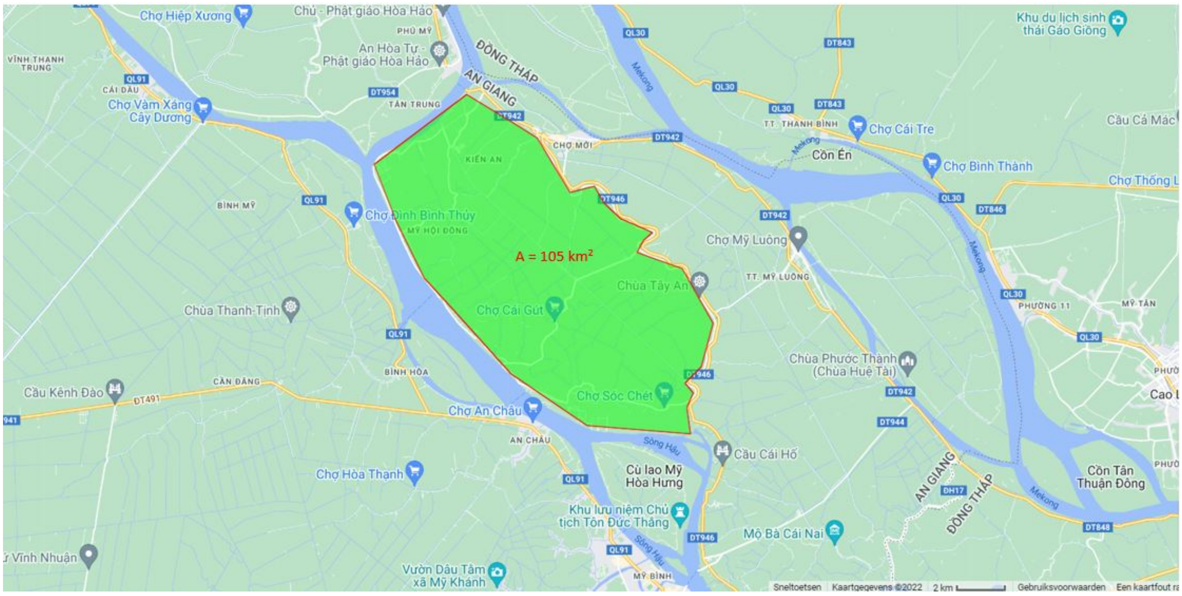


Figure 6.12: Wetland northern area

The two wetlands in the south are located just upstream of Can Tho (see Figure 6.13) so that the city optimally benefits from the effect of the peak discharge reduction. The top left area in this figure is 70 km^2 and will store approximately 30% of the total peak discharge surplus. The remaining 20% will flow into the last wetland with an area of 45 km^2. Already existing highways are not present in the designated wetland area.

Figure 6.13: Wetland southern areas

Design details

A schematic cross-section of the proposed design is shown in Figure 6.14. The required storage capacity for each wetland can be used to calculate the velocity and overflow height above the levee. This is done by applying the rule of Torricelli. The desired overflow height is used to determine the height of the first levee in the double levee system. For the northern wetland, which has a width of 14 km, the height and specific discharge over the levee are calculated as follows:

$$q = \frac{Q}{B} = \frac{5,833}{14,000} = 0,417 \quad m^2/s$$

$$u = \frac{q}{h_{overflow}} \tag{6.1}$$

$$u = \sqrt{2 \cdot g \cdot h_{overflow}} \tag{6.2}$$

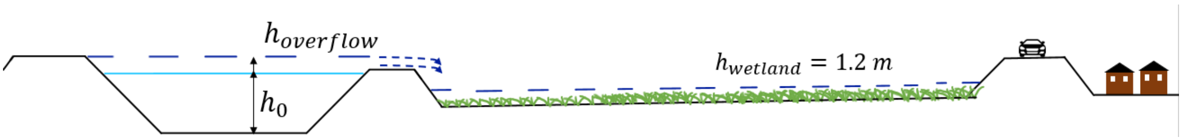


Figure 6.14: Schematic cross-section design of the double levee system

The water level over the levee should be 0.20 m with a velocity of 2.08 m/s. This results in a discharge that is just lower than the maximum allowed discharge of 5,833 m^3/s. The wetland will almost fill up completely, but it will not overflow:

$$Q = u \cdot h_{overflow} \cdot B = 2.08 \cdot 0.20 \cdot 14,000 = 5,824 \quad m^3/s < 5,833 \quad m^3/s$$

At the end of the wetland another levee should be built so that the area behind it is protected.

The same method with the rule of Torricelli is used to find the overflow heights for the other two wetlands. Wetland 2 has a design discharge of 3,889 m^3/s and a width of 21 km $h_{overflow}$. This results in a velocity over the levee of 0.12 meter and 1.54 m/s respectively. This means that the levee on the wetland side should be 0.12 meters lower compared to the levee on the other side of the river. The same calculations were performed for wetland 3 with a discharge of 2,500 m^3/s and a width of 17 km. The water level and velocity over the first levee are 0.10 meters and 1.42 m/s respectively. This means that the levee on the wetland side should be 0.10 meters lower compared to the levee on the other side of the river. An overview of the characteristics of each wetland is summarized in Table 6.3.

Wetland	**Volume [m^3]**	**Width [m]**	**Overflow height [m]**	**Inflow velocity [m/s]**
1	126,000,000	14,000	0.20	2.08
2	84,000,000	21,000	0.12	1.54
3	54,000,000	17,000	0.10	1.42

Table 6.3: Characteristics for each wetland

6.2.5 Delft3D flooding model

To implement the wetlands in the Delft3D model the depth profile has to be changed. For the wetlands in Figure 6.15 the area has to be lowered with respect to the calculation in subsection 6.2.4. In Table 6.4 the changes are shown that were made to these areas.

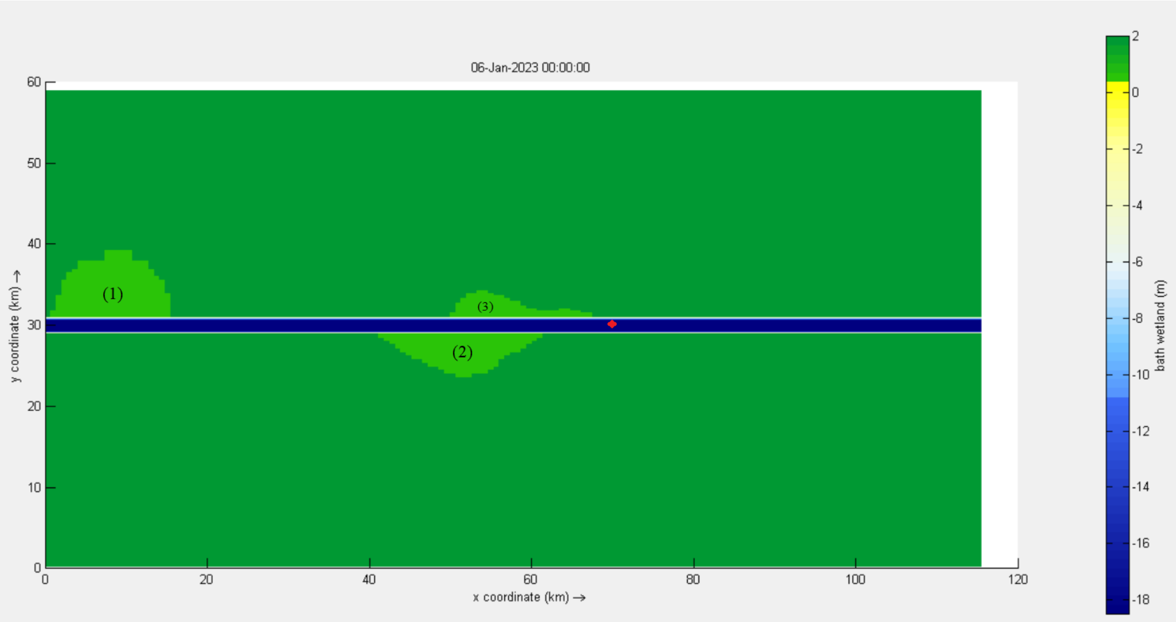


Figure 6.15: Depth profile of the wetland grid

In Table 6.4 the changes shown that were made to the wetland areas.

Wetland [-]	Wetland level [m]	Bank level [m]
1	-0.60	-1.80
2	-0.68	-1.88
3	-0.70	-1.90

Table 6.4: Depth levels of the wetlands and their banks

The model ran with the same initial conditions and boundaries. Figure 6.16 shows that the wetlands would give a reduction of about 0.50 meters of water level during high tides combined with a representative river discharge of 16,000 m^3/s.

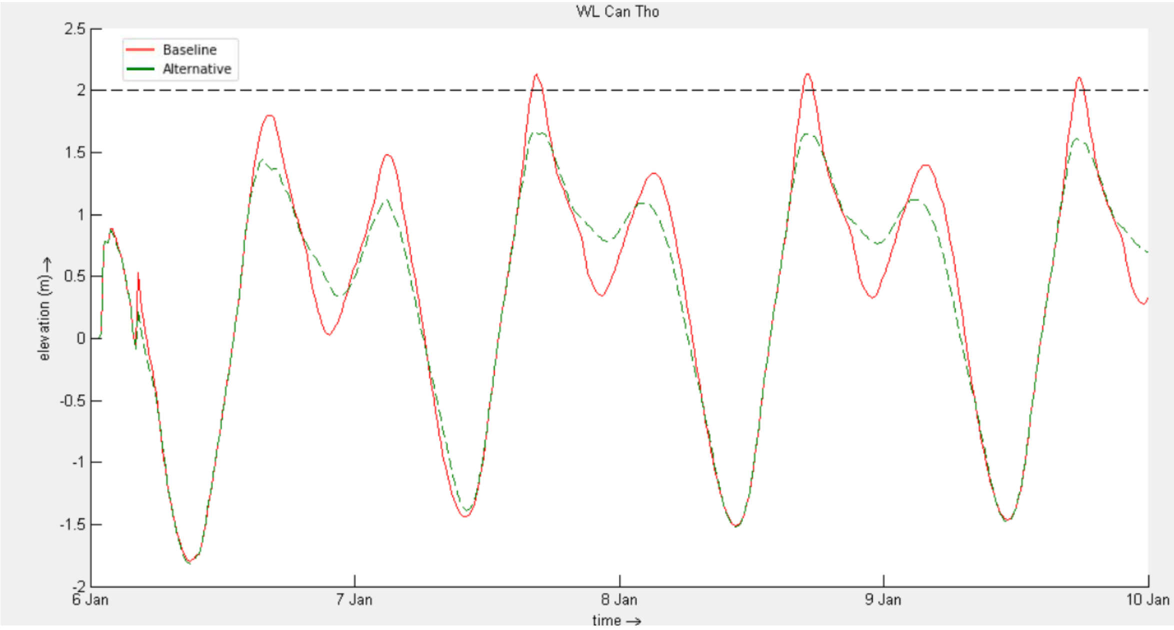


Figure 6.16: The calculated water level in Can Tho baseline and with wetlands

The adjacent area around wetland 1 will experience flooding as the water level there is exceeding 2.0 meters as is shown in Figure 6.17. The other wetlands however will fill up but will not flood the adjacent area. It was not possible to add extraction coefficients to the wetland areas so the areas could fill up but could not empty themselves. This could be the reason why the first wetland will flood.

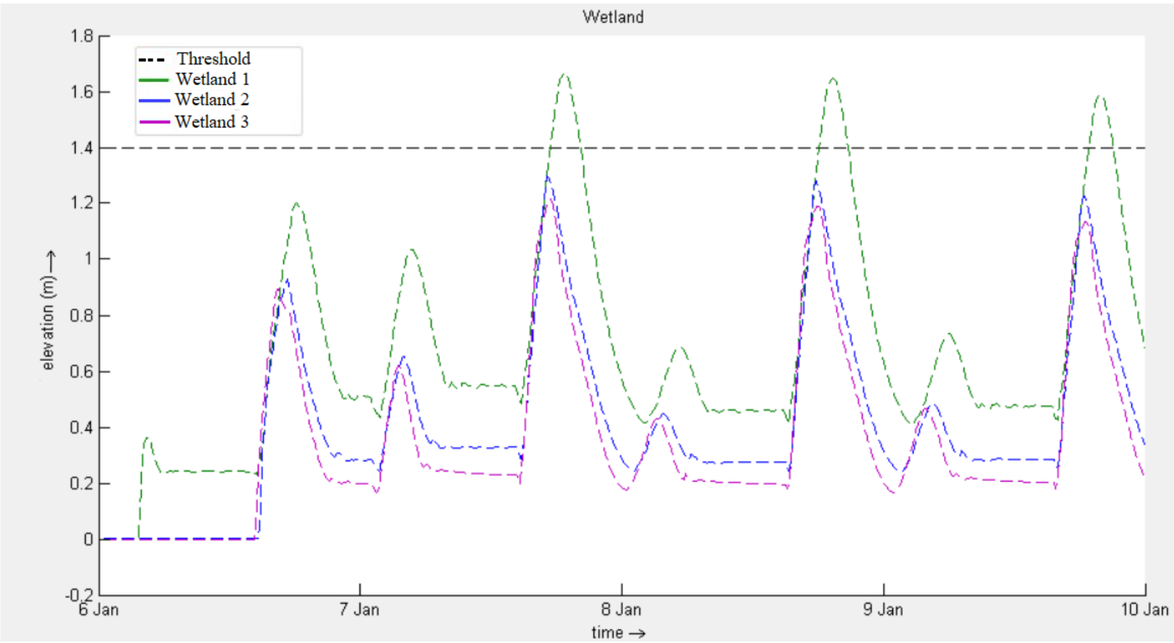


Figure 6.17: Water levels in each wetland

6.2.6 Transport

With the construction of wetlands in the area, the road network functions as a constraint for the size of these wetlands. The road network can be a physical boundary when situated on a ring levee, as shown in Figure 6.14. This also gives opportunities to solve bottlenecks within the network. From the base year, the volume of the national highway between Long Xuyen and Can Tho shows to be higher than the actual capacity (see Figure 5.7). Therefore, the investments in a levee can be combined with upgrading the existing road network.

The new road which is modelled is an expressway. This expressway is linked to the expressway near Can Tho linking it with Long Xuyen, with two lanes in each direction. To make this investment more feasible, the roads between Cao Lanh and Long Xuyen will also be improved. This is in line with the development goals of 2050 in the Mekong Delta plan (Veerman, 2013). On the network, this is shown within the red circle in Figure 6.18.

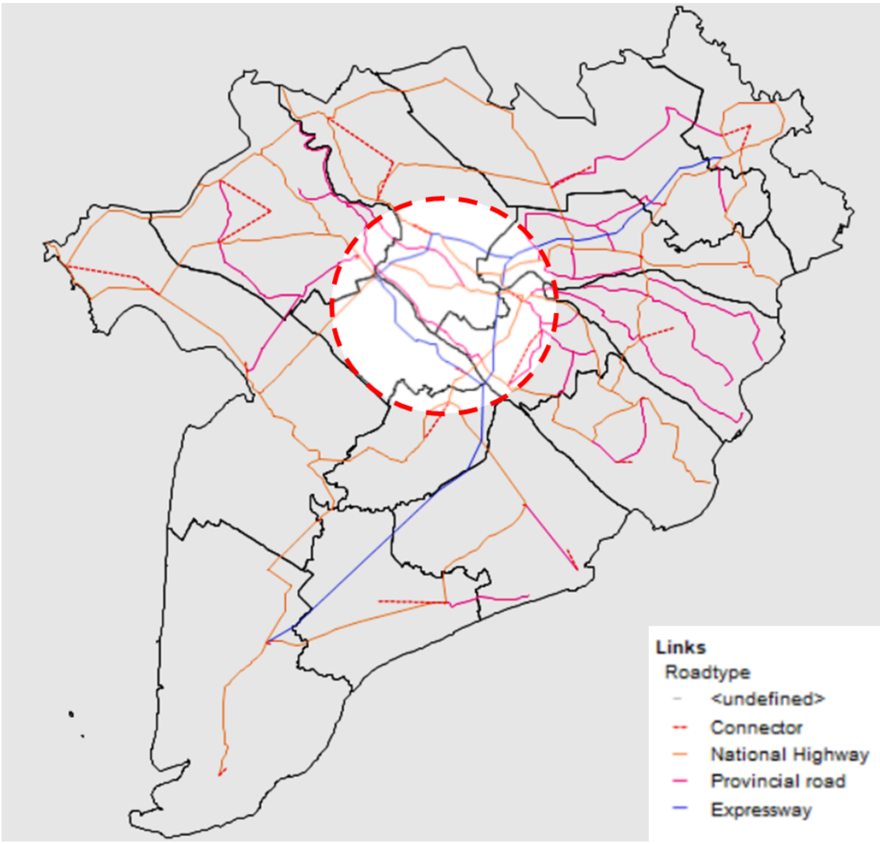


Figure 6.18: Transportation model for solution 2

By doing these investments, the travel time of multiple origin and destination pairs will be shortened. After calculation, it appeared that the travel times from mainly Long Xuyen around the network have decreased. The full calculation can be found in Appendix G. Since the improved links are part of the central axis of the MKD this has a wide influence. The highest travel time savings are found between Ca Mau and Long Xuyen with a 26-minute improvement. Travel times to HCMC and the Soc Trang port however are not very much improved. By doing the All-or-Nothing assignment on the network, the following VCR is found (Figure 6.19). It can be seen, that the VCR between Long Xuyen and Can Tho has improved significantly. However, around the new port of Soc Trang travel time is not enhanced. Major transportation-related challenges will therefore arise with the development of the port. Extra investments in this area are thus recommended.

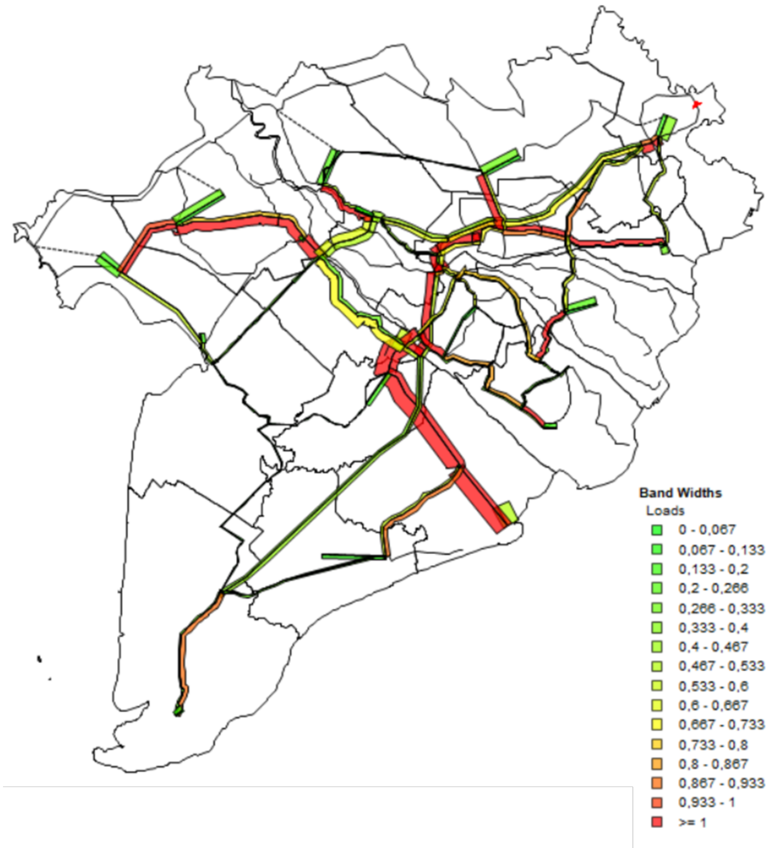


Figure 6.19: Network load solution 2

6.2.7 Socio-economics

By investing in transportation facilities around Can Tho this specific area becomes more accessible. Trading between Can Tho and Long Xuyen can be increased since the VCR on the link between these urban areas is lower. However, by only investing in these links the port of Soc Trang would have insufficient accessibility. Therefore it is not likely that the full capabilities of the port will be utilized. When the hinterland connection is insufficient it is not interesting for ships to moor at the port. This leads ships to choose another port in the area. The most likely destination is the Vung Tao port. This can lead to people to move closer to this Vung Tao port instead of living in the MKD.

The area can also be improved in a socio-economical way by upgrading the road. This has a positive influence on the tourist sector if the wetlands will develop into an environmental tourist attraction. Both trading and tourist industries will improve the economical revenues and therefore the local economy will be boosted. In addition to the economic boost, the new expressway will also improve the mobility of the citizens during a flood event. The biggest concern from the flooding, as stated in section 2.5, is limiting transportation. Although the wetlands will decrease the flood risk, it will not rule out the probability completely. Having transport in a way that could evacuate citizens, the overall safety perspective of these citizens will increase.

Moreover, community safety will also increase when a levee system is built. Figure 6.20 shows what most parts of the river bank look like in the Hau River. A higher astronomical tide already feels like a dangerous situation. Levees can therefore provide a safety barrier. This would raise the awareness of the locals that building too close to the river could be catastrophic in the future.

Figure 6.20: Average river bank of the Hau River

More drought is experienced further upstream of the river (Minh et al., 2022). As stated in subsection 6.2.2 the new freshwater collection could be used for the benefit of the people living in this area. For example, rice farmers, who at this moment have to deal with decreasing rice yields because of the droughts, can use the stored water. This redistribution of water can be a trigger to start a province's overarching irrigation company in the same way as is done in the Red River delta. The renewed irrigation systems would give a boost to the attractiveness of the cities as it will provide jobs with expertise for highly educated people.

The buffer zones inside the cities can also be connected to the new irrigation system and prevent the rainwater from reentering the Hau River directly. These buffer zones will also provide a safe space for markets and playgrounds for children because traffic will be rerouted around the zones.

One of the downsides of creating a wetland is the relocation of the inhabitants that are living in the recollected areas. The average population density of the MKD is 424 people/m^2. This means that approximately 100,000 people have to move from their homes. In reality, this number will be lower as this number is an average over the whole MKD and the areas that are used to make a wetland are primarily rural. Nevertheless, this will be a drastic change for a lot of people. People that were living there for generations have to build a new existence somewhere else. A lot of explanation and lots of money have to make available for buy-out fees.

For each wetland two levees have to be constructed which will require a lot of sediment. Most of the sediment is coming from the Hau River. Currently, there is a sediment shortage in the river. Capturing the sediment from the river induces this even further. One must find another way to get these large amounts of sediment for the construction of these levees.

6.2.8 Overview

The wetlands in combination with a double levee system and buffer zone give the Hau River more space. A part of the discharge can flow into the wetlands, increasing the total flooding capacity. The precipitation that normally will flow into the river can be stored in the buffer zones. The water that is stored in the wetlands and buffer zones can be used as a freshwater supply for the dry months. In the wetlands, the biodiversity will also increase. The relative shallowness of a wetland makes that a huge area is needed to store discharge volume. This results in the relocation of people that live in that area. The second levee in the wetland area can be used to build a road on top of it. In this way, the road network will not be harmed. In Table 6.5 the pros and cons of the wetland are listed.

Pros	**Cons**
The nature-based solution which helps for funding	Relocation of people
Can store flooding water which can be used in times of drought	Lots of sediment needed
Ecological benefits from natural habitat development	
Transport via levees can be used	

Table 6.5: Pros and cons wetland in combination with a double levee system and buffer zones solution

6.3 Solution 3: Bypass channel to Gulf of Thailand

One possible solution to reduce the Hau River's inundation problem in the estuary is to reduce the discharge upstream. This can be achieved by adding a bypass channel to the system starting just upstream of Long Xuyen. The outflow point will be in the Gulf of Thailand above Rach Gia. The canal will fully open in the wet season reducing the discharge in the Hau River downstream of this canal. During the rest of the year, the water levels in the canal could be controlled to reduce salinity from downstream and to make sure there is more fresh water available for irrigation. Also linking opportunities for (water) transport are investigated. A drastic measure like this has a big impact on the environment. Not only on the ecosystems and nature but also the lives of the people. These aspects have to be considered carefully.

6.3.1 Location

The canal will start upstream from Long Xuyen and the outflow point will be in the Gulf of Thailand north of Rach Gia. By putting the canal upstream of Long Xuyen the discharge in this city can also be regulated. The outflow point is chosen in a location where the resulting canal between the 2 points has the least populated area in between them. This way the impact on the existing towns and infrastructure will be minimised. The canal will only be opened during periods with big discharges that will flood the cities downstream. This will be during the wet season which lasts from May through November.

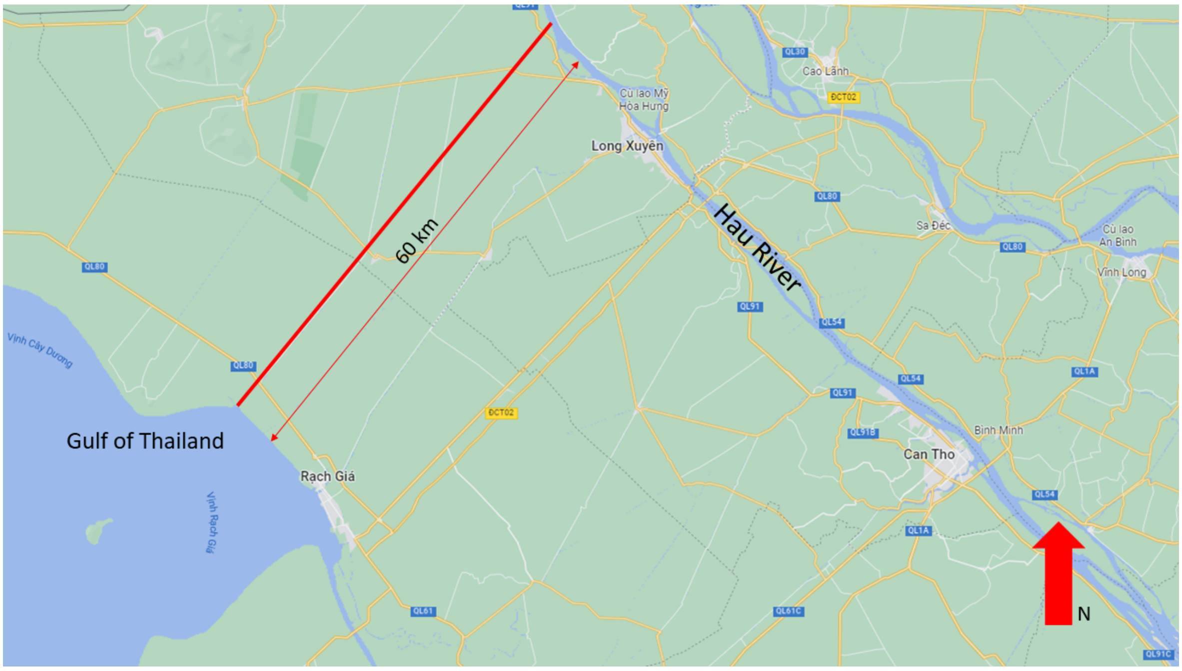


Figure 6.21: Overview situation with a bypass channel

6.3.2 Preliminary discharge design

A model was set up to determine the required discharge capacity of the canal. This is then used to determine the dimensions of the canal. This basic model serves to define a preliminary design for the canal and to get an idea about the order of magnitude and should not be used to make hard decisions. The model has three inputs. Discharges for the Hau River are measured hourly by a measuring station in Can Tho in m^3/s ("SIWRR dataset", 2011) and a selected discharge for the bypass channel in m^3/s. The dimensions for the bypass channel will be derived from this. The last input is the threshold discharge for which the canal will be opened in m^3/s. Using this as input the resulting discharges for the river downstream could be calculated by assuming and plotting different discharge values in the bypass channel. The threshold in the model is the discharge for which the canal opens and starts draining water from the Hau River. This guarantees the river downstream of the canal will never have a discharge lower than $Q = 5{,}000\ m^3/s$ and the river downstream will never be dry.

The reference months for which the required discharge capacity was calculated are from the first of September to the first of November since the Hau River has the biggest discharge during these months. It would be better to use the water height in the Hau River as input for the discharge in the bypass channel but this data is not available at the location of the bypass. Furthermore, it requires more complex models to be calculated. The principle for conservation of discharge ($Q_{in} = Q_{out}$) does hold and that is why this principle is used to make this preliminary design. All the discharges are then averaged over a larger amount of time, resulting in the magnitude of the inflow in the system. Nothing can be said about short-term behaviour because the models lack accuracy for this. The results for different design discharges are shown in Figure 6.22.

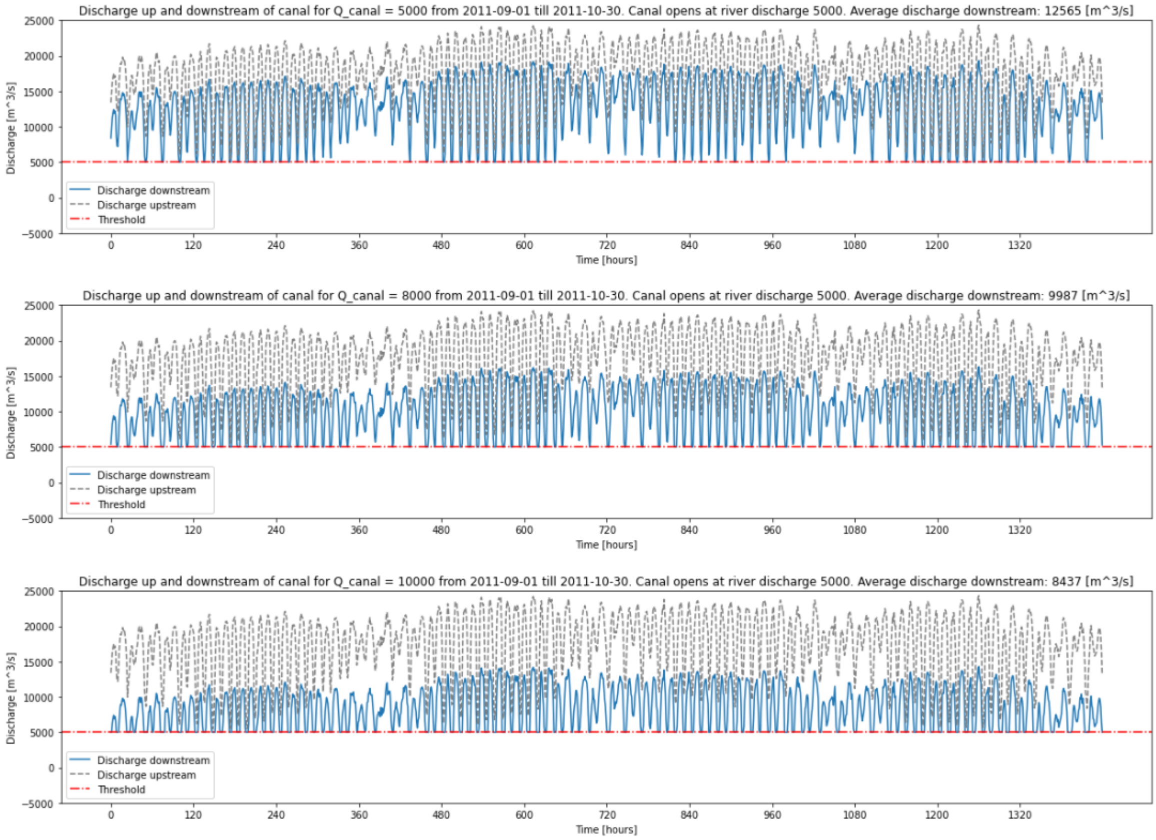


Figure 6.22: Results of using a bypass channel with different discharges

6.3.3 Preliminary channel dimensions

Following arguing from section 3.4 it is aimed to reduce discharge in the Hau River near Can Tho to approximately 10,000 m^3/s. As can be seen in Figure 6.22 the discharge of the canal has to be 8,000 m^3/s to achieve this. With the now-known design discharge the dimensions of the bypass channel can be determined. To transport huge amounts of water, which is required since an anti-flood system is being designed, a bigger flow velocity is favourable. The material with the biggest permissible flow velocity is concrete, in which water can flow with a velocity of $u = 2.5\ m/s$ (Kosichenko, 1993). The dimensions required to drain 8,000 m^3/s from the main channel with a velocity of 2.5 m/s have been computed. The cross-section of the canal will thus require an area of 3,200 m^2. In Table 6.6 several widths and depths are proposed. For simplicity purposes the shape of the canal is assumed to be rectangular and the flow velocity is assumed to be constant.

The bigger the width of the channel the more land has to be bought. This means more people are affected by the construction of the canal and less space is available for other things. Buying out more people might also mean there is more resistance against building the canal. Choosing a deeper canal might result in less area needed to construct the canal. The downsides of a deeper canal are higher initial costs and more maintenance during the lifetime of the canal.

Depth [m]	Width [m]
1	3,200
3	1,067
5	640
10	320
12	267

Table 6.6: Different dimensions for the canal with a constant flow velocity of $u = 2.5\ m/s$

6.3.4 Delft3D flooding model

The Delft3D model from section 4.2 is adjusted for this solution by creating a channel that can dispose of excessive water downstream. Firstly, the depth profile is adapted so that a channel is created with a width of 640 meters and a depth of 5.0 meters. An overview of the new depth profile can be seen in Figure 6.23. The red dots are observation points.

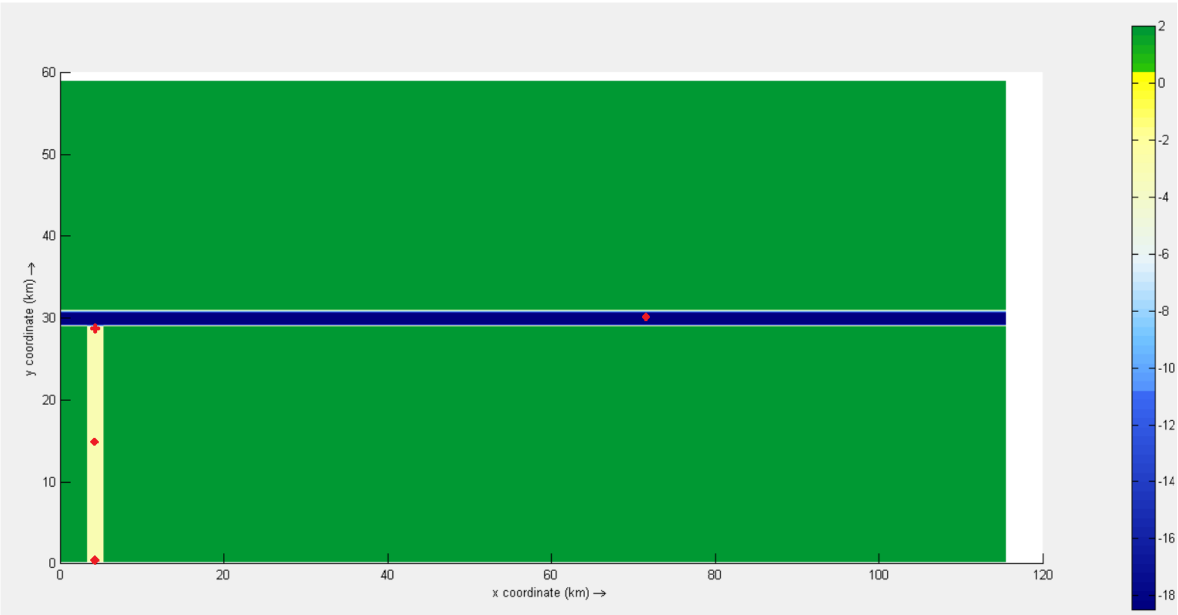


Figure 6.23: Depth profile of the grid with a side channel

Secondly, a new open boundary has to be added to simulate the outflow of the system. A Riemann invariant is imposed on the outflow side with a constant velocity of 2.5 m/s. The water level in the bypass channel at the start is 3 meters. The rest of the input is kept the same to make a comparison with the baseline output from section 4.2. This comparison is shown in Figure 6.24 and the reduction of water level is approximately 0.35 meters.

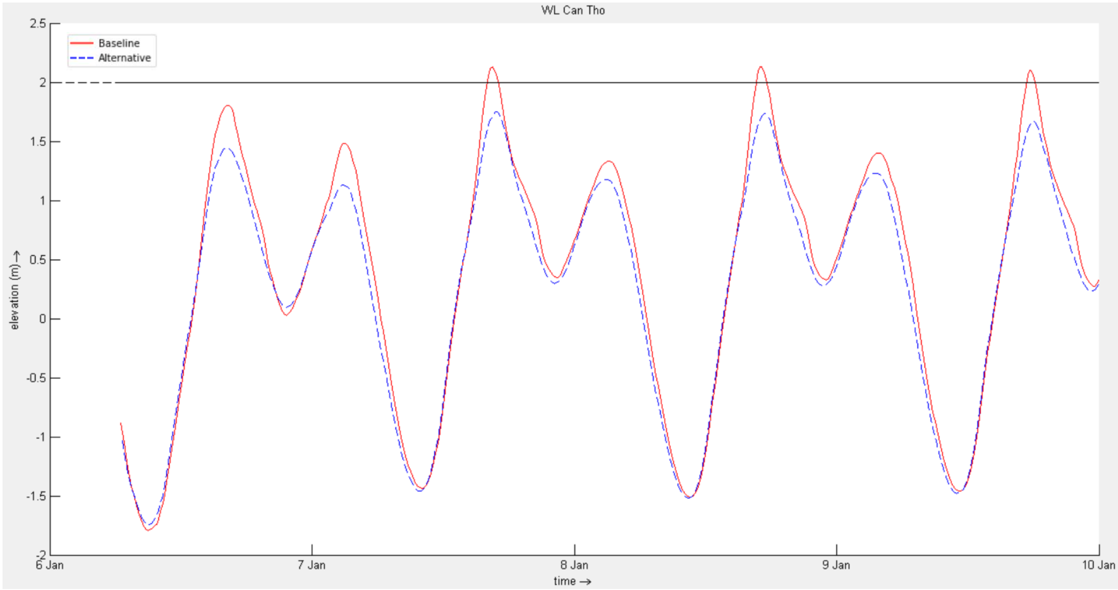


Figure 6.24: The calculated water level in Can Tho baseline and with the bypass channel

The discharge of the side channel fluctuates because of the water levels in the river. The maximum discharge that is extracted is approximately 10,000 m^3/s. This however will exceed the capacity of the channel which is determined on 8,000 m^3/s. As a result, this will cause the water level to exceed the threshold of 2.0 meters at the extraction point, as is shown in Figure 6.25. Because a non-stop peak river discharge of three days is assumed this simulates an extreme case and flooding would not be strange. The other two lines who represent the water level in the middle and end of the bypass channel show that the water level in the channel reduces significantly going downstream. The local flood only occurs at the crossing.

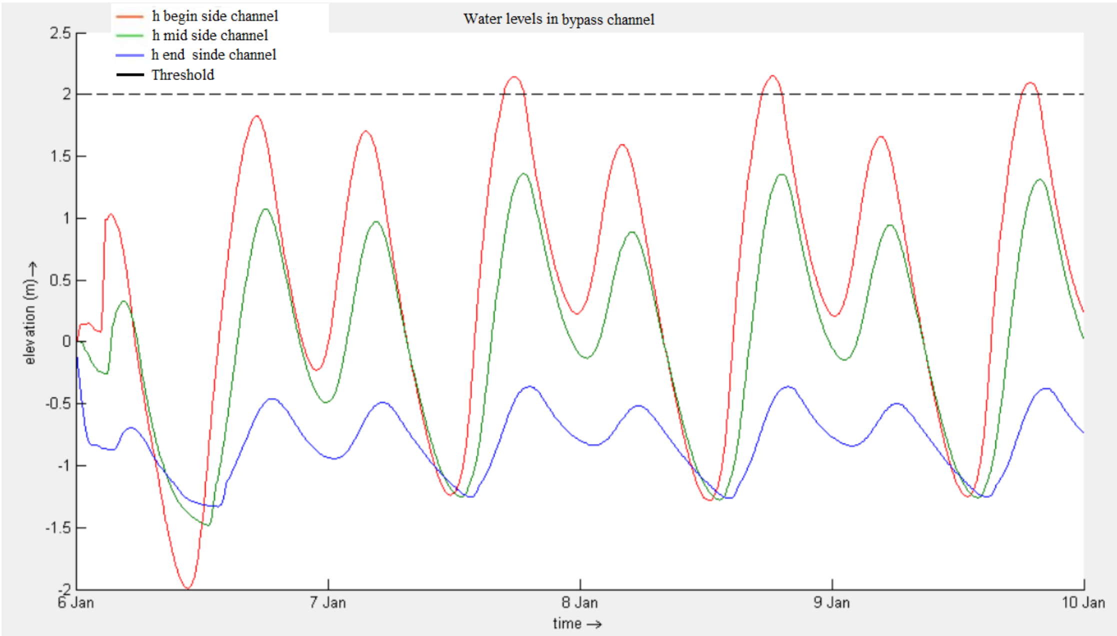


Figure 6.25: Water levels in the bypass channel over time with peak discharges

6.3.5 Structural feasibility

Digging and constructing a channel with dimensions of this magnitude is a challenging engineering project. The biggest challenge for this project is the size. The first problem encountered is digging out the necessary amount of soil. A quick calculation shows that a channel 60 km long, 1,067 km wide and 3.0 m deep requires at least 192 million m^3 of soil to be moved. After digging out the soil it has to be transported away. The soil can be used for levees or other structures to protect other parts of the delta from flooding. When the soil is taken out and transported away, the channel has to be filled with concrete. A concrete bottom of the channel will be more durable and stable than a soil bottom. It also allows for higher flow velocities which allow for more drainage from the Hau River. This concrete floor and sides will have an area of approximately 64.38 million m^2. The production and transport of all this concrete can also be quite challenging.

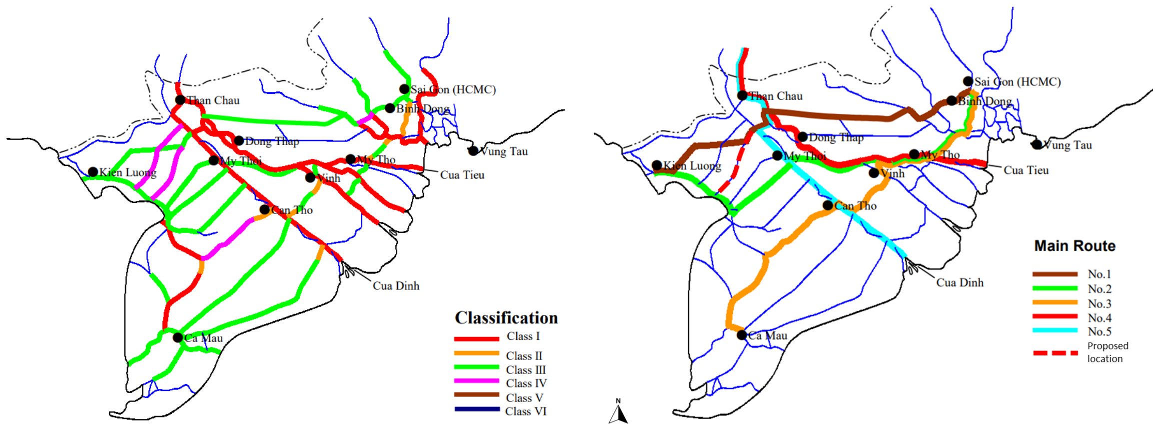
During construction it is important that no groundwater flows into the construction area. For a project this big it can be hard to prevent groundwater from flowing into the construction area. It is important this does not happen because it can ruin the concrete and soil conditions. On top of that the sides of the channel should not collapse during and after construction.

Another challenge in the construction of the channel is the locks on the top and bottom of the channel. They are important to regulate the water levels in the channel and to prevent salinisation. They have to be strong enough to stop the water, be able to open and close reliably, be stable enough in the soil and deal with the challenging tropical conditions of the area and the salt water. Building locks and other structures to regulate the water is the most challenging task in building channels like this.

Another challenge is making sure the channel is watertight over its length. If this is not done correctly the water will leak out. This will damage the structure but also the surroundings. It is even worse if this happens close to the sea since there will also be salt intrusion there.

6.3.6 Transport

Regarding the location of the bypass channel to the Gulf of Thailand, existing waterways are taken into account. From Figure 6.26a it can be seen that the Hau River is classified as a Class I inland waterway. For inland waterways, this relates to a minimum depth of 3.0 meters and a width of a minimum of 90 meters. Perpendicular to the Hau River are canals which connect the hinterland. Most canals are Class III, which means the depth is between 2.5 and 3.0 meters. This class has a total width between 30 and 40 meters. Taking national shipping routes into account (Figure 6.26b) the main shipping route 1 is considered. This route connects HCMC to Kien Luong and is predominantly used by barges. Plans have been made which propose to make this canal suitable for 300 DWT (Class III) vessels (JICA, 2009).



(a) Inland waterways MKD

(b) Shipping routes MKD

Figure 6.26: Nautical characteristics MKD (Ministry of Transport, 2021)

For the existing waterways, the canal between the Vam Nao Pass and Rach Gia (dashed red line in Figure 6.26b) jumps forward. With the necessary canal dimensions as proposed in subsection 6.3.3, the canal can be upgraded to a Class I canal. This indicates that larger ships up to 5,000 DWT can make use of the canal. When designing a Class I waterway, the following dimensions need to be used as indicated in Table 6.3.6. Improvement of the connection between the Hau River and the Gulf of Thailand can also influence the function of Can Tho Port. Relating to the position towards the new canal, this port can also function as a shipping hub.

Canal depth	$\geq$ 4.0 m
Canal width	$\geq$ 50.0 m
Canal radius	$\geq$ 700 m
Bridge span	$\geq$ 50.0 m
Bridge clearance	$\geq$ 10.0 m

The dependency on road transportation is lowered with the development of more convenient shipping routes. Therefore the impacts of flooding on the resilience of the supply chain are improved. Since less traffic is expected, the VCR on the links in the road network is optimized. Besides the benefits which come with the construction of a Class I canal, also new bridges have to be constructed to maintain facilities for road transportation.

On an international scale the bypass channel can also contribute to better connectivity for Phnom Penh (Cambodia). In Figure 6.27 the current vessel route from Phnom Penh is shown in the solid red line. Via this route, river vessels follow the Mekong River to the Cai Mep and HCMC ports. From these ports, the load is reloaded on sea-worthy vessels for shipment to Singapore/Europe and East Asia/North America (dashed red line) (MPWT, 2012). In 2015 a new route is proposed over the Hau River (white solid line). Via the new Soc Trang port goods are transported all over the world (dashed white line) (Hem & Asai, 2015). With the new bypass channel, travel times can be made shorter for shipment to Singapore and Europe. Downstream of the Vam Nao Pass, the bypass channel connects to the Gulf of Thailand (solid yellow line). To reload the load on sea-worthy vessels also means investments have to be made in a new port in the Rach Gia area. From this port, cargo can be shipped to Singapore and Europe (dashed yellow line).

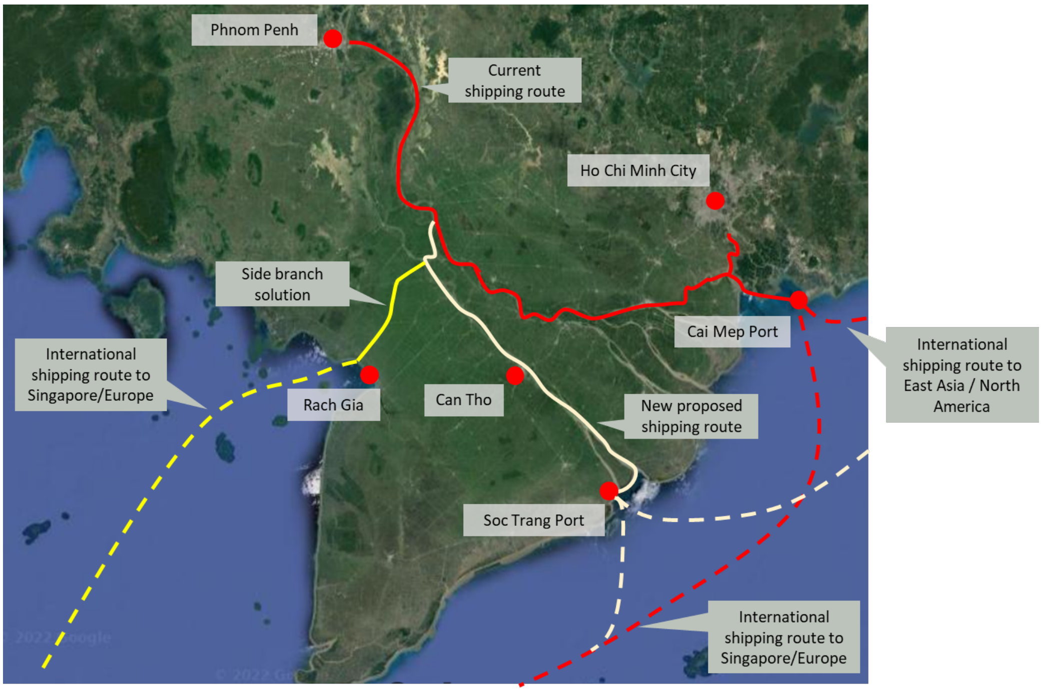


Figure 6.27: International shipping routes with bypass channel ("Google Maps", 2022; Hem & Asai, 2015; MPWT, 2012)

6.3.7 Socio-economics

Building this bypass channel will not only affect the hydrology of the area but will also have an impact on the community and the economy downstream of the bypass channel. By considering these aspects carefully, a more complete design of the structure can be established and the feasibility of the structure can be better determined. By digging this bypass channel the safety of the people living downstream of the Hau River will be increased.

Also for transportation means there can be an increase in economic development. Since the construction of a new seaport in the Gulf of Thailand is necessary, new jobs will be generated. Trading facilities will also contribute to economic prosperity. Without a sufficient road network to connect the port to the hinterland, this port cannot be utilized optimally. Therefore other infrastructural investments will be necessary. The bypass channel can also increase the hub function of the MKD within the distribution of cargo. Therefore international shipping routes and cargo flows to Singapore/Europe can use the MKD as the destination. This is expected to increase economic operations and thus the GDP per capita.

A big project like this can create short and long-term employment opportunities. The short time employment opportunities consist of creating jobs in the construction sector. The long-term employment opportunities consist of jobs in the maintenance sector but the project might also create new job opportunities in different sectors. Also, some problems may arise. Because of the increased availability of fresh water in the area new agricultural businesses may arise. This means that the water levels in the bypass channel have to be managed correctly and transparent to the local population. They might get too dependent on the new fresh water supply, but since this water is not always available (the canal is used as a runoff for the Hau River to prevent flooding) that might create undesired situations. The ending of the bypass channel into the sea can also result in local salinisation. This should be kept in mind when designing the discharge sluice at the end of the channel. One can think for example of a small barrier at the bottom of the river, which can also serve as the foundation of the structure. The same solution is applied in section 6.1.

As discussed in subsection 6.3.3 a bypass channel to drain the needed discharge from the Hau River will have significant dimensions. This means there is a lot of land that have to make way for the canal. The people that have to be relocated to make room for the canal have to be compensated sufficiently. This means they should get financial support and also be guaranteed a new place to settle down and build a new life. It is important that the wishes of the local population will be heard.

6.3.8 Overview

To significantly stop flood problems in Can Tho approximately 12,000 m^3/s has to be drained from the Hau River upstream of Can Tho. To drain this much water from the river a bypass channel is an option. There are different options for the dimensions of this canal. A broader canal requires more space but needs less depth to drain the water. A deeper more narrow canal is the other option. The downside to having a deeper canal is that the initial investment is bigger and the maintenance is more expensive. Building a canal like this brings challenges. Not only the construction or maintenance can be challenging but also the socio-economic part. A project of this scale can have a huge impact on the population. The interests of the people should always be considered and their demands should be heard. In Table 6.7 the pros and cons for the bypass channel are listed.

Pros	**Cons**
Discharge regulation	Relocation of people
Employment opportunities	Maintenance
More water transport options	

Table 6.7: Pros and cons bypass channel solution

6.4 Solution 4: Protection of valuable assets and adaptation of local citizens

It is intended with this scenario that the control of the landscape of the area is transferred back to nature. The main idea for this solution comes from the Mekong Delta Plan (Veerman, 2013). Most of the studied area, the Hau River estuary, will be flooded from the Hau River, by either fresh or salt water. The latter intrudes on the river through tidal waves. It is intended to move those assets that can be moved and save those that can not be moved. Consequently, only the big cities in the area will be protected with a levee system. People who live in rural areas will have to deal with regular flooding from the Hau River. As a consequence, the farmers who experience the negative effects of saltwater intrusion should change their agricultural product that needs fresh water (rice), to a new product that can grow in brackish or even salt water (shrimp farms). Some farmers will experience little inconvenience, as they have already been working with brackish/salt water for a long time. For others, this can cause complications as they will have to adapt their crops and/or move to another location.

6.4.1 Protected cities

Only a limited amount of cities adjacent to the river can be protected with flood-defence systems. It is decided to protect the cities which have a population higher than 100,000. The cities in the MKD with this population are shown in Figure 6.28.

City	Population
Can Tho	1,250,792
Rach Gia	403,120
Long Xuyen	382,140
Ca Mau	315,270
My Tho	270,700
Bac Lieu	240,045
Soc Trang	221,430
Tan An	215,250
Cao Lanh	211,912
Vinh Long	200,120
Tra Vinh	160,310
Ben Tre	124,449
Vi Thanh	104,244
Chau Doc	101,765

Figure 6.28: Inhabitants of important cities in MKD (Knoema, 2021)

Considering Figure 6.28 one can see that adjacent to the Hau River there are two important cities: Can Tho and Long Xuyen. Other indicated cities won't be considered, as they are not adjacent to the Hau River. The protection of Can Tho and Long Xuyen will be discussed in further detail.

Can Tho

Can Tho is the biggest city in the MKD with a population of approximately 1.25 million people. Floods occur regularly, which cause a lot of damage in the city and have a significant impact on mobility. An anti-flood embankment on the sides of the Hau River can prevent this from happening. A hard structure is currently being built to protect the city of Can Tho from riverine flooding (Figure 6.29). It is a slope made of block revetments and on top of that, a vertical wall is placed. However, construction has been going on for two decades already (Long, 2022a). The whole part of the Hau River that flows through Can Tho should eventually be provided with this kind of structure at the banks. With these measures, a higher water level in the Hau River would not directly lead to flooding in Can Tho.

Figure 6.29: Protective measures in Can Tho

Long Xuyen

The city of Long Xuyen is located upstream of Can Tho. It would benefit from a similar anti-flood embankment as in Can Tho. The city is mostly of interest because of its vicinity to the Long Xuyen Quadrangle (LXQ), which is highlighted Nort-West in Figure 6.28. This is the largest rice-producing region in the MKD, responsible for 25% of the production (Lee & Dang, 2018). The area is allowed to flood, but only with fresh water coming from the river. Salt water would ruin the crop. Regular flooding of the area is desirable, as the rice benefits from it and it stores a great amount of water in the wet season (Vu, 2021). The area acts as a wetland, which reduces flooding downstream in Can Tho. Since LXQ is more upstream, flooding is mostly caused by extreme river discharges in the wet season, when the water is fresh. The beneficial effects of controlled flooding in LXQ are of great importance to the rice-producing capacity. However, it should be noted that reliable warning systems are required to monitor flooding. On top of that, the salinity of the water should be known at all times, as high concentrations of salt can ruin yields.

6.4.2 Adaptation

Due to sea level rise, saltwater infiltrates increasing lengths of the Hau River. When flooding occurs, the water that flows over the land has a higher concentration of salt. Areas closer to the coast will be subjected to flooding from brackish instead of fresh water. Agricultural farmers which are dependent on freshwater should thus change to aquaculture that can deal with brackish water. There is already a significant number of aquaculture shrimp ponds in the MKD. However, shrimp ponds alone are not durable, as it is prone to disease, water quality problems and yield failure. This affects the resilience of the shrimp farms as an economic motor. The mono-culture of shrimp farming should change to a poly-culture where multiple types of fish and shrimp can live together. There is an already proven concept which also takes the mangrove restoration into account: "First step is brackish water intake in which carnivore sea bass is grown for consumption and cleaning of the water. The second step is (herbivore) tilapia farming to prepare the brackish water for shrimp farming in the third step. The effluent is discharged into the near shore to form a good base for the restoration of mangrove" (Veerman, 2013). The three-step shrimp farming creates a mangrove-friendly environment in which the tree can thrive. When the mangroves are fully grown, they can be used as a buffer protection zone for the MKD. The further land inwards, the lesser adaptation is required, as the salinity in the Hau River decreases.

6.4.3 Transport

Three distinctive key zones in the MKD, the upper Delta, middle Delta and coastal zone are shown in Figure 6.30. Lengths of the networks in each zone are present in the same figure.

Zone and Road type	Length [km]
Coastal Zone expressway	49.0
Coastal Zone national road	538.1
Coastal Zone provincial road	186.5
Middle Delta expressway	226.2
Middle Delta national road	657.6
Middle Delta provincial road	472.3
Upper Delta national road	585.4
Upper Delta provincial road	305.5

Figure 6.30: Zones in the MKD with road network (Veerman, 2013)

The road links in the coastal zone are most vulnerable to sea level rise (see Appendix A). For instance, a sea level rise of one meter will damage on average 29.7% of the roads in the MKD. Some provinces will be impacted harder than others, varying between 6.4% and 48.6% per province (Chinowsky et al., 2015; ICEM, 2009). As the three defined zones are not dependent on the administrative boundaries of the provinces, percentages of damaged roads per zone are mentioned in Table 6.8 on the next page.

	Coastal zone	Middle Delta	Upper Delta
Percentage of damaged roads [-]	17.8	17.3	9.8
Road Length [km]	774.1	1,356.1	890.9
Damaged road length [km]	138.1	234.4	87.4

Table 6.8: Damaged roads per zone due to sea level rise

Based on the calculation of damaged road lengths, it can be concluded that the road network in the middle region is most vulnerable to flooding. This part of the MKD is host to most urban centres and therefore has a higher road density than the upper and coastal regions. Considering the number of inhabitants, the coastal area is of most interest with more than 13 million people. The transport model from subsection 5.4.2 indicates the coastal zone as the most important one. However, this is a bit deceptive, as the main parameter for this model is the size of the population. The coastal zone in the model includes HCMC, whereas it actually is not part of the MKD. Without HCMC approximately the coastal area accommodates 4.4 million citizens. The middle and upper delta has approximately 7.9 million and 5.2 million people inhabitants respectively. Addressing the problems in these two zones is considered of higher importance.

Different measures can be taken to increase resilience on the road network. New roads can be constructed on embankments above the expected flooding level. However, this requires substantial funding which makes it unrealistic. Other more realistic investments would be to provide existing roads with sufficient road drainage. Via these investments, the roads can stay accessible when there is flooding for a longer time. Also, investments in spillway-culvert crossings can be of use. With these ducts, roads do not function as a barrier for water but let it flow underneath. Other measures can include the increase of clearance of bridges above the design flooding level (ICEM, 2009).

6.4.4 Socio-economics

It will have consequences when no measures are taken against the flooding of the Hau River in certain areas. People that live in rural areas near the Hau River will have to relocate or adapt. A crop change by farmers from agriculture to aquaculture is deemed profitable. Shrimp farms are more cost-effective than rice fields. With the three-step method, the farmers can change their mono-culture to a poly-culture, giving them more certainty of income.

The aforementioned adaptation should not be considered too lightly. Although a crop change can be beneficial in the long term, the change itself can cause complications. Farmers that have been growing rice for multiple generations might need some persuasion to be convinced to change to the three-step system. This can especially be challenging when the negative impact of salinisation is not directly noticeable. Increasing salinity is a slow process, that reduces the yield of each harvest. This incentive might not be strong enough for farmers to make the decision to switch. If this is the case, campaigning and informing should be taken into consideration.

When land outside of Long Xuyen and Can Tho is allowed to flood, it can impact people's faith in the government. The inhabitants of smaller villages might feel deprived when no measures are taken to protect them from flooding. Ultimately, this can cause great dissatisfaction among the population, which is to be avoided. Eventually, the discontent can have the consequence that civilians will move to bigger cities or other parts of the country. Furthermore, regular flooding will have an effect on the economics of the area. The outflow of people can cause economic depression, resulting in decreased housing prices, bankruptcies etc.

The natural evolution of the delta will encourage an increase of biodiversity, which allows for the strengthening of the ecosystem. Furthermore, this offers possibilities for exploiting this nature for recreational goals. This can, contrary to what was written above, provide an economic boost to the area.

The susceptibility of the road network to water-related damage causes challenges in maintaining and attracting business enterprises in the area. Since there is uncertainty regarding the transportation of goods, considerations can be made to move the company elsewhere. If these companies choose to do so, also inhabitants might move too, which will drain the economic competitiveness of the MKD.

6.4.5 Overview

With this solution, the natural development of the delta is accepted in the unprotected areas. The big cities will be protected by an anti-flood embankment system and therefore are not greatly affected to increases in the water level of the Hau River. A part of the farmers on the other hand, should switch their cultivation from agriculture to aquaculture. This can be combined with the three-step approach of which sea bass, tilapia and shrimps form the basis, allowing for the restoration of mangroves (see subsection 6.4.2). This concept can be applied in the coastal zone in the MKD and near to the banks of the Hau River. This solution is a combination of hard structures and Building with Nature. In Table 6.9 the pros and cons for the adaptation are listed.

Pros	**Cons**
Relatively cheap option	Possible relocation of people due to flooding
Nature-based solution allows for better funding opportunities	Required switch from agriculture to aquaculture for farmers
Increased biodiversity	Reduced road transport
Aquaculture is more costly effective than rice farming	

Table 6.9: Pros and cons protection and adaptation solution

6.5 Survey results

In the questionnaire, participants were asked in which of the four proposed solutions they had the most confidence. The bypass channel solution was most chosen, followed by the discharge sluice coming second. The wetlands came in third place. This can be seen in Figure 6.31. The fourth solution with the adaptation of people did not get any votes. Respondents often based their opinions on the flood reduction capacity of a solution. Other reasons relate to the feasibility of implementation. It was argued that the discharge sluice is the easiest to implement since it does not affect people's daily lives and they can continue with business as usual. Participants that voted for the bypass channel, named its ability to supply fresh water during the dry season as a decisive factor. Another point addressed for the bypass channel is the feasibility with regard to the limited land use necessary. Arguments in favour of the wetlands solution relate to an increase in biodiversity.

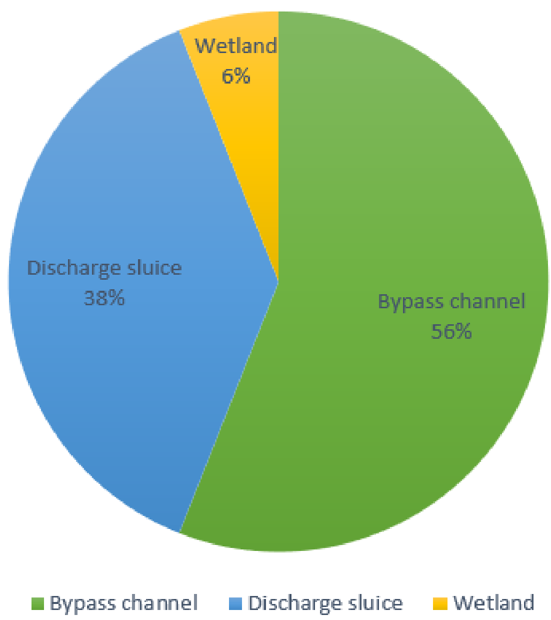


Figure 6.31: Best proposed solutions from survey

7 | Assessment

In this chapter, the proposed solutions are assessed and compared. This serves to support decision-makers in choosing which steps to take. Considerations about the different solutions were made with a variety of assessment methods. For these methods, two main groups are distinguished (i.e. deliberative methods and traditional methods). Within the deliberative methods, the focus lies on civilian participation. Shortall (2021) noted that these methods are increasing in popularity in different sectors. The traditional methods rely more on a utilitarian basis (Mouter, 2021), focusing on gaining the highest overall utility for society via valuation functions (Defra, 2004). Traditional methods determined by Mouter (2021) which are often used by governmental bodies are the Multi-Criteria Analysis (MCA), and . Since citizen involvement is not frequently used in decision making (as discussed in section 1.3) the traditional appraisal methods are used. This is supported by the survey in section 5.6, where improvement of public participation has the lowest relative weight.

The MCA method usually starts with the determination of criteria- and alternative set. The power of this assessment method lies in the performance matrix which is filled in using the unit of the criterion. This means quantification of the criteria is more representative. By normalizing these values the criteria are made comparable. Preferences of criteria can be made insightful by adding weights (Dean, 2020). Within sCBA similar criteria- and alternative sets are used. However, this method uses a monetary quantification to compare alternatives. Monetizing effects which do not have direct monetary impacts can be seen as a challenge. It is necessary to determine the willingness to pay of society to lose or gain specific effects (Addae-Dapaah, 2012). At last, the EIA method aims to predict the environmental impacts of a development. In the first stage, the (dis)advantages and constraints are determined. Based on these characteristics the next step is to define the related factors and effects. In the last step of the assessment environmental effects take place (Transport Scotland, 2013). From the stakeholder analysis in section 1.3 it is noted that the environmental agencies have to be kept satisfied. By using environmental criteria within either the MCA or sCBA this is expected to be sufficient. An EIA is therefore put forward. Regarding the other two methods, within the sCBA there is significant uncertainty in the determination of the willingness to pay. Since the MCA method does not use the monetary effects this method is used to determine a preferred solution.

7.1 Criteria set

The attributes to which the solutions are tested are compiled in the criteria set. This set of criteria is shown in Table 7.1. In this table, different criteria are indicated with units. These units form the basis on which each criterion is quantified. However, it has to be noted that these units are not necessarily used within this report. Since insufficient data is available for some criteria, the solutions are ranked with pluses and minuses on a scale of 0 to 5. This means that the worst score is $--$ (= 0) and the best is ++ (= 5) (Garau et al., 2017). When covering the solutions with more depth, it is recommended to use these units. Five assessment groups are indicated from the table: financial, hydraulic, structural, transportation and socio-economics. These groups and the units which are used are further elaborated below.

Criterion	Unit
Building costs	€
Development costs	€
Secondary costs	€
Funding opportunities	Likelihood of providing funding
Flood reduction	cm
Salt intrusion	g/L
Fresh water supply	–
Construction time	Years
Structural complexity	–
Maintenance	Frequency of expected maintenance
Expected lifespan	Years
Robustness	Vulnerability
Travel time savings	Vehicle hours
Accessibility	Degree of connectivity
Water transport	–
Biodiversity	–
Building with Nature	–
Tourism	–
Long term employment	–
Short term employment	–
Adaptation	Amount of people that have to adapt

Table 7.1: Recommended assessment criterion set

7.1.1 Financial

The building costs of the solutions are rated with pluses and minuses since there is only little data available. A low score means that the solution is noted as expensive, while a high score indicates low costs for construction. The discharge sluice solution is very expensive, therefore it is graded with −−. For the wetland, this is related to the extent to which the existing land has to be excavated for the area to overflow. Since the amount of land that has to be excavated is approximately the same for the bypass channel they should both get a score of −. The bypass channel does need however a costly discharge sluice at the start and end of the channel. This bypass channel solution is therefore graded with −−. The protection and adaptation solution does not need extensive finances and is therefore rated with a +.

Development costs relate to the preparatory costs which have to be made for the realisation of the solution. An example of this is the buyout of people for construction. If many people have to be bought out then a low score is given. The wetland needs the most land, followed by the bypass channel. They therefore get a −− and − respectively. The discharge sluice and protection and adaptation solution do not need to buy people out. Therefore these solutions are graded with ++.

Secondary costs relate to social costs. Think of the expectation of a backlash in the local economy due to the solution. Whenever a solution negatively impacts the local economy this is given the lowest score of −−. If the local economy is boosted by the development the highest scores (++) is handed. Since many people have to adapt their businesses to the protection and adaptation solution it is expected that the economy will drop. Therefore this solution is scored with a −−. Other solutions are not to be expected to cause a significant impact on the local economy and are therefore graded with a 0.

Another financial criterion regards funding opportunities from moneylenders. As described in section 1.3, the IMF and world bank can lend money to solutions which incorporate sustainability and reduce poverty. To measure the likelihood of funding the described +/− method. Since the wetland solution complies with the sustainability goals it is expected that this will have a high likelihood of funding. Since the protection and adaptation solution also incorporates sustainability this is assessed with a +.

7.1.2 Hydraulic

Assessment of the hydraulic factors relates to flood reduction, salt intrusion and freshwater supply. The flood reduction criterion is measured in water level reduction. The discharge sluice solution has the biggest water level reduction, while the protection and adaptation solution does not have any influence on the water level.

The salt intrusion is measured by looking at the change of salinity in the Hau River estuary. When the estuary becomes more saline in the future, the rating will be −, while a reduction in saline water would result in a +. The discharge sluice will close with high tide, resulting in less salt intrusion in the Hau River. Therefore this solution is graded with ++. The protection and adaptation solution assumes that the salinity will increase, resulting in the adaptation of the local farmers. Therefore this solution is graded with −−.

The fresh water supply can be measured by looking at the amount of freshwater that can be stored. When there is almost no fresh water storage available, the grading will be a −, while it will be a + when there is even enough fresh water for the dry season. The wetland and discharge sluice solution can store the fresh water, resulting in a positive rating.

7.1.3 Structural

The construction time criterion is graded in years of construction. The discharge sluice solution will need the most time to be built, while the protection and adaptation solution can be realised relatively quickly.

The structural complexity criterion is graded with a − when it is hard to build the solution, while a + means that it is easy to build the solution. The Building with Nature solutions can be seen as relatively easy to build and are therefore graded with a +. The discharge sluice is a complex structure, resulting in a −−.

Maintenance is graded in the frequency in which maintenance is needed. A − means that there is relatively a lot of maintenance needed, while a + means that the solution does not need any maintenance. Again hard structures are rated lower compared to Building with Nature solutions because these hard structures need more maintenance.

The expected lifespan is graded in years. Concrete and steel in hard structures mostly have a lifespan between 50 and 100 years. The Building with Nature solutions has a very long lifespan.

For the robustness there is looked at the vulnerability of the solution is. A − means that is relatively vulnerable, while a + means that it is not vulnerable.

7.1.4 Transportation

Regarding transportation two main modes of transport are distinguished; road- and water transportation. Within road transportation, two key parameters will be discussed. The first criterion is travel time saving along the complete network. This saving is measured in vehicle hours. For the discharge sluice solution, the travel time savings (6,580 vehicle hours) for location 2 & 3 are used. With regards to the wetland solution the estimated travel time savings are 2,839 vehicle hours. For the other two solutions, no travel time savings are addressed.

Sadri et al. (2020) states that a change in accessibility can be measured in terms of the betweenness centrality of each node. This relates to the number of shortest paths that traverse through a certain node (Hansen et al., 2020). Betweenness centrality, therefore, is the parameter for this second criterion. For the discharge sluice solution, a new link is proposed which increases the betweenness centrality to 0.238. For the other three solutions, no additional measures are taken which leads to a value of 0.224 as shown in subsection 5.4.2.

When severe constraints limit the accessibility of vessels to the Hau River estuary this water transportation criterion will be rated with −. Whenever the solutions will enhance transportation facilities and thus growth a ++ score is given. Since the discharge sluice limits shipping capacity on the Hau River, there is a clear disadvantage. However, when a ship lock is constructed there will be a possibility for vessels to pass the structure when closed. Therefore this solution is scored with a −. For the bypass channel, there is an opportunity to incorporate new shipping routes which is a high advantage. However, within the dry season, low discharges are expected which is a disadvantage. Therefore a + score is handed. The wetland- and protection and adaptation solution have no impact on water transportation. Therefore these solutions are rated with a 0.

7.1.5 Socio-economics

Looking at socio-economical aspects six criteria are distinguished. The first criterion relates to biodiversity. To rate the biodiversity the increase in fauna habitat is measured in m^2. When this is the case, the solution is rated with a +, while a decrease results in a −. The wetland solution is the only solution with an increase in flora and fauna habitat and is therefore graded with a ++.

The degree to which the Building with Nature concept is applied within a solution is rated in the Building with Nature criterion. If this concept is fully applied, then a ++ score is given. If this concept is fully neglected the lowest score (−−) is handed out.

The tourism criterion gets graded with a + when the tourism sector would benefit from this solution, while a − means that the tourism sector would get harmed by this solution. The only solution from which the tourism sector can benefit is the wetland solution because this solution increases the biodiversity in a huge area.

The employment opportunities are split into the long and short term. The solution with an increase in employment gets graded with a +, while the solution with a decrease gets graded with a −. The big projects will all be graded with a ++ for the short term. In the long term, only the discharge sluice solution will create more jobs.

Another criterion which is used is the adaptation of people. For this criterion, the unit is the number of people that have to adapt due to the implementation of the solution. When constructing a discharge sluice no people have to change their current profession. For the Protection and adaptation solution, on the other hand, approximately 700,000 people have to change their daily business. This number is determined by taking the average agricultural population in the provinces adjacent to the Hau River. By implementing an area of influence of 10 km inland the total area within these provinces is determined. For the bypass channel and wetland solutions, a similar process is followed which results in 20,000 and 100,000 respectively.

7.2 Performance matrix

The performance matrix shows the performance of each solution and the base scenario for the criteria. In the respective units, the solutions are modelled with the (technological) models. By normalizing the performance values, comparable outputs can be generated. Normalizing the values can be done with a variety of functions. The most common are the linear-sum and linear-max-min methods. Jahan and Edwards (2015) proposed that the linear max–min normalization offers the most benefits for distinguishing differences between solutions. The equations used for normalizing the performance values are shown in Equation 7.1 and Equation 7.2.

$$\text{Benefit} : n_{ij} = \frac{r_{ij} - r_j^{min}}{r_j^{max} - r_j^{min}} \tag{7.1}$$

$$\text{Cost} : n_{ij} = \frac{r_j^{max} - r_{ij}}{r_j^{max} - r_j^{min}} \tag{7.2}$$

	Discharge sluice	**Wetland**	**Bypass channel**	**Protection and adaptation**	**Base scenario**
Building costs	−−	−	−−	+	++
Development costs	++	−−	−	++	++
Secondary costs	0	0	0	−−	−−
Funding opportunities	0	++	0	+	0
Flood reduction [cm]	150	50	35	0	0
Salt intrusion	++	−	0	−−	−−
Fresh water supply	+	+	0	−−	−−
Construction time [years]	10-15	5	3	2	0
Structural complexity	−−	++	−	++	++
Maintenance	−−	0	−	+	++
Expected lifespan [years]	50-100	100+	50-100	100+	20
Robustness	−−	0	−	++	++
Travel time savings [hours]	6,580	2,839	0	0	0
Accessibility	0.238	0.224	0.224	0.224	0.224
Water transport	−	0	+	0	0
Biodiversity	−	++	−	0	0
Building with Nature	−−	++	−	+	0
Tourism	0	+	0	0	0
Long term employment	+	−	0	0	0
Short term employment	++	++	++	−	−
Adaptation [people]	0	100,000	20,000	700,000	2,000,000

Table 7.2: Performance matrix

7.3 Criteria weights

Relative weights are determined in order to show the preferences of the criteria. Ways to determine the weight of a criterion are called multi-attribute valuation methods. Different methods that can be used are the Marginal rate of substitution, AHP and Best-Worst Method (BWM).

In the marginal rate of substitution method clarity and understandability for the research processes is provided. Moreover, within this method, there is a possibility to utilize both qualitative and quantitative metrics (D. Brombal & Marcomini, 2017). Regarding the ethical considerations, within this method, the trustworthiness of the decision-makers to provide subjective arguments is of utmost importance. This can however not be guaranteed, which can cause any unethical decision to be pushed through. While the method is very useful with regards to understanding, it causes for a single best solution.

In AHP, a pairwise comparison is used between attributes. When using many attributes the overview can be lost easily as does an understanding of the method. Also, the calculations which are done within this method can be confusing for someone who does not have a background in these methods. Some ethical dilemmas arise which apply to it being a subjective process. The key is that subjectivity is inevitable with regard to ethical principles as much as problem formulation and evaluating alternatives. Even if there is consensus amongst decision-makers, the methodology cannot guarantee the right decisions. This can thus also mean that AHP can be used to manipulate others (Millet, 1998). The method is however very useful since it proves a single best alternative.

BWM provides weights that are used in the value function. By providing insight in the vectors determined by the expert (Best to other and Others to worst) insight in the process is provided (Rezaei, 2015). This gives an easy understanding towards the public, of which the choices are made. With regards to the calculations, these are convenient for stakeholders. Ethical considerations, on the other hand, show that there is a validation of the results to check whether the decision maker is consistent. Therefore, it is hard for people of power to manipulate the decision-maker. From an ethical point of view ensuring transparency, honesty and as well as timely, full, and unbiased information in decision-making can arise issues (G. van de Kaa & Taebi, 2019). Regarding usefulness, the BWM method can be applied in group decision-making. Moreover, it shows the most feasible alternative within consistency (T. Balezentis & Streimikiene, 2021).

Based on the transparency, ethical and usefulness considerations as described qualitatively above, the conclusion can be drawn that BWM is the method which fits the purpose of this report best. Since the results can be validated and thus ethical considerations can be considered. In Appendix K, the BWM method is executed. This gives the relative weights of the criteria as shown in Table 7.3. From this table, it can be noted that the opportunities for funding and flood reduction play a significant part in finding a preferred solution. While also the building costs itself form a role in the decision-making. Other factors which have a low influence on the outcome are tourism, lifespan, robustness and water transportation.

Criterion	**Weight**
Building costs	0.106
Development costs	0.053
Secondary costs	0.028
Funding opportunities	0.258
Flood reduction	0.204
Salinity	0.028
Fresh water supply	0.048
Construction time	0.018
Structural complexity	0.012
Maintenance	0.002
Lifespan	0.004
Robustness	0.006
Travel time savings	0.061
Accessibility	0.024
Water transport	0.008
Biodiversity	0.011
Building with Nature	0.013
Tourism	0.005
Employment long-term	0.055
Employment short-term	0.022
Adaptation	0.033

Table 7.3: Criteria weights

7.4 Preferred solution

To determine a preferred solution based on the performance matrix and the weights a value function is used. The function used is dependent on the independence of the solutions. Whenever there is mutual preferential independence between the criteria, an additive value function can be used (Defra, 2004). The first part is thus to determine whether the criteria are mutually preferential independent. When doing so different criteria need to be considered. For this the following criteria are used: Costs, Salinity, Complexity, Accessibility and Biodiversity. Toreffig:Independence$_{c}riteriatheindependenceofthesecriteriaforthesolutionsisshown.Fromthisfigure, itc$

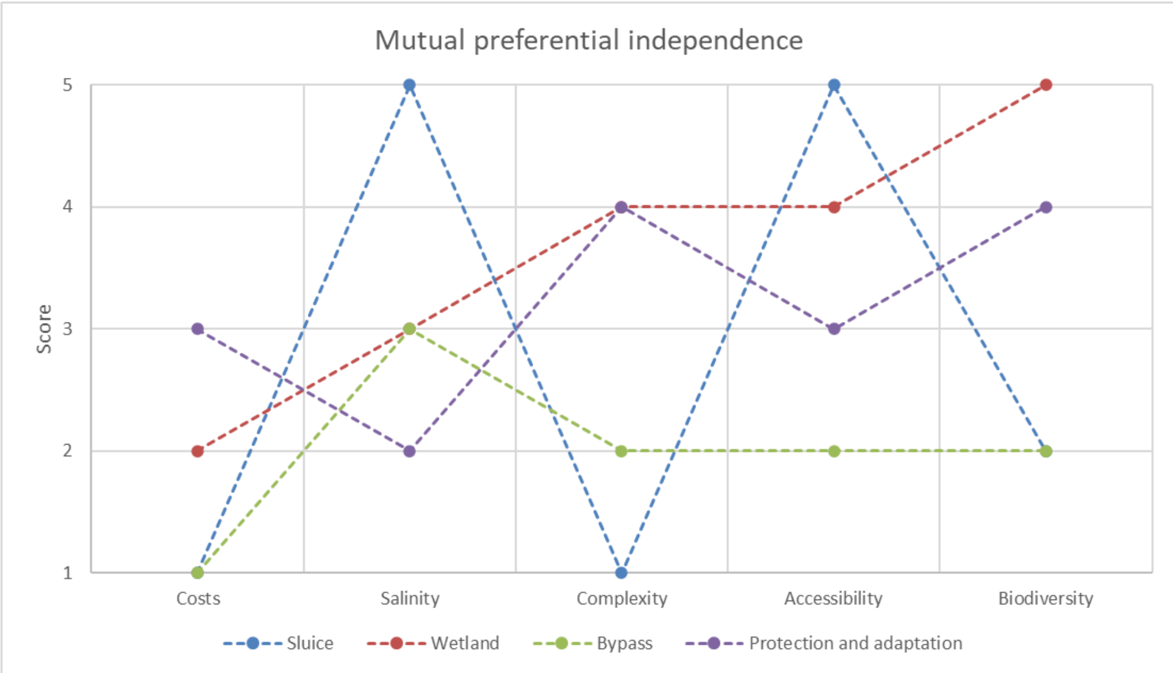


Figure 7.1: Mutual preferential independence

Since the independence of criteria is shown, the additive value function can be used. This function is shown in Equation 7.3. In this function, v is the value and j is the solution number. The weight of each criterion i is denoted by x.

$$v_j = \sum_{i=1}^{n} v_i(x_i) \tag{7.3}$$

Based on the weights, performance matrix and value function the solutions are assessed. The final assessment matrix is shown in Figure 7.4. In this table, the criteria with their respective weights are shown on the left. The performances of the solutions which are shown are the standardized values from Equation 7.1 and Equation 7.2. The total values are the outcome of the additive value function. This is indicated in Figure 7.4.

	1. Discharge sluice	2. Wetland	3. Bypass channel	4. Portection and adaption	Base scenario
	0.000	0.027	0.000	0.080	0.106
	0.053	0.000	0.013	0.053	0.053
	0.028	0.028	0.028	0.000	0.000
	0.129	0.258	0.129	0.193	0.000
	0.204	0.068	0.048	0.000	0.000
	0.028	0.007	0.014	0.000	0.000
	0.048	0.048	0.032	0.000	0.000
	0.018	0.007	0.004	0.003	0.000
	0.000	0.012	0.003	0.012	0.012
	0.000	0.001	0.000	0.001	0.002
	0.003	0.004	0.003	0.004	0.000
	0.000	0.003	0.001	0.006	0.006
	0.061	0.026	0.000	0.000	0.000
	0.024	0.000	0.000	0.000	0.000
	0.000	0.004	0.008	0.004	0.004
	0.000	0.011	0.000	0.004	0.004
	0.000	0.013	0.003	0.010	0.007
	0.000	0.005	0.000	0.000	0.000
	0.055	0.000	0.028	0.028	0.028
	0.022	0.022	0.022	0.000	0.007
	0.000	0.002	0.000	0.012	0.033
Total	**0.67**	**0.55**	**0.34**	**0.41**	**0.26**

Table 7.4: Assessment matrix

In this table the scores of the alternatives are shown together with a 'do nothing' base scenario. The effects of the proposed solutions can therefore be described. From this table, it can be noted that the bypass channel has the lowest score. This stands forward because the other solutions score well on either funding opportunities or flood reduction. The bypass channel solution does not score well on either of those. The bypass channel scores well on other criteria such as secondary costs, water transport and short-term employment. However, these criteria don't have a significant impact on the outcome. The fourth solution (Protection and adaptation) is ranked third. It does score well on the funding opportunities, but on other criteria, this solution has the lowest scores. Only relating to structural criteria this solution score well.

Regarding the discharge sluice and wetland, the overall outcome is slightly in favour of the discharge sluice solution. Since these values are very similar a clear distinction cannot be made. Since the weights of funding opportunities and flood reduction are somewhat similar, and both solutions score well on one of the two criteria, this similarity is explained. The equivalence of these two solutions is also underpinned by the division among experts (subsection 1.2.7).

7.5 Roadmap

The long-oriented goal of the central authorities is to make plans towards a safe, prosperous and sustainable delta. With the roadmap visible in Figure 7.2 this goal can be achieved.

In this flowchart, the input from this report is shown in blue. Other inputs which are necessary are shown in grey. The work packages where input from the central authorities (i.e. the decision makers) will be recommended are shown in orange. With this input different work packages can be obtained to find the preferred solution.

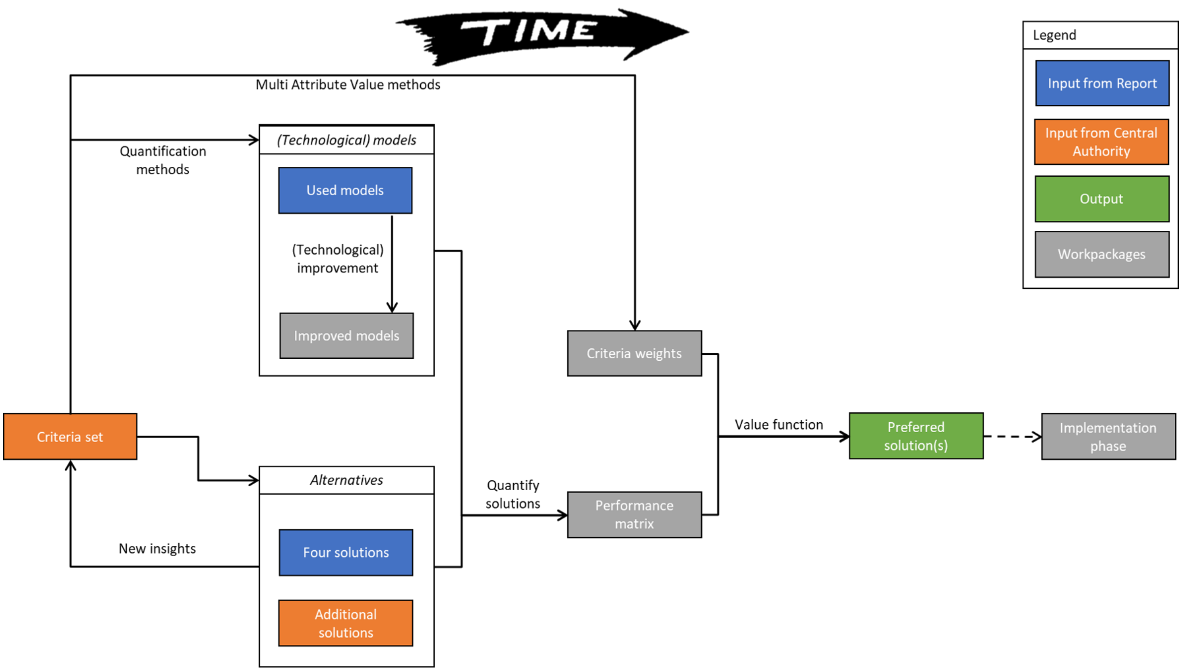


Figure 7.2: Flowchart of assessment method

At first a criteria set has to be made. This is followed by finding the solutions. Afterwards, the technological quantification methods are used. By combining the solutions with the (technological) models a performance matrix can be obtained. The determination of the relative importance of the criteria is the next step. When combining the criteria weights step with the performance matrix, a preferred solution can be obtained. The final part is the implementation of this solution.

8 | Discussion

This section contains the interpretation and limitations of the results from this study. The data are dealt with first, followed by the models. The discussion section finalizes with the consideration of the assessment method that was used to compare the proposed solutions.

8.1 Data

As stated before, collecting reliable data on the MKD is complicated. Many available data are deemed unreliable by experts. Especially measuring the bathymetry of the Hau River is problematic, as the river is wide and would require many measurements.

Some of the online available flooding tools are not up to date with the newest developments on land elevation measurements. A new and more reliable method revealed that the mean elevation level of the MKD is lower than previously expected. While this is taken into consideration for this study, some of the predicted flood maps (by WRI) do not. They are recognizable by the diagonal elevation lines (see Figure 1.6 and Figure 3.11). These figures are only used to describe the problem statement. In reality, the elevation is even lower and more land would be flooded.

The research into the hydraulics of the Hau River estuary was, amongst others, based on a dataset from 2011. This year is representative of designing for flooding conditions. However, as the data was measured more than a decade ago, the most recent developments caused by climate change were not taken into account. Nevertheless, this was the most complete data set at hand. It included water levels and discharges of five different stations, all for a year. Other available data only contained information on one location or only consisted of water levels or discharges, but not both. The most usable data set was the one from 2011.

The tide at sea is a dominant factor for the water level in the Hau River. Therefore, any deviations in the tidal water level at sea are of influence on modelling. The location where the tide is measured can thus have a great impact. The data set from 2011 only contained tidal water levels at Vung Tau. This location is not exactly at the mouth of the Hau River. However, data from the same set ought to be used, as the tides at sea and experienced in Can Tho should match in time. A shift in time would make the data unusable for zero-dimensional modelling. A shift in space was less severe.

8.2 Zero-dimensional model

In the assessment of the effectiveness of the discharge sluice, a zero-dimensional model was used. It is a traditional way of engineering to simulate reality with a simple model at first and improve on the complexity and detailing of the model along the way. The zero-dimensional model can only predict water levels at one location because it treats the system as a reservoir that fills up and drains. This is a deep limitation of the model. The principles on which this model is based, do not apply to one-dimensional modelling. While the zero-dimensional model can be of great use as a proof of concept, its results should not be used to base designs on. The simplicity of the model is its strength and its weakness at the same time.

8.3 Delft3D

The Delft3D model was made for conceptual purposes to give insight into the effectiveness of the wetland- and bypass solution. The base model showed a reduction in levels of flooding for the compared solutions. However, the obtained bathymetry data, which is used throughout the whole model, is uncertain. This could change the outcome of the model. Furthermore, islands, local widening and local narrowing are neglected, but these could result in local flooding which could result in losing water from the system. Additionally, the validation of the model resulted in some differences from the obtained data. It turned out that the model overestimated the levels of flooding. There are also concerns about the reliability of the user data as discussed in section 8.1, so the chance of input errors will always form a problem in an area where the data is so scarce. Due to the very complex software of Delft3D minor alternations in the system setup will result in significant changes in the output. By making a very simple model, which can be easily interpreted, greater uncertainty in the results is generated. However, the initial condition and boundaries are kept constant and used in every run for each solution. Therefore the quantification of the problem and reduction are expected to be in the same order of magnitude.

8.4 Transport model

In the transportation model, only national and provincial roads are taken into account. Detours which can be taken between two nodes are therefore not used in the model. The capacity on the road is taken from reference locations. Local capacity on the roads can be very different to the key numbers used. Regarding the attraction of the zones, many assumptions have been made. More research into the trip attraction of different agricultural purposes can make attraction characteristics in the zone more specific. Also taking other attraction types (i.e. education, attraction per workspace, etc.) into consideration can result in a higher resolution of attraction.

The model which is used contains only one mode. By modelling for other modes such as motorbikes, reality can be simulated more accurately. Also, the deterrence functions which are used can be utilized better, for instance by taking freight transport into account. The assumption is made that freight follows the same pattern as passenger transport. Since freight focuses on industrial areas instead of inhabited areas, trip distribution is very different. Including these differences in the skim matrices will add depth to the model.

8.5 MCA

The MCA was used to find the best solution(s) to reduce the riverine inundation in the Hau River estuary. The criteria set that was used is made by the writers of the report. The performance matrix that followed this criteria set contained some real numbers. However, most of the criteria could only be rated with a plus or minus by the writers of the report. The final step in the MCA is the determination of the weights for the criteria. This was done with the Best-Worse method. This method is again dependent on the input from the writers of the report. This input can be subjective, while for the perfect scenario, this should be objective. This can result in a biased outcome from the MCA, which is not preferable.

9 | Conclusion

The Hau River estuary is in danger as it is exposed to the following problems: riverine inundation, subsidence of land, salinisation and freshwater supply. This will aggravate due to climate change over the following decades. In this study, it was chosen to mainly focus on the reduction of riverine inundation. Based on the above, the following research question has been formulated:

Which integrated solutions reduce riverine inundation problems in the Hau River estuary while also considering socio-economical aspects?

Four solutions are proposed (discharge sluice, wetland, bypass channel and protection and adaptation) to deal with the riverine inundation problems in the Hau River estuary as stated in the question above. The design of each solution is analysed with different models to show their impact on the discharge, water level and transport. From the models, it can be concluded that the discharge sluice, wetland and bypass channel will reduce the water levels and therefore reduce the flood risk.

After this analyse the four solutions are assessed with the help of an MCA. The two most important criteria in this MCA are flood reduction and funding opportunities. From the MCA it follows that the discharge sluice and wetland solution both get the best rating. This does not mean that the bypass channel and adaptation solution do not work and these solutions should therefore not be neglected. Following the MCA, the discharge sluice and wetland solution can be seen as the best solutions to reduce the riverine inundation in the Hau River estuary, while also considering socio-economical aspects.

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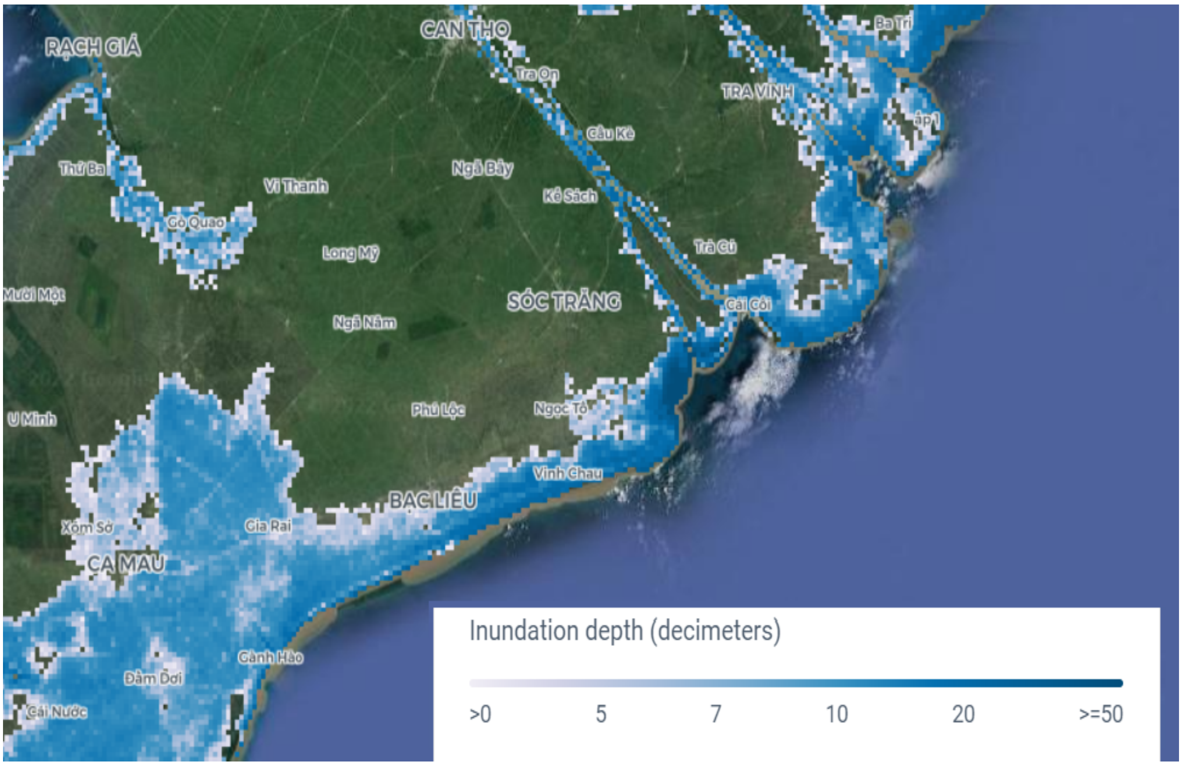
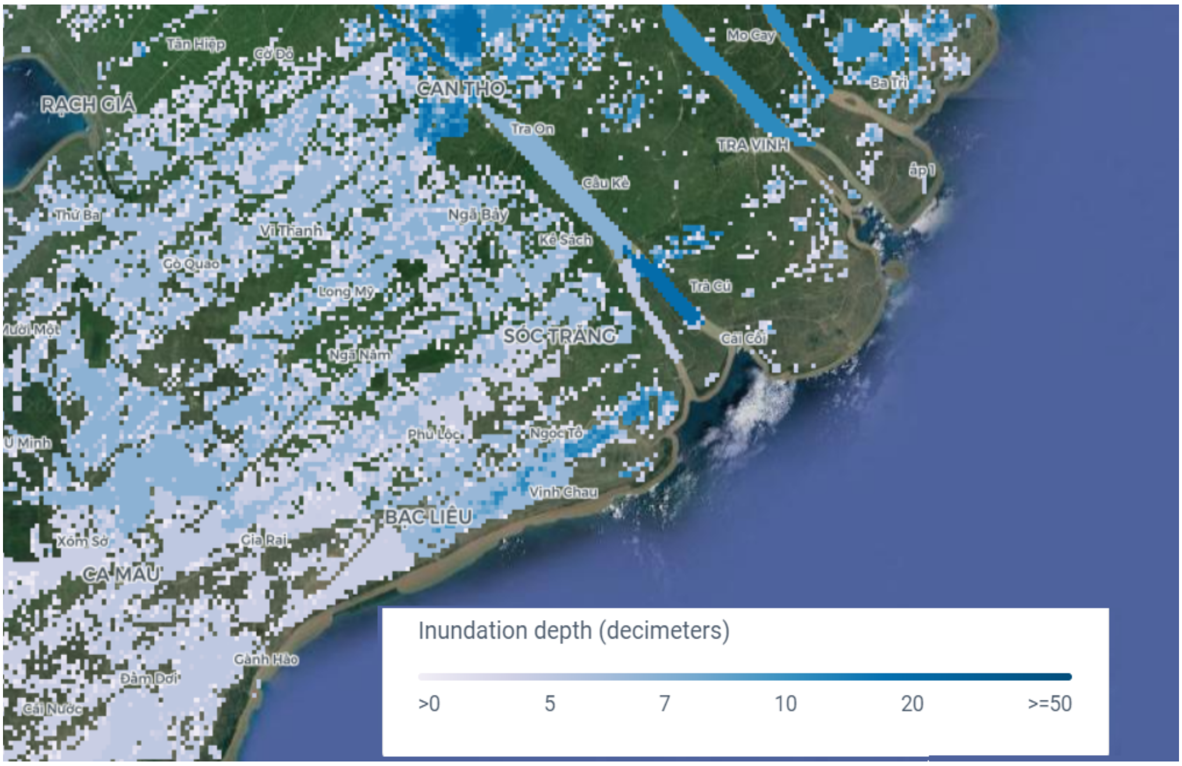
A | Additional Data

A.1 Flooding in future

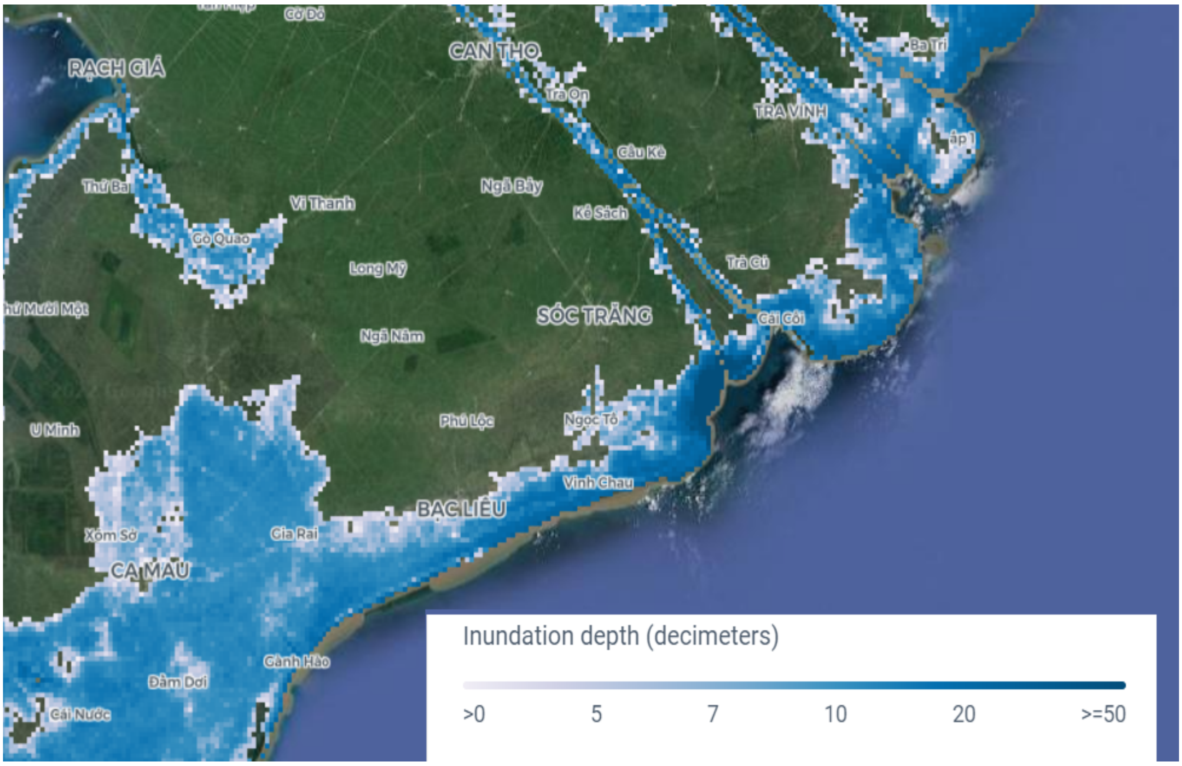
- A pessimistic future scenario both for riverine and coastal flooding is used.
- A return period of 1000 years is used for both types of flooding. This is done because human lives have to be protected.
- For both riverine and coastal flooding 4-time frames are taken into consideration. First, the baseline reference, followed by the scenarios of 2030, 2050 and 2080.
- For the coastal flood application a sea level rise scenario of high is used. This corresponds with a probability range of 95%.
- For the riverine flood application the projection model of the Geophysical Fluid Dynamics Laboratory (NOAA) is used.



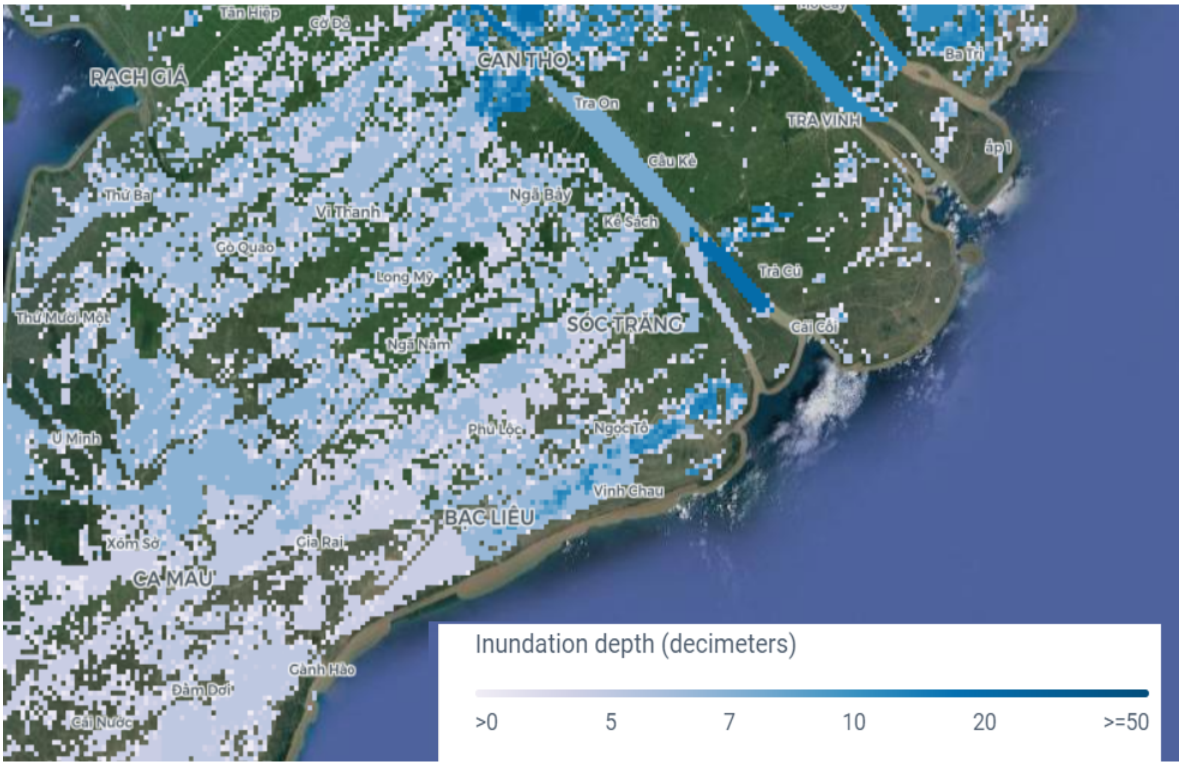
(a) Coastal 2030



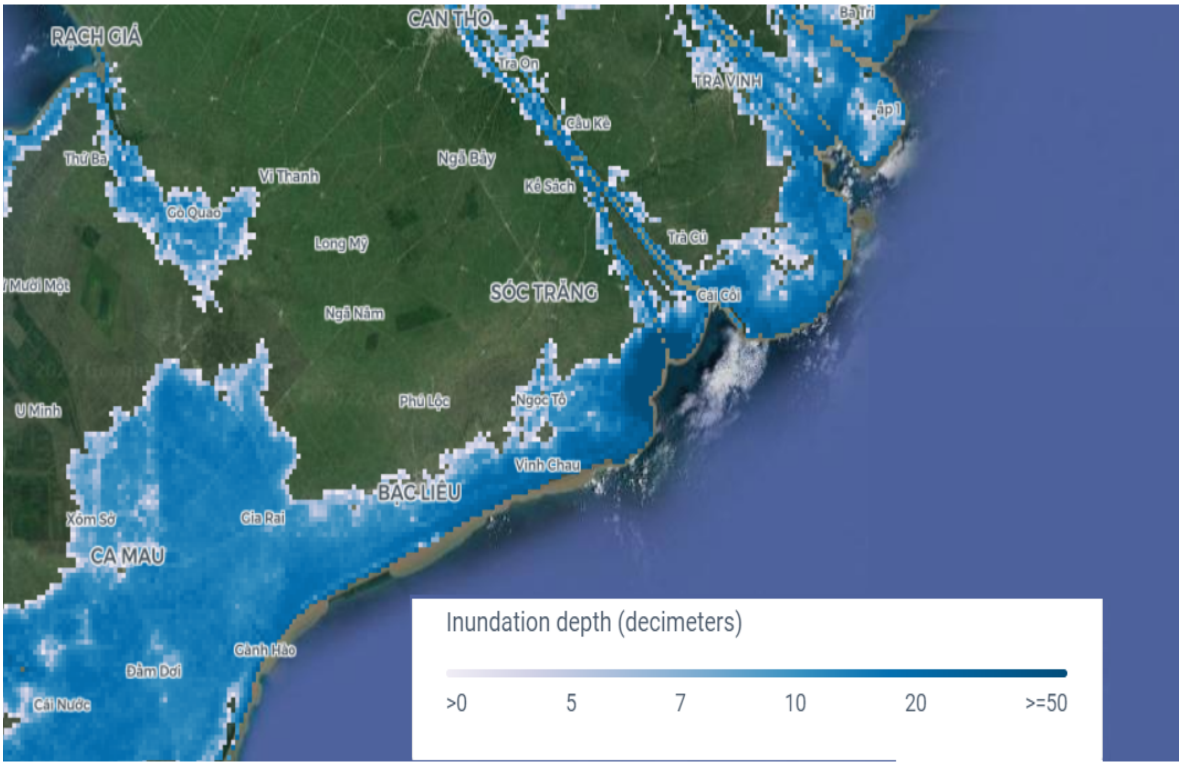
(b) Riverine 2030



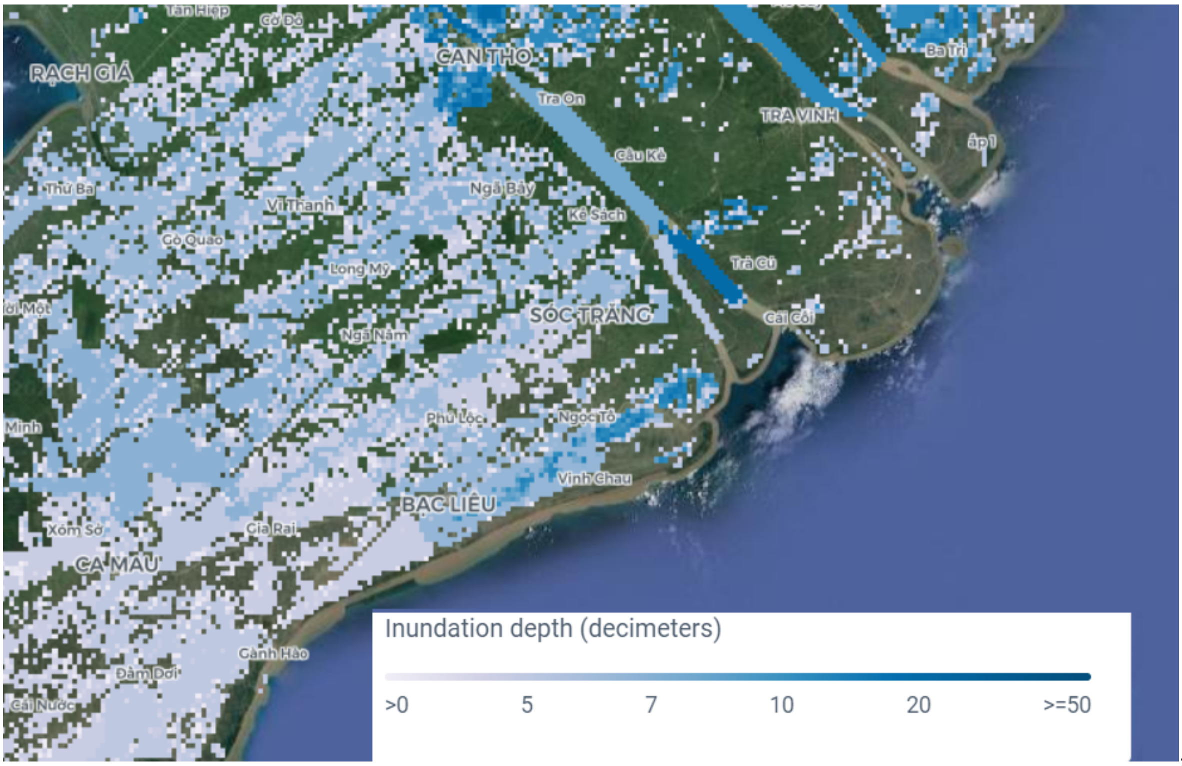
(c) Coastal 2050



(d) Riverine 2050



(e) Coastal 2080



(f) Riverine 2080

Figure A.3: Future scenarios for both coastal and riverine flooding (WRI, 2020)

A.2 Storm surge data

To determine the storm surge set up at the coast, storm data from Thuyloi University is used. It contains data on all the storms until 1952. Since 1980 the wind speeds are measured every six hours. The highest wind speeds per storm are taken and listed and used for the calculation of the maximum set-up during one storm.

	Symbol	**Value**	**Units**
Friction coefficient (calibration coefficient)	C_d	0.002	[-]
Density of air	ρ_{air}	1.25	[kg/m^3]
Density of water	ρ_{water}	1025	[kg/m^3]
Water depth to MSL	h_o	50	[m]
Funnelling factor (funnel type coasts)	C_f	1	[m]
Fetch length to coast	F	250	[km]

Table A.1: Coefficients and assumptions made for the wind set-up calculation

τ_{wind} is the wind stress in N/m^2. The formula to determine the wind stress is:

$$\tau_{wind} = C_d \cdot \rho_{air} \cdot u_{wind}^2$$

A is a dimensionless coefficient needed to calculate the wind set-up. It can be calculated in the following way:

$$A = \frac{0.8 \cdot \tau_{wind} \cdot F}{\rho_w \cdot g \cdot h_0^2}$$

S is the set up in m and it can be calculated with the following formula:

$$S = C_f \cdot h_0 \cdot (-1 + (1 + 2 \cdot A)^{0.5})$$

All the storms with their specific characteristics are shown on the next page in Table A.2.

Name	Birth	Duration	Max wind speed [kt]	Wind set up [m]
Noul	15-9-2020 18:00	2 Days 18 Hours	50	0.618
Doksuri	12-9-2017 12:00	3 Days 12 Hours	80	1.567
Haiyan	4-11-2013 00:00	7 Days 6 Hours	75	1.379
Nari	9-10-2013 12:00	6 Days 6 Hours	125	3.745
Son-Tinh	23-10-2012 12:00	5 Days 18 Hours	85	1.765
Mirinae	27-10-2009 06:00	6 Days 12 Hours	80	1.567
Ketsana	26-9-2009 00:00	4 Days 6 Hours	70	1.204
Lekima	30-9-2007 00:00	4 Days 6 Hours	60	0.887
Xangsane	26-9-2006 00:00	6 Days 0 Hours	85	1.765
Vicente	16-9-2005 12:00	2 Days 6 Hours	45	0.501
Chantu	10-6-2004 18:00	2 Days 12 Hours	60	0.887
Nepartak	12-11-2003 18:00	6 Days 12 Hours	65	1.040
Lingling	6-11-2001 18:00	5 Days 6 Hours	85	1.765
Zack	27-10-1995 00:00	5 Days 18 Hours	95	2.196
Angela	26-10-1995 18:00	10 Days 18 Hours	115	3.187
Colleen	18-10-1992 18:00	10 Days 0 Hours	55	0.747
Vanessa	26-4-1991 00:00	2 Days 0 Hours	45	0.501
Mike	7-11-1990 18:00	10 Days 0 Hours	100	2.427
Dan	9-10-1989 00:00	5 Days 0 Hours	75	1.379
Irving	21-7-1989 00:00	3 Days 12 Hours	55	0.747
Skip	3-11-1988 18:00	8 Days 12 Hours	80	1.567
Cary	14-8-1987 12:00	8 Days 18 Hours	75	1.379
Betty	9-8-1987 00:00	8 Days 0 Hours	110	2.923
Herbert	8-11-1986 06:00	3 Days 18 Hours	60	0.887
Georgia	18-10-1986 06:00	4 Days 6 Hours	45	0.501
Cecil	12-10-1985 12:00	4 Days 0 Hours	80	1.567
Agnes	1-11-1984 06:00	7 Days 0 Hours	105	2.670
Hope	5-9-1982 00:00	2 Days 12 Hours	55	0.747
Hazen	14-11-1981 18:00	7 Days 6 Hours	70	1.204
Kelly	30-6-1981 12:00	4 Days 12 Hours	60	0.887
Herbert	24-6-1980 12:00	4 Days 0 Hours	50	0.618

Table A.2: Calculation wind set up of storms

B | Meeting reports

In this appendix, the meeting reports with external experts are shown. These meetings are held to get a broader knowledge of the problems and solutions in the area. They can also help in understanding the MKD.

B.1 Witteveen+Bos

Present:	V. Nijholt	TU Delft	**Date and time:**	10-10-2022 15:00
	J. Lijftogt	Witteveen+Bos		
Absent:	-		**Location:**	Microsoft Teams
Mailing list:	-			

B.1.1 Introduction

Mr J. Lijftogt is the Business controller of the Vietnam branch in Vietnam. The office of Witteveen+Bos is based in HCMC. However, in this office, there are only country representatives present. This means there is no technical knowledge with regard to watermanagement projects in their office. Via their office in Vietnam, Witteveen+Bos is present in the market and they can execute projects. They have performed for example a part in the Mekong Delta Plan.

B.1.2 MKD problems

In the Mekong, there are various problems. One where Witteveen+Bos is currently working is related to the sediment transport in the area. There is a wide variety of transportation projects planned to finish in the near future. To finalize these projects there is a lot of sand needed. This sand could be extracted from the Mekong/Hau rivers. However, due to the many developments upstream of the river, there is less sediment available. Also, the Vietnamese people themselves extract sand upstream of the river for other purposes than construction.

Other problems which they have found in the MKD relate to drought in the area. Since there is less precipitation in the dry period the freshwater resources dry up. This is also related to the upstream developments, where there is less discharge coming from Cambodia. This is closely related to climate change, where the dry seasons will be dryer and the wet seasons will be wetter. The last part causes inundation problems in the area.

Citizens participating in the political decision in Vietnam is close to none. If there is a decision to make within the area, usually the government makes the decision. This goes by the saying "The government makes the decision and doesn't know and has no opinion".

B.1.3 Further actions

Mr Lijftogt has forwarded information about the projects Witteveen+Bos has done in the area. Also, he has forwarded contacts from the Dutch Embassy. Moreover, the NUFFIC fund, Dutch Climate Fund and Dutch Fund for Climate and Development have been introduced, and all have been contacted.

B.2 Dutch Department of Foreign Affairs

Present:	V. Nijholt	TU Delft	**Date and time:**	31-10-2022 15:00
	L. Umans	Dutch Ministry of Foreign Affairs		
Absent:	-		**Location:**	Microsoft Teams
Mailing list:	-			

B.2.1 Introduction

The meeting with the business director of Witteveen+Bos Vietnam, Mr L. Umans has been forwarded. He is the former first secretary of water at the Dutch Embassy in Vietnam. From this position, he was highly involved in the execution of the Mekong Delta plan and other relevant studies in the MKD. He was mainly a spokesperson between the Dutch companies and the government and the Vietnamese government/clients. Therefore he has high knowledge of the area and the studies which have been done recently. Nowadays, he works at the ministry of foreign affairs in the Netherlands. During this meeting, the problems and previous studies in the MKD have been shared.

B.2.2 Problems MKD

As already discussed by Mr J. Lijftogt there are plenty of problems in the Mekong. However, Mr Umans came up with a counterargument to the statement that sedimentation is a major problem in the Mekong. There is a problem with sedimentation, this is however not a problem caused by the countries upstream but by the country Vietnam as well. They have no single policy with regard to sand mining and thus there is no real way to use the sand for construction purposes. Moreover, he has told that there is a form of participation from citizens in public decision-making. This is however not often used in the MKD.

Also in relation to the grey vs. nature-based solutions he agreed there is a contradiction. The Dutch market, which is present in the area (partly due to the sustainability goals), is steering towards nature-based solutions. This is also backed by external money lenders who will cause the financing of the area. However, the Vietnamese people and government are more fond of grey infrastructure such as barriers. Therefore, Mr Umans agrees that the project has added value to the area.

B.2.3 Further actions

From this meeting with Mr. Umans, a better understanding of the MKD system was achieved. Also he forwarded 12 papers which have been used during review of the system. Moreover, he has introduced the MDP-team to the people from Royal Haskoning DHV and the current trade advisor of the Dutch Embassy in Vietnam.

B.3 Royal Haskoning DHV

Present:	V. Nijholt	TU Delft	**Date and time:**	10-11-2022 11:00
	L. Engel	TU Delft		
	C. Dirks	Royal Haskoning DHV		
Absent:	-		**Location:**	Microsoft Teams
Mailing list:	-			

B.3.1 Introduction

From the meeting with Mr. Umans, the team has been introduced to Mr. C. Dirks of Royal Haskoning DHV (RHDHV). Mr. Dirks has a background in urbanism and spatial planning. Within RHDHV he has been involved in the Mekong Delta Integrated Regional Planning (MDIRP) which has been published in 2022. In this report, solutions to different kinds of problem in the area have been developed.

B.3.2 Data and Models

From the meeting with Mr. Dirks, the aim is to gather data and models which have been used in the MDIRP project. Different kinds of models have been used by RHDHV to model the situation in the area. Examples of models they have used are salinity-, flood-, water levels- and precipitation models. Also the data they have collected is coming from these models or are used in the models as input.

B.3.3 Further actions

A meeting is planned with Mr. Dirks, together with Mr. Vuong in Hanoi to discuss further about the proposal. He expects that the team can make use of these models. This meeting will take place at the office of RHDHV in Hanoi.

B.3.4 Meeting in Hanoi

Present:	V. Nijholt	TU Delft	**Date and time:**	23-11-2022 14:00
	G. van de Wakker	TU Delft		
	C. Dirks	Royal Haskoning DHV		
	N. Vuong	Royal Haskoning DHV		
Absent:	-		**Location:**	RHDHV Office Hanoi
Mailing list:	-			

By the project team, five different problems have been detected in the MKD: subsidence, fresh water shortage, salinisation, inundation and sedimentation. To model these problems, the MDP-team wants to use the numerical models which are in use by RHDHV. Together with these models, the following data is available to use:

- Discharges
- Sediment values
- Salinisation
- Subsidence
- Water levels
- Precipitation

To work on these models, the MDP-team will go to HCMC. Together with an expert who works with the models on a daily level the team can make use of different kinds of numerical models.

C | Site investigation and study related visits

Some field trips were organised, both in the Red River delta in Hanoi and in the MKD. These aimed to get a better feeling and understanding of the physical problems. The first field trip was a tour trough the Red River delta close to Hanoi. During this field trip several hydraulic structures were visited where different employees gave presentations about the water management in the delta. It was intended with this trip to comprehend the complications of constructing, maintaining and operating hydraulic structures in Vietnam, compared to the Netherlands.

In Hanoi the national laboratory of fluid mechanics and hydraulic structures was visited. It was intended here to learn the differences in available money for hydraulic research between the Netherlands and Vietnam, as well as the quality and methods of research this brings about.

The third field trip consisted of travelling to Can Tho, where a boat tour was planned in the Hau River downstream of the city. A better insight in the size of the Hau River, the current status of flood-protection, tidal variation and hydraulic structures was gained, along with the number of boats and industrial traffic that make use of the river. The stay in Can Tho was complemented with a visit to Can Tho University to learn about the flooding in the urban area.

C.1 Bac Hung Hai irrigation system

This field trip to the irrigation system of the Red River had place on the first of December 2022. It included a visit to two discharge sluices and the irrigation system operating company. While the scale of the structures in this system is not comparable to those required in the MKD, the trip taught valuable lessons on construction and operation of hydraulic structures in Vietnam.

The first sluice (Figure C.1) that was visited is called Dai Thuy Nong Bac Hung Hai. It was constructed in 1958. Excavations were executed by hand. While bank protections on either side of the river were planned to be constructed from the beginning, up to now only one of them is finished, due to lack of money (Son, 2022). This illustrates potential complications in a proposed solution. It is not unlikely that construction will start before financing is in place.

The name of the second sluice (Figure C.2) is Cong Cau Xe Moi. This sluice is three years old (Son, 2022) and was constructed from the water, instead of construction in a dry dock. This saved time and money. The heavy doors are vertically separated, to allow the limited power of the motors to lift them. The top half moves up, while the bottom is stored in the ground. The sluice performs well, although the first signs of wear are already visible. Big cracks and chunks of concrete cause the relative new structure to be leaking. Figure C.4 shows that a significant amount of water flows through the sluice in closed position, leaving a trace of sediment in the water.

To complete this broad field trip in the irrigation system, the system regulation company was visited. This is where water levels are checked, decisions on opening the sluices are made. It was told that there are some money and contamination related issues in the irrigation system. The operational company, which is a government controlled organisation, structurally receives too small budget to maintain the system and its sluices. The budget is complemented with income from water sales. Clients pay for the difference in water level instead of usage of water, which causes unfair distributions of costs. This is aggravated by the fact that most companies are spared, as they only pay once per year. Furthermore, the water quality can not be guaranteed as sewers and company waste water are both released on the system without filtering.

Figure C.1: Only one embankment is finished (Dai thuy nong bac hung hai)

Figure C.2: Sluice leaks due to bad concrete conditions (Cong Cau Xe Moi)

Figure C.3: Sluice leaks due to bad rubber conditions (Cong Cau Xe Moi)

Figure C.4: Sluice leaks due to bad conditions (Cong Cau Xe Moi)

Figure C.5: In the office of the Red River irrigation system operating company

C.2 National laboratory of fluid mechanics

On 09-12-2022 the group was invited to the National laboratory of fluid mechanics. A water flume and a 2D-wave generator were observed. There is limited time available to run tests with these installations, as they are expensive in use. Furthermore, the scale of the water flume is not comparable to ones in the Netherlands, these are significantly smaller, resulting in more unreliable outcomes. In the absence of funding for intensive research and complex modelling, a Hau River scale model was built to assess the effects of water flow, scour holes, structures and erosion on the system.

Figure C.6: Part of the scale model in national laboratory of fluid mechanics

C.3 Site investigation Can Tho and Hau River

From 13 December 2022 to 17 December 2022, the group has visited Can Tho. The goal of this trip was to view the research area, get a better understanding of the dimensions of the Hau River and to be able to conduct a survey amongst local experts and residents. The statements in this appendix chapter are made by one of the accompanying experts. These experts are professor Le Hai Trung (Thuy Loi University, faculty of hydraulic engineering), dr. Truong Hong Son (Thuy Loi University, faculty of hydraulic engineering) and dr. Vo Quoc Thanh (Can Tho University, faculty of environment and natural resources).

C.3.1 River tour

The river tour was organised in the afternoon at 14 December 2022. In the company of supervisors from Thuy Loi University Hanoi, dr. Son and professor Trung. The trip was organised by dr. Thanh, former employee of Deltares and lecturer at Can Tho university, who also came along. During this river tour by boat some observations were made.

Along the river there are lots of buildings, varying from huts and houses to factories and industry. Some bigger structures have a (minimal) flood protection system in the form of a dike around the property, but most don't. People are living close to the river, in unprotected area, leaving them extremely vulnerable to flooding.

In the city itself, a flood protection wall is under construction. Although this already spans two decades, it is not finished yet (Long, 2022a). On multiple locations an interrupted embankment was observed, partially displayed in Figure C.9.

A lot of sand is being mined in the river, of which the better part is illegal, according to professor Trung. Sand mining companies have a limited amount of sand they can mine legally. When that number is reached, the companies don't stop. The professors didn't allow to make pictures, fearing it could cause trouble.

Companies releasing their wastewater on the Hau River were spotted too. A severe discoloration was observed near the outlet of several industries. These companies often use only one parameter (for instance salinity level) to determine whether they can release fluids.

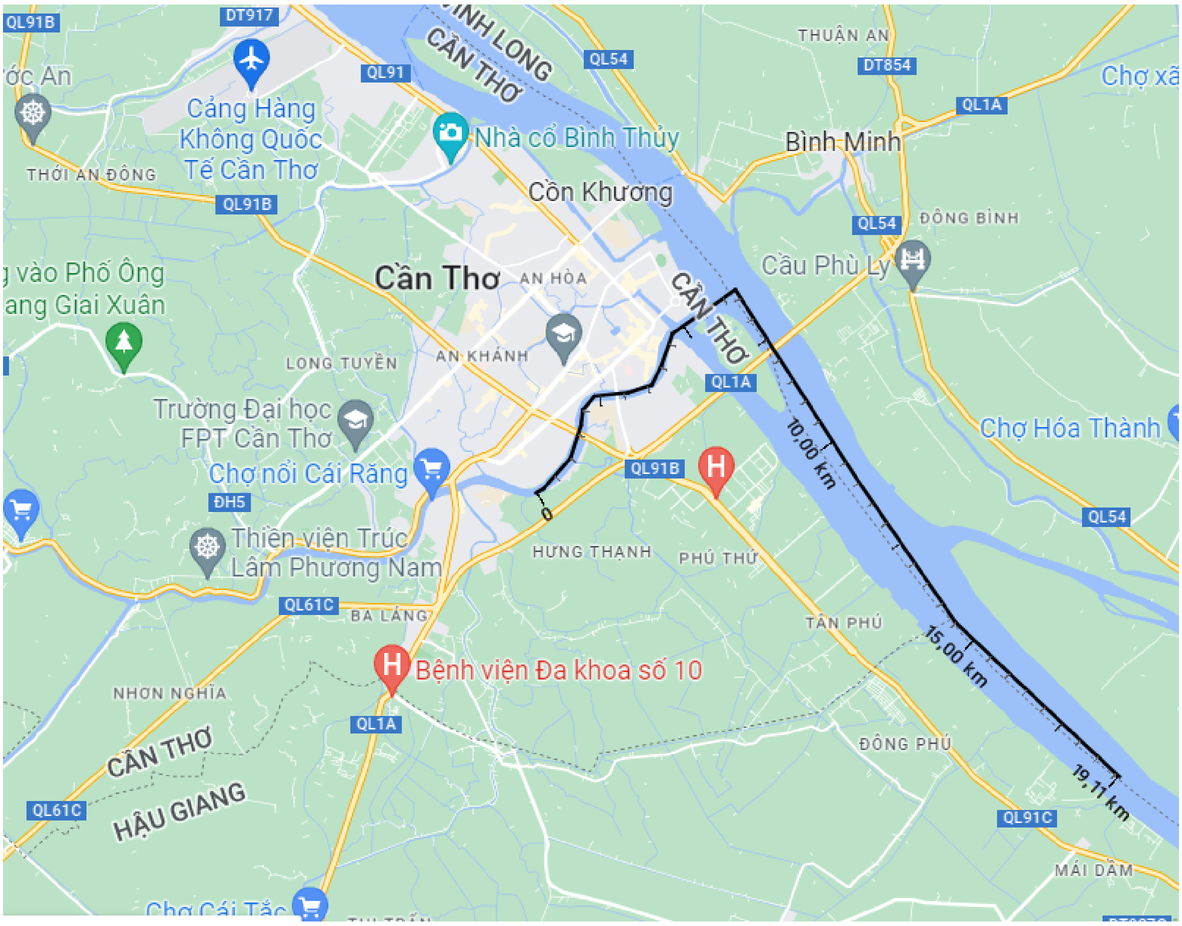


Figure C.7: Route on the Hau River

Figure C.8: On the boat, standing is doctor Vo Quoc Thanh

Figure C.9: Anti-flood embankment in the city of Can Tho

C.3.2 Visiting Can Tho University, College of Environment and Natural resources

The local expert said that the consequence of inundation which has the most impact is the limited accessibility and transport. A layer of water on the streets prevents vehicles from traveling. Furthermore, it became clear that a water level of +2.00 meter with respect to Hon Dau can be used as a threshold value for which inundations will occur. This water level causes the faculty building (Figure C.10) to flood.

Figure C.10: Can Tho University, faculty of environment and natural resources

D | Red River delta

Reference deltas and their solutions to problems have been studied to understand which best practices can be implemented. A delta with similar properties and problems see (Figure D.1) is the Red River (Song Hong) delta. Located in northern Vietnam, this delta is close to Hanoi, the capital of the country. The RR delta has a high population density. In 1077 a levee system was built to control the river. These levees have an influence on the natural sedimentation and drainage. This drainage problem is still not solved completely (Molle, 2015).

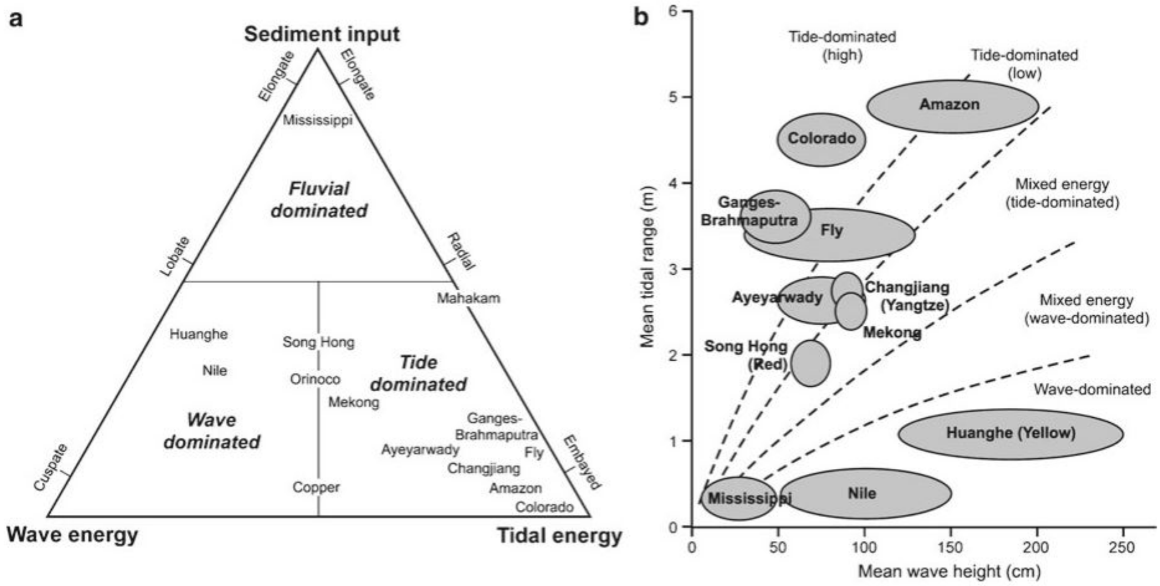
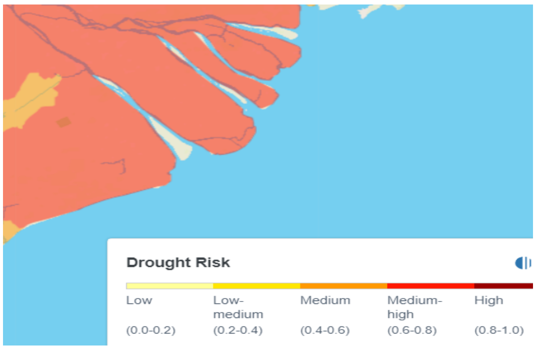


Figure D.1: Deltas classified by dominance (a) and wave height and tidal range (b) (Goodbred & Yoshiki, 2011)

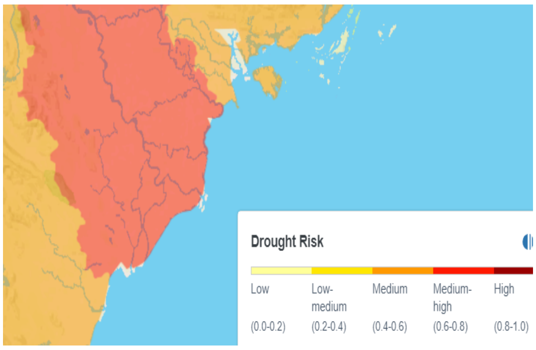
Important differences between the two deltas are: the MKD has a longer wet season compared to the Red River. The Red River delta has a "mosaic", somewhat mountainous environment, while the Mekong is more flattened. Due to the earlier settlements and the higher population density it is more difficult for the Red River delta to develop than for the MKD (Molle, 2015).

D.1 Risks

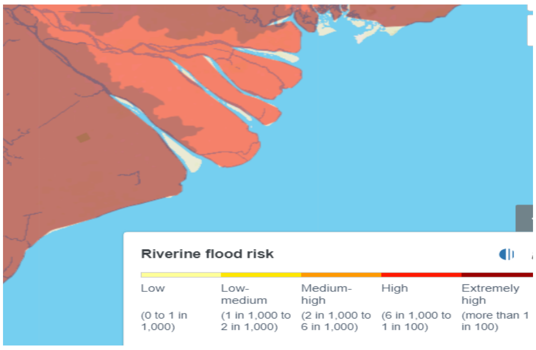
In Figure D.1 one can see that the Red River (Song Hong) delta and the MKD are both mixed energy deltas, where the Mekong is more tide dominated. The main difference is that the Mekong has a higher mean wave height and mean tidal range. Drought risk and riverine flood risk is present in both systems, forming a very high risk. The difference between the two systems lays in the coastal flood risk. The Red River has a higher probability of coastal flooding compared to the the Hau River estuary as can be seen in Figure D.2.



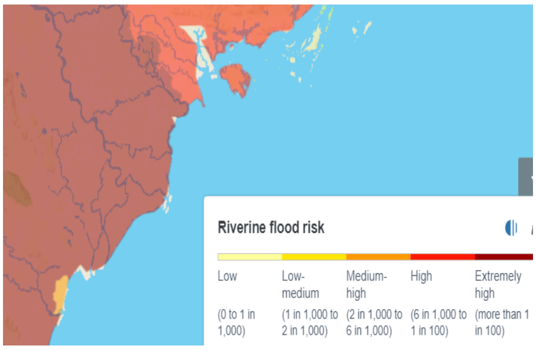
(a) Hau River drought risk



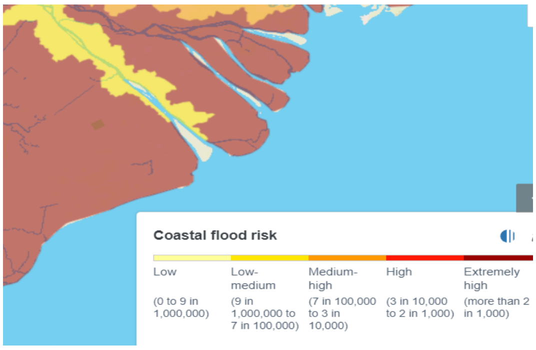
(b) Red River drought risk



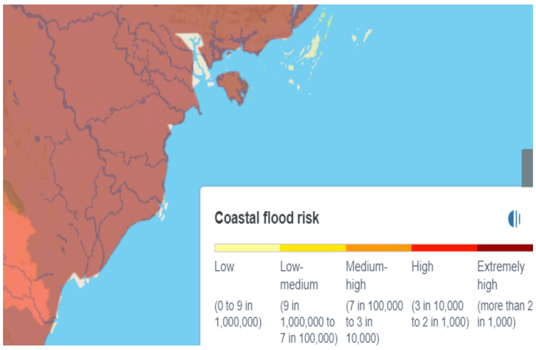
(c) Hau River riverine flood risk



(d) Red River riverine flood risk



(e) Hau River coastal flood risk



(f) Red River coastal flood risk

Figure D.2: Comparison of water risks (World Resources Institute, 2022)

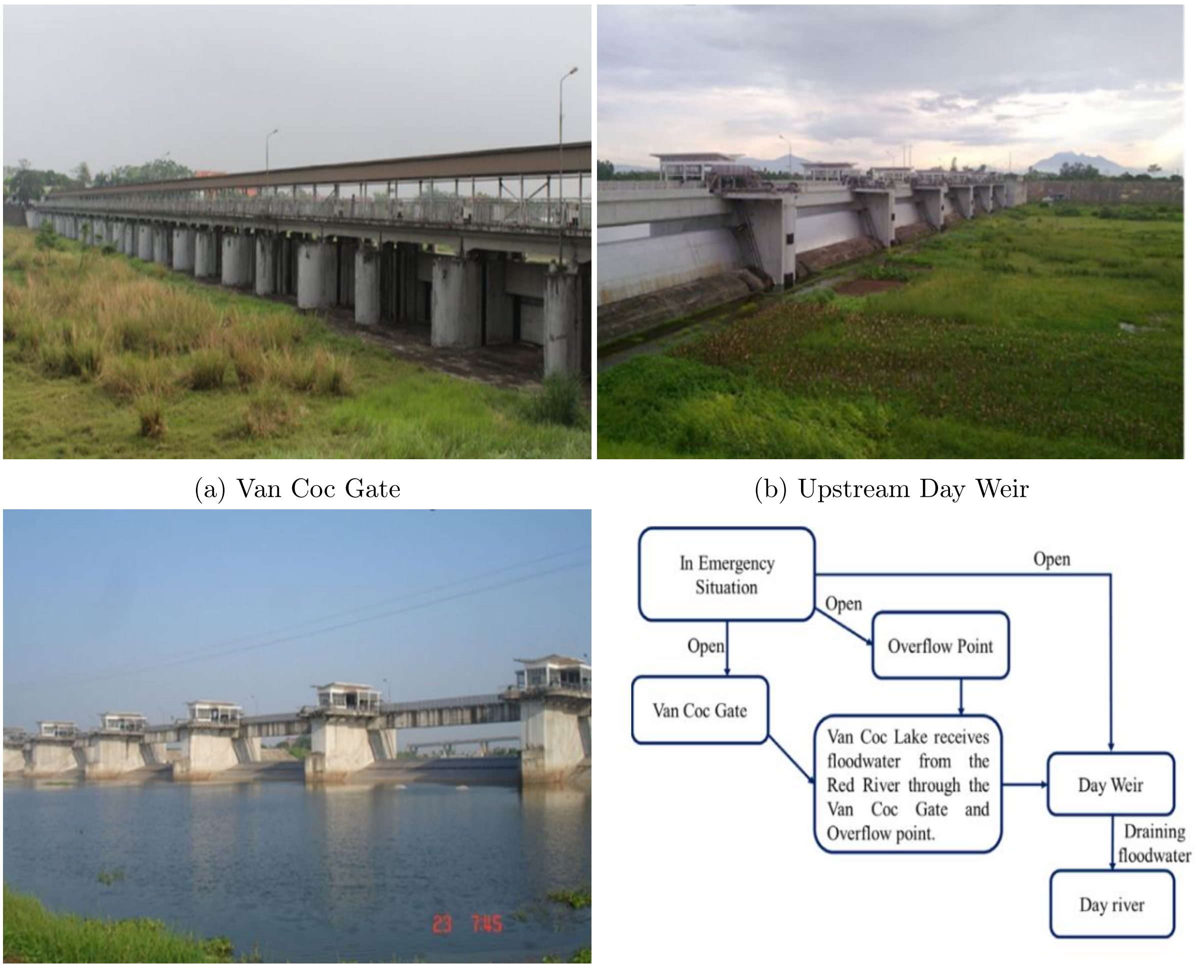
D.2 Solutions

In the Red River Delta 3,000 km of river levees and 1500 km of sea and estuary levees have been built to protect land against flooding. Most of the levees are old and were built with cheap material and without the right knowledge. This has led to unstable and degraded levees. They often suffer from damages like piping, under-seepage and forms of instability like sliding or local collapsing during periods of high discharge. The river levees were considered more important than sea levees throughout the past and are therefore in better shape. With a rising sea level this might become a bigger problem in the future (Molle, 2015).

Figure D.3: Hoa Binh reservoir (Andritz Group, 2022)

Another solution that was used to solve the riverine inundation problems in the RR delta was the realisation of the Hoa Binh reservoir in the Da River (see Figure D.3). The reservoir reduced the water level with 1.2 to 1.5 m in Hanoi. It did however create other problems such as reduction of sediment transport, risk of saturation and stability problems (Pilarczyk & Nguyen, 2005). The construction of a reservoir in the MKD is unrealistic as there are no mountains in the delta and the is relatively flat.

A solution that causes less problems is the discharge regulation through an old river branch. This was achieved by the construction of the Van Coc Gate and Day Weir. "With this solution, floodwater is discharged into Van Coc Lake as a regulating reservoir through the Van Coc Gate (Figure D.4: (a)) and the overflow point located on the bank of the Red River before draining to the Day River through the Day Weir. The Van Coc Gate has 26 controlled gates with a sluice gate form, and Day Weir has six controlled gates with a radial gate form (Figure D.4: (b) and (c)). In emergencies, they are fully open" (for conceptual model see Figure D.4: (d) (Sai et al., 2020). The result was a reduction of 0.2 meter of flood level in Hanoi (Dijkman et al., 1996).



(a) Van Coc Gate (b) Upstream Day Weir

(c) Downstream Day Weir (d) Conceptual model

Figure D.4: Pictures of the Day Weir, Van Coc Gate and conceptual model (Sai et al., 2020)

E | Local citizen interview

E.1 Questionnaire

TRƯỜNG ĐẠI HỌC THUỶ LỢI
THUYLOI UNIVERSITY

Hello! We are a group of students from The Netherlands doing research in your community. We will ask you a few short questions to assess which (water-related) problems you experience. The results of the questionnaire will be shown when the complete report is finished at the beginning of 2023.

Name: ______________________________ Date: __________________________

Profession: ____

Please fill in the ☐ with a ✓ or ✗.

Q1. The Mekong Delta has many problems related to both water management and the economy. Out of the following, what would you consider the most challenging in the area?

☐ Flood protection.
☐ Water supply.
☐ Water quality.
☐ Citizen welfare.
☐ Other,
....

Q2. In the area next to the Hậu-River, can you rank the following main topics from *most* important to *least* important on a scale from 1 (Most important) to 4 (Least important)?

Environmental aspects. ☐
The well-being of citizens. ☐
Economic prosperity. ☐
Societal benefits. ☐

Q3. In the previous question, you have made a ranking of the four topics. Now we are going to see to which extent you find an aspect more important compared to another. Please fill in the table below.

Ranking of main topics	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance
1 vs. 2	☐	☐	☐	☐	☐
1 vs. 3	☐	☐	☐	☐	☐
1 vs. 4	☐	☐	☐	☐	☐
2 vs. 3	☐	☐	☐	☐	☐
2 vs. 4	☐	☐	☐	☐	☐
3 vs. 4	☐	☐	☐	☐	☐

Q4. Considering **environmental aspects**, the following key aspects have been indicated. Can you rank the following aspects from *most* important to *least* important on a scale from 1 (Most important) to 3 (Least important)?

Ecological value. ☐

Reduce air pollution. ☐

Energy efficiency. ☐

Q5. Can you compare the importance of each criterion over another? Use the ranking you have made in the previous question.

Ranking of environmental aspect	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance
1 vs. 2	☐	☐	☐	☐	☐
1 vs. 3	☐	☐	☐	☐	☐
2 vs. 3	☐	☐	☐	☐	☐

Q6. Considering the **well-being of citizens**, the following key aspects have been indicated. Can you rank the following aspects from *most* important to *least* important on a scale from 1 (Most important) to 3 (Least important)?

Reduce flooding ☐

Clean fresh water facilities (e.g. drinking water, sanitation, etc.) ☐

Fresh water supply in the dry season ☐

Q7. Can you compare the importance of each criterion over another? Use the ranking you have made in the previous question.

Ranking of well-being of citizens	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance
1 vs. 2	☐	☐	☐	☐	☐
1 vs. 3	☐	☐	☐	☐	☐
2 vs. 3	☐	☐	☐	☐	☐

Q8. Considering **economic prosperity**, the following key aspects have been indicated. Can you rank the following aspects from *most* important to *least* important on a scale from 1 (Most important) to 3 (Least important)?

Improving transportation facilities ☐
Industrial economic development ☐
Sustainable agricultural production ☐

Q9. Can you compare the importance of each criterion over another? Use the ranking you have made in the previous question.

Ranking of economic prosperity	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance
1 vs. 2	☐	☐	☐	☐	☐
1 vs. 3	☐	☐	☐	☐	☐
2 vs. 3	☐	☐	☐	☐	☐

Q10. Regarding **societal considerations**, the following key aspects have been indicated. Can you rank the following aspects from *most* important to *least* important on a scale from 1 (Most important) to 3 (Least important)?

Improving public participation ☐
Cultural preservation ☐
Practicability of solution ☐

Q11. Can you compare the importance of each criterion over another? Use the ranking you have made in the previous question.

Ranking of societal considerations	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance
1 vs. 2	☐	☐	☐	☐	☐
1 vs. 3	☐	☐	☐	☐	☐
2 vs. 3	☐	☐	☐	☐	☐

Q12. Four alternative solutions are proposed, which of these would be best in your perception?

☐ Discharge sluice

With a sluice, the total outflow of the Hậu-River can be regulated. Also, this construction can withstand storm surges from the sea.

☐ Wetlands

A wetland is a natural part of the land connected to the river's bank. A limited area is subjected to allowable flooding.

☐ Bypass creation

With the realization of a bypass, a great amount of water will be redirected. This canal will open in the wet season, reducing discharge in the Hậu-River.

☐ Protection of valuable assets and adaptation of the people

The agricultural industry (rice farming) will be replaced by a more cost-effective aquatic industry. People living in rural areas will have to deal with regular flooding. Big cities will be protected with a dike system.

Q13. Why do you think this alternative is best to deal with the problems in the Mekong Delta?

……….

……….

……….

……….

……….

……….

……….

……….

E.2 Results

To determine the results the Analytical Hierarchy Process (AHP) method is used. In this method relevant attributes are determined based on a hierarchical process. The relevant attributes which are measured are based on four main groups (Environmental aspects, Well-being of citizens, Economic prosperity and Societal benefits). For each group three sub attributes are formulated. The complete hierarchy tree is shown in Figure E.1.

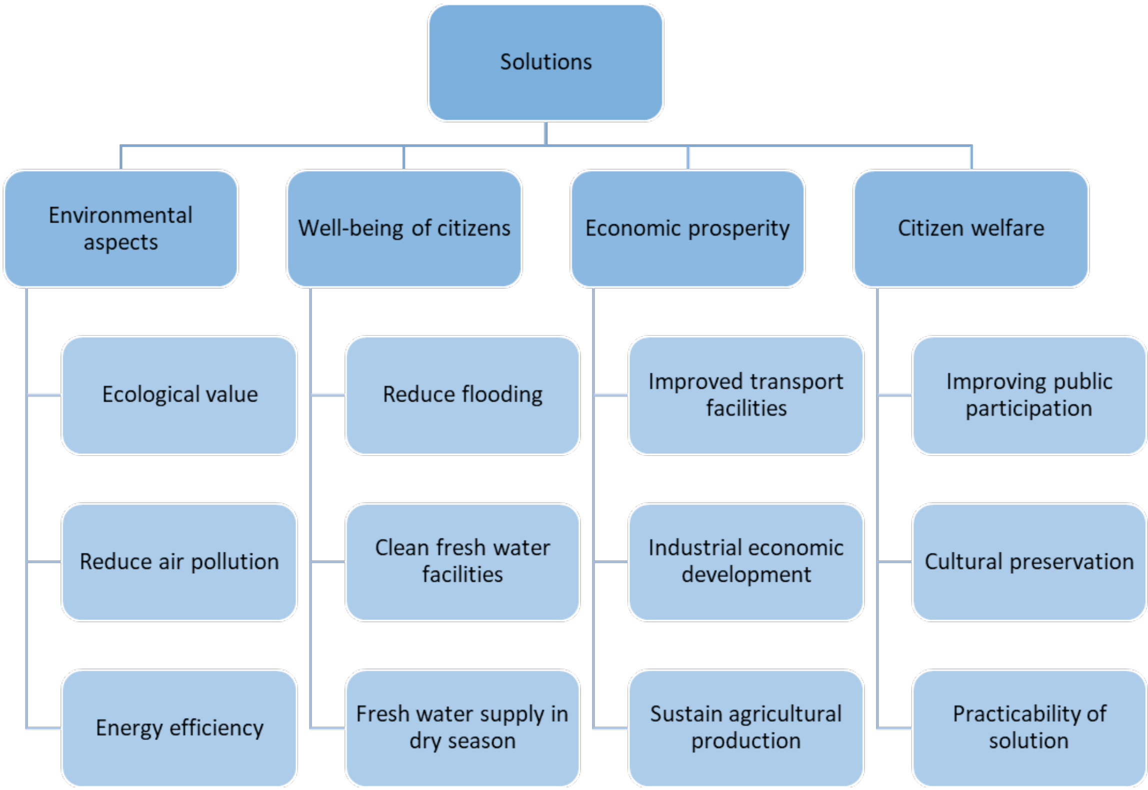


Figure E.1: Questionnaire attributes

The attributes are compared on a scale from 1 to 9. In this scale the relative importance of one attribute over another can be indicated. The scale is indicated in Table E.1. A matrix is obtained with the priorities of the attributes. By normalizing the eigenvector and solving the system of equations (Equation E.1), the priorities can be computed. Afterwards, the consistency is checked to confirm whether the outcomes are within bounds (Saaty, 2008).

$$A \cdot w = \lambda_{max} \cdot w \tag{E.1}$$

Intensity of importance	Definition	Explanation
1	Equal importance	Are equally important
3	Moderate importance	Judgement slightly in favour over another
5	Strong importance	Judgement strongly in favour over another
7	Very strong importance	Dominance demonstrated in practice
9	Extreme importance	Highest possible favouring one over another

Table E.1: Fundamental scale of numbers AHP (Saaty, 2008)

The questionnaire was completed by 20 respondents ($N = 20$). However, some were not filled in correctly which brought the number down to $N = 16$. The aim of the survey is to show the opinion of all the stakeholders. Therefore a society wide recommendation can be given. The groups which have filled in the questionnaire are shown in Figure E.2. The majority of the people who have participated are local citizens and students. Other stakeholders which have been identified in section 1.3 are recommended for a higher societal support.

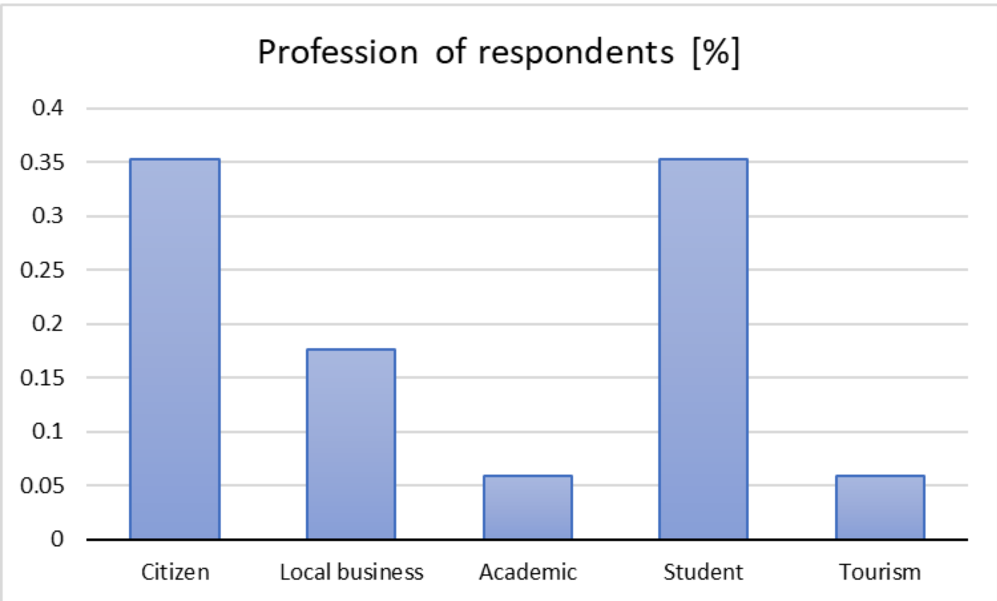


Figure E.2: Profession of respondents

Also, the question is asked which problems are indicated as main problem. In Figure E.3 the results are shown. Almost 50% of the respondents have indicated that flooding is the biggest problem in the area. Water supply is however never chosen as a key problem.

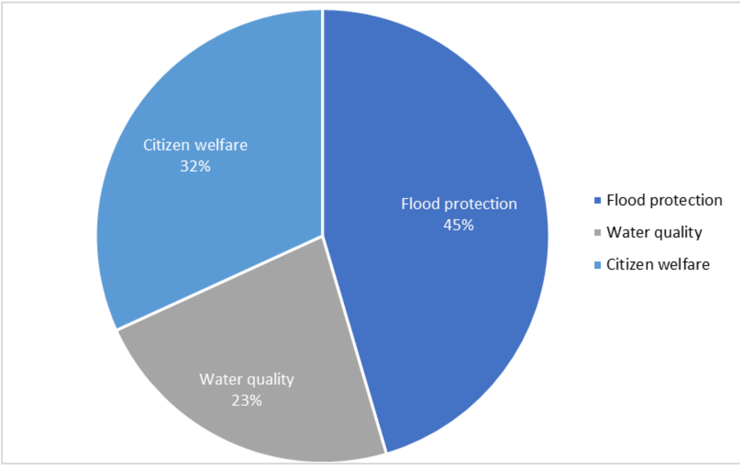


Figure E.3: Main problems from respondents

Also the consistency of the respondents is be checked. By checking the consistency, validity of the results can by measured. The output of the respondents are two matrices (4x4 and 3x3). Following equations Equation E.2 and Equation E.3 the consistency index of each matrix is indicated. RI for the two matrices are 0.89 and 0.52 for the 4x4- and 3x3 matrix respectively. Whenever $CI \leq 0.1$ there is informed consent of the respondent (Saaty, 2008).

$$CR = \frac{\lambda_{max} - n}{n - 1} \tag{E.2}$$

$$CI = \frac{CR}{RI} \tag{E.3}$$

	Consistency Ratio	**Environmental aspects**	**Well-being of citizens**	**Economic prosperity**	**Societal benefits**
Respondent 1	0.20	0.38	0.54	0.28	0.42
Respondent 2	0.13	0.00	0.00	0.28	0.13
Respondent 3	0.41	0.31	0.20	0.20	0.22
Respondent 4	0.90	0.73	0.54	0.54	0.32
Respondent 5	0.18	0.28	0.22	0.13	0.01
Respondent 6	0.41	0.54	0.58	0.31	0.90
Respondent 7	0.22	0.54	0.58	0.42	0.06
Respondent 8	0.37	0.42	0.38	0.08	0.04
Respondent 9	0.19	0.04	0.58	0.42	0.13
Respondent 10	0.28	0.01	0.73	0.42	0.54
Respondent 11	0.22	0.54	0.54	0.54	0.00
Respondent 12	1.03	0.01	0.28	0.00	0.00
Respondent 13	0.33	0.28	0.84	0.90	0.54
Respondent 14	0.53	0.42	0.54	0.28	0.42
Respondent 15	0.98	0.73	0.38	0.73	0.68
Respondent 16	0.64	0.54	0.28	0.54	0.42

Table E.2: Consistency Ratio

As can be seen in Table E.2, the consistency ratio of the respondents is shown. Also it can be concluded that the respondents have been inconsistent with filling in the survey. This can be explained by people not understanding the meaning and final goal of the questionnaire.

E.3 Discussion and recommendations

The number of respondents of the questionnaire is not representative for the people. It can only be discussed that this gives an opinion of some individuals. By including the other stakeholders in the research, a broader perspective can be generated. Therefore the relative importance of the attributes will be more complying with society. Also the method to determine the priorities of attributes for AHP, a mini-public is often used. Within this method, randomly selected inhabitants are provided information on the subject. From this, the people can form their opinion based on a contextual framework (Ayano, 2021).

More specifically, the planning cell method can be used (Dienel, 2002). In this form of deliberative assessment, a group of approximately 25 randomly selected citizens is divided into smaller groups. In groups of 5-6 people their received information is discussed. Afterwards the participants opinions are summarized in the outcome. A downside of using this method is the legitimacy of the citizens who are privileged to be in the committee (Lafont, 2014). Lafont (2015) questioned that non-elected citizens cannot always oversee the considerations of decision makers. In the first phase of the method, the citizens are informed about the issue with written materials. This also includes the stakeholder analysis for the people to understand the perspectives of all focus groups (Dienel, 2002). Afterwards the information is processed through group discussions. From this the groups are cut into smaller groups whom prioritize their interests and identify criteria to analyze the problem (CDPN, 2006). Based on the groups' recommendations a plenary group discussion will take place in which the participants are made aware of the opposed solutions. The results are then incorporated into a finalized report, containing procedures and problems addressed (Garbe, 2006). The method is adapted in this report due to time constraints. Whereas the total group gets together in a total group of 25 people, here multiple smaller groups are used. This can cause for the outcome to be biased towards individuals perception. For example if a local person is involved in property development they put interest in the value of land. This conflicts with people who are involved in agriculture who want to use the land effectively. The questions which are asked to the local people are shown in Appendix E.

F | Transport details

In this section, additional information is provided about three other modes of transportation. At first the water transportation with regards to the inland waterways in the MKD is elaborated. Afterwards, the development plans on railways is shown. Lastly, air transportation is discussed. An overview of these changes is shown in Table F.1. In the table below the changes in land use and processing value are indicated. From this table one can see that there is an expected increase in fruit orchards, aquaculture and multi-purpose agriculture (General Statistics Office, 2019).

Land use	2018	2050	Change	%	Processing value [%]
Triple rice	912,100	387,300	-524,800	- 58	- 34
Double rice	541,100	570,000	28,900	5	-
Aqua (Pangasius)	5,400	10,800	5,400	100	165
Aqua (Shrimp)	494,000	537,550	43,550	9	50
Aqua (Other)	134,000	145,750	11,750	9	44
Pineapple	24,200	32,000	7,800	32	52
Coconut	147,000	194,500	47,500	32	75
Mango	45,000	59,650	14,650	33	75
Dragon fruit	19,200	25,400	6,200	33	75
Other fruit	88,400	88,400	0	0	75
Vegetables	280,000	350,000	70,000	25	113
Rice-Shrimp	177,700	255,900	78,200	44	- 37
Rice-Vegetables	0	150,000	150,000	-	-
Other agriculture	338,500	213,650	-124,850	- 37	-
Forest	192,300	365,200	172,900	90	90
Total	3,399,150	3,386,150	-13,000	0	24

Table F.1: Expected land use changes in the MKD (Royal Haskoning DHV, 2022)

F.1 Water transportation

On the Hau River the DWT, which is accepted by the "Standards of Technical Class of Inland Waterways in", is equal to 5.000 in high tide season and 2.500 during low tides (Mekong River Commission, 2015). Other important national transport routes are the HCMC - Ca Mau route and the HCMC - Kien Luong route which are of grade III for inland waterways standards following Table F.2. There are 2 other canals of grade I (Xa No canal and Cai San canal). Inland waterways of grade II are on the O Mon – Xa No route, O Mon River and Thi Doi canal. Other canals are of lower classification (Can Tho City Statistics Department, 2014).

	Self-propelled vessel			
Class	Weight (tons)	Length [m] 50%/90%	Width [m] 50%/90%	Draft [m] 50%/90%
I	601 - 1.050	44/50	9.0/10.0	2.85/3.1
II	301 - 600	39/42	7.7/8.8	2.50/2.75
III	101 - 300	25/36	6.5/7.5	2.15/2.55
IV	51 - 100	18/22	5.1/5.8	1.80/2.10
V	10 - 50	14/16	3.4/4.4	1.08/1.50
VI	<10	11/13	2.3/2.7	0.65/0.85
	Pushed barge			
Class	Weight (tons)	Length [m] 50%/90%	Width [m] 50%/90%	Draft [m] 50%/90%
I	4 x 400/600	87/92	20.6/22.0	2.55/2.80
II	4 x 400/600	87/92	20.6/22.0	2.55/2.80
III	2 x 200/250/400	80/87	8.5/9.4	2.30/2.80
IV	2 x 100	54/68	6.1/8.0	1.20/1.60
V	N/A	N/A	N/A	N/A
VI	N/A	N/A	N/A	N/A

Table F.2: River Fleet by Inland Waterway Class for 50 and 90 % Load Factors (Mekong River Commission, 2015)

Also smaller ships that use one of the two routes to HCMC are bound to this port. At this port, there are several container terminals present with a throughput volume of nearly 2.1 million Twenty-foot Equivalent Units (TEU) in 2021 (Mekong River Commission, 2015; The World Bank, 2021). Moreover, this has specific emphasis on providing three primary shipping corridors across the delta from east HCMC to west (the northern, central and southern corridors). In the first phrase, Tan Cang – Cai Cui Port can receive ships with a capacity of up to 20.000 DWT (VietnamPlus, 2016). In the area, six ports of significance are indicated (Can Tho, Soc Tran, Tra Vinh, Ba Tri, Cai Mep and Ho Chi Minh City). At the Can Tho port, investments have been made to increase the throughput to 2.5 million DWT (Mekong River Commission, 2015). Also on the Tra Vinh port, developments are in place. This port functions only lower classes with a total expected throughput of 3.7 million DWT (Vietnam News, 2021). Smallest port is the Ben Tre port. This is used by local fisherman to dispence their catch. Therefore the total troughput is 210.000 DWT (VietnamPlus, 2021). The largest operational port in the area lies just outside of the MKD. This Cai Mep port has a total throughput of 21 million DWT (TCIT, 2022). Lastly, the total throughput of HCMC port currently is 10 million DWT (SCG, 2021).

F.2 Railway transportation

Nowadays there is no significant railway transportation network present in the MKD. However, along with the development of expressways, experts also stressed the need to soon form a high-speed railway connecting HCMC – Vietnam's largest economic hub – with the MKD, thereby improving freight transport capacity in the region. Currently, the Ministry of Transport is preparing a pre-feasibility study report for the HCMC – Can Tho railway with a view to starting work on it by 2030. The railway, with a speed of about 190 km/h for passenger trains and 120 km/h for freight trains, could shorten travel times from Can Tho to HCMC to only 75-80 minutes instead of 3-4 hours by road. It is also expected to help reduce traffic congestion in the region (VietnamPlus, 2022).

The high-speed railway project from HCMC to Can Tho will link 2 significant economic zones in the area. In this project, freight trains start at An Binh and Di An stations (Binh Duong). While passenger trains willdepart from Tan Kien station (Binh Chanh) and end at Cai Rang station (Can Tho). The total length for freight trains will be 174 kilometers and passengergers will travel for 140 kilometers. The complete route passes through the provinces of Binh Duong, HCMC, Long An, Tien Giang, Vinh Long, and Can Tho and has 13 stations. With regards to the estimated development demand, by 2030, the passenger demand will be 4.1 million passengers per year. This takes into account a share of around 3% of the passenger transport market. By 2050, passenger demand will be over 22 million, accounting for 8.8% of the passenger transport market. Cargo transport will grow from approximately 5 million tons of goods in 2030, accounting for 0.85% of the market, to 41 million tons of goods in 2050, accounting for 3% of the market (L. Q. Manh, 2020).

The average speed for passengers on the present route is between 60 and 80 km/h. For cargo this average speed is 50 km/h. If the high-speed railway, with a top speed of 200 km/h, goes into service, the cost is projected to be 5-10% more than that of regular rail transit. To maximise the value of the railway, there is suggested that by developing hi-tech industrial parks in proximity to the stations the potential and value of the high-speed rail can be utilized (SaigonTimes, 2022).

This region will have to complete a number of key projects such as Trung Luong – My Thuan – Can Tho, Can Tho – Ca Mau, and Chau Doc – Can Tho – Soc Trang expressways; national highways; the entire coastal route; some important roads connected to HCMC, the Southeastern region and airports (VietnamPlus, 2022). When complete, the My Thuan-Can Tho section will be linked with the North-South Expressway to improve links between HCMC and the MKD, which comprises 13 localities (VNExpress, 2020).

F.3 Air transportation

The current Can Tho International Airport is classified as a IV grade airport, according to ICAO standards (ICAO, 2022). The airport has a 3000 m long and 45 m wide runway which can handle B747-400 airplanes. In total the airport can handle a total of 3 million passengers per year. International routes shall be opened to countries in ASEAN and Northeast Asia (Can Tho City Statistics Department, 2014).

In renovation of the airport the airport improves its capacity to 5 million passengers. Also part of the improvement of the airport is installation of night lighting. Moreover due to the addition of precise landing systems airplanes such as B777-300ER can land at the airport. Therefore, Can Tho can be linked with other countries in the world (ACV, 2019).

G | Transportation model

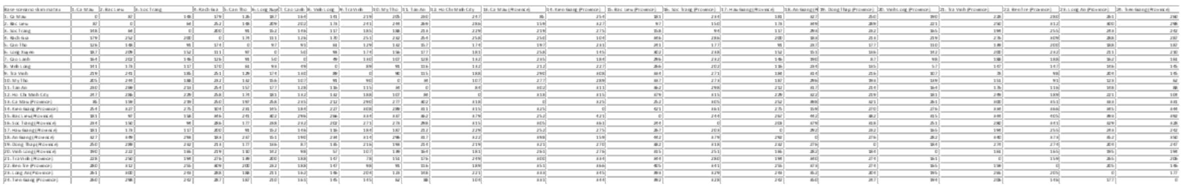
Some tables that were used to determine the traffic model are displayed in this section.

City	Total production	Attraction agricultural land	Attraction other jobs	Attraction port	Total Attraction
Can Tho	1,250,792	113,400	1,300,311		1,413,711
Rach Gia	403,120		419,080		419,080
Long Xuyen	382,140		397,269		397,269
Ca Mau	315,270		327,752		327,752
My Tho	270,700		281,417		281,417
Bac Lieu	240,045		249,548		249,548
Soc Trang	221,430		230,196		230,196
Tan An	215,250		223,772		223,772
Cao Lanh	311,912		324,261		324,261
Vinh Long	200,120		208,043		208,043
Tra Vinh	160,310		166,657		166,657
Kien Giang	1,325,750	460,300			460,300
An Giang	1,522,390	278,800			278,800
Ca Mau	878,620	147,900			147,900
Tien Giang	1,501,840	179,200			179,200
Bac Lieu	673,435	102,800			102,800
Soc Trang	974,310	208,800		1,000,000	1,208,800
Long An	1,498,410	313,300			313,300
Dong Thap	1,288,098	258,900			258,900
Vinh Long	822,850	117,900			117,900
Tra Vinh	849,630	148,000			148,000
Hau Giang	729,780	133,800			133,800
Ben Tre	1,292,400	144,000			144,000
HCMC	9,077,000		9,436,358		9,436,358

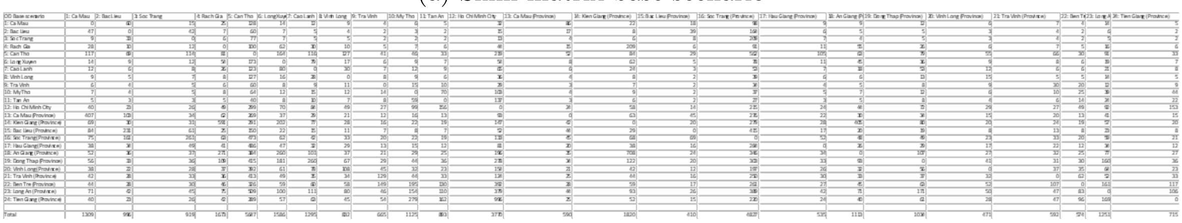
Table G.1: Production and attraction attributes

	Production	Attraction
Can Tho	2,376	2,852
Rach Gia	766	845
Long Xuyen	726	801
Ca Mau	599	661
My Tho	514	568
Bac Lieu	456	503
Soc Trang	421	464
Tan An	409	451
Cao Lanh	592	654
Vinh Long	380	420
Tra Vinh	305	336
Kien Giang (Province)	2,518	929
An Giang (Province)	2,892	562
Ca Mau (Province)	1,669	298
Tien Giang (Province)	2,853	361
Bac Lieu (Province)	1,279	207
Soc Trang (Province)	1,851	2,438
Long An (Province)	2,846	632
Dong Thap (Province)	2,447	522
Vinh Long (Province)	1,563	238
Tra Vinh (Province)	1,614	299
Hau Giang (Province)	1,386	270
Ben Tre (Province)	2,455	290
HCMC	1,724	1,904

Table G.2: Production and Attraction



(a) Skim matrix base scenario



(b) OD matrix base scenario

G.1 Notes on the transport model

Within the model, international bound traffic to Cambodia is not taken into account. As is traffic from and to HCMC. This is to do with limitations in the model. Since the data processed with a student license there is a maximum of 25 centroids within the model. Therefore, external influences are not taken into account.

In addition to this, other developments such as the railway link between Can Tho and HCMC can have significant impact on the model. By taking this into account, the loads on the roads can be lower which causes for lower necessary investments. Moreover, by adding toll fares on the expressways the loads will be lowered. Nowadays a tolls are being levied on the expressways which lowers the load on expressways. Also, these roads are only accessible by car traffic. When other modes are taken into account in the model, specific link uses also need to be elaborated.

Also, the AON assignment method which is used does not take into account congestion on the links. By using an DUE assignment these effects are taken into account on the network. This can significantly increase loads on other links in the network. Since people can choose for other routes if they know that other roads are more likely to congest. In bullet points these recommendations apply for:

- Use cordon model to model external influence;
- Determine average free speed and capacity on location;
- Calibrate model with actual counts;
- Take higher resolution socio economic details into account and determine attraction more specific;
- Higher order of assignment with congestion effects
- Take into account the flow of cargo

G.2 Skim matrices solutions

The travel time savings for each OD pair is shown. When the colour of a cell is more green this indicates a higher travel time saving.

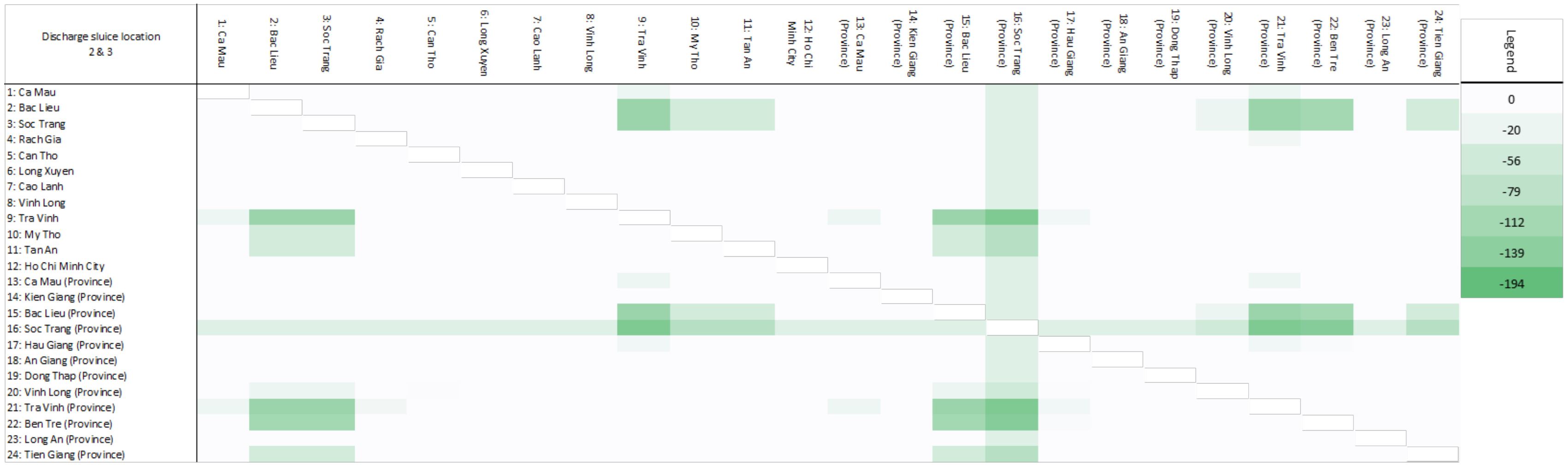


Figure G.2: Travel time savings of skim matrix solution 1 location 2 & 3

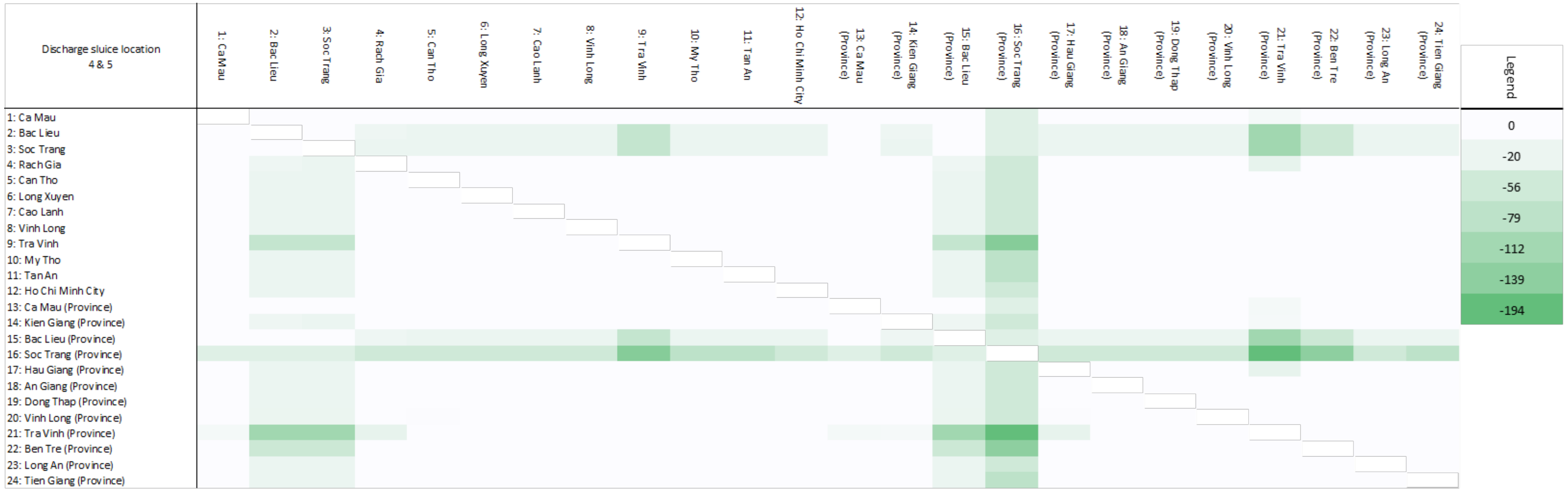


Figure G.3: Travel time savings of skim matrix solution 1 location 4 & 5

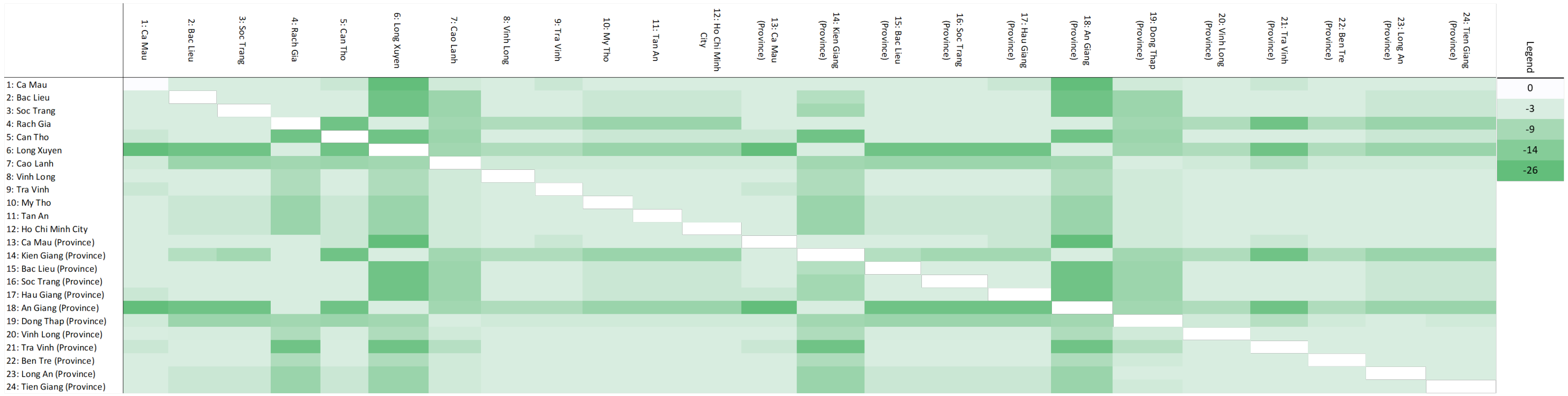


Figure G.4: Travel time savings of skim matrix solution 2

H | Southern Institute of Water Resources Research

In the beginning of this study, talks with Royal Haskoning DHV were planned. It was intended to use some of their hydraulic models to assess the effectiveness of proposed solutions in reducing water levels. Quickly it became clear that they do not run their own models, but hire an external institute to do so. This is the Southern Institute of Water Resources Research. Via RHDHV contact was made with SIWRR. They were found willing to run their one-dimensional models with the proposed solutions. As the institute is located in HCMC and the contact person of SIWRR insisted on meeting in person to discuss the modelling, a one-week trip to HCMC was made.

The first meeting in HCMC was scheduled and there was an agreement on the simulations that would be run. Several scenarios for all solutions would be tested, adding up to 20 model runs in total. Although it was emphasized that it was at the end of the lunar year and only limited time was available to perform these simulations, it was confirmed that this was perfectly possible. However, a day after this meeting the following email was received:

"Dear mr. Gerwin,

After yesterday's meeting, I asked my team in our organization to use the workstation computers for running these scenarios. Unfortunately, they said that all machines are now busy with some urgent projects for our organization. So, I must say so sorry but I could not help you at this time. I saw that your simple model is also quite good for study purposes, or maybe you can use some open-source software for quick simulation of these scenarios.

Best regards,
Vinh."

This setback had as a consequence that simpler models were eventually used to assess the effectiveness of solutions. The advantage of the simpler models is that their inputs are easier to understand and outputs are easier to interpret.

I | Discharge sluice

In the assessment of the structural feasibility of the discharge sluice, several schematisations were made of the design. In subsection 6.1.4 it is argued that vertical opening of the sluice doors is too heavy for the lifting motors. therefore, the horizontal opening system is chosen. A span of 30 meter is chosen, to provide passage for the largest ship size, which is 23.2 meter wide (see subsection 5.4.1). This results in two identical doors with a span of 15 meter and a length of 15.5 meter (see Figure I.1).

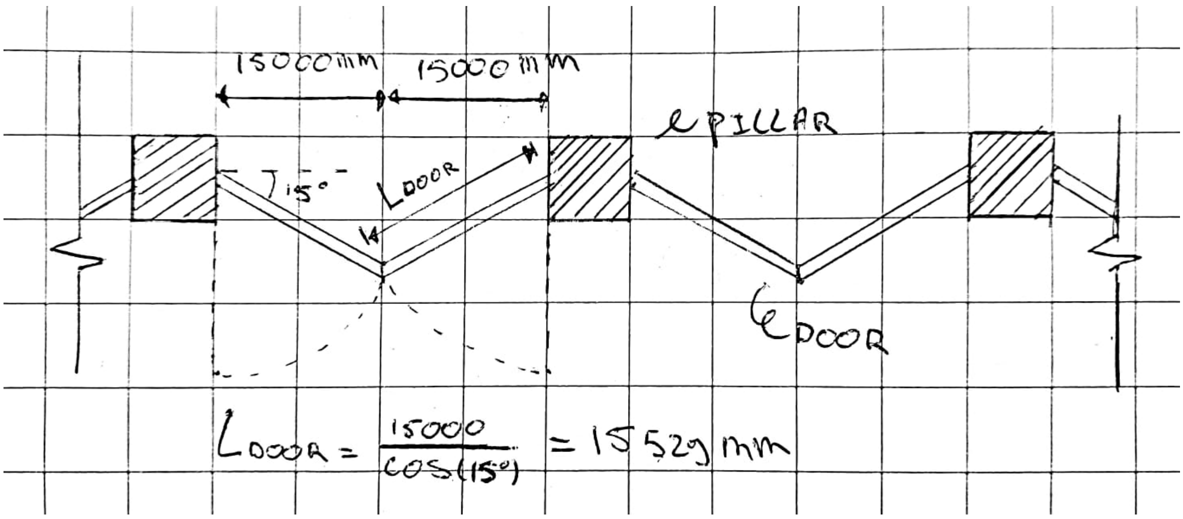


Figure I.1: Schematisation of the discharge sluice top view

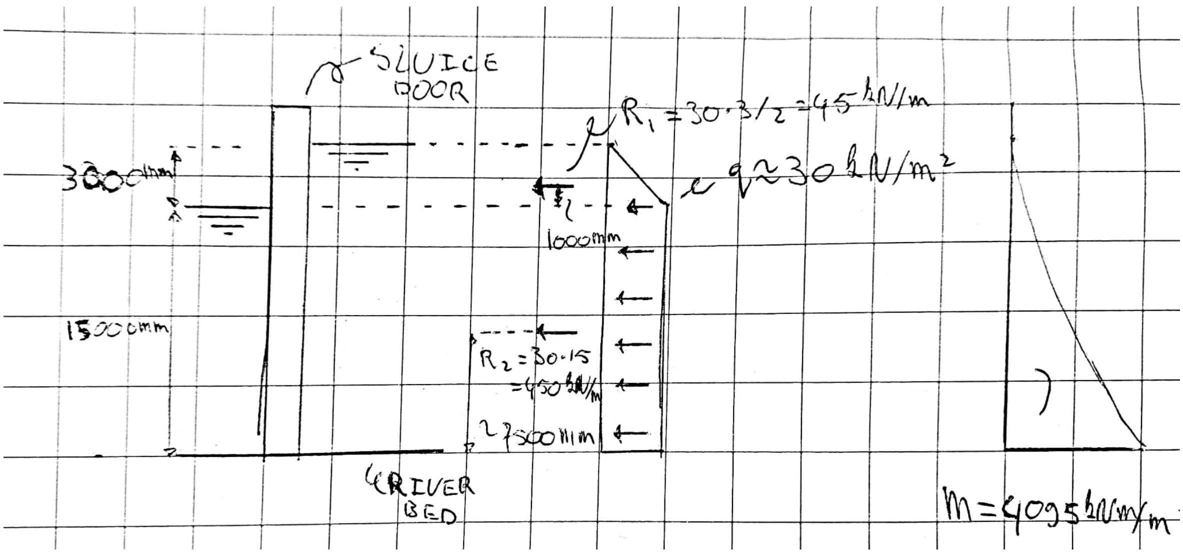


Figure I.2: Schematisation of the discharge sluice side view

A side view of the discharge sluice is illustrated in Figure I.2. An average depth of 18 meter was used for the calculations, based on the bathymetry of the river (see section 3.1). The water difference of 3 meter results in a load of 30 kN/m^2, following from $P = \rho g d$. This pressure results in a horizontal support reaction and a moment at the base of the gate:

$$F_{h,distributed} = R_1 + R_2 = q \cdot \frac{\Delta h}{2} + q \cdot (d_{total} - \Delta h) = 30 \cdot \frac{3}{2} + 30 \cdot (18 - 3) = 495\ kN/m \tag{I.1}$$

$$\begin{aligned} M_{distributed} &= R_1 \cdot \left(\frac{\Delta h}{3} + (d_{total} - \Delta h) \right) + R_2 \cdot \frac{d_{total} - \Delta h}{2} \\ &= 30 \cdot \frac{3}{2} \cdot \left(\frac{3}{3} + (18 - 3) \right) + 30 \cdot (18 - 3) \cdot \frac{18 - 3}{2} = 4095\ kNm/m \end{aligned} \tag{I.2}$$

The two formulae above indicate the support reactions on the gate per meter. Transferring these to the pillars results in the below. Each pillar has to support half the span twice ($L_{span} = 30 meter$), supporting two sluice doors left and right of the pillar. This results in the following forces on each pillar:

$$F_{h,pillar} = F_{distributed} \cdot 2 \cdot \frac{L_{span}}{2} = 495 \cdot 30 = 1.485 \cdot 10^4\ kN \tag{I.3}$$

$$M_{pillar} = M_{distributed} \cdot 2 \cdot \frac{L_{span}}{2} = 4,095 \cdot 30 = 122.85\ MNm \tag{I.4}$$

The weight of the heaviest Oosterscheldekering door is 480 ton, measuring 42 meter in length and 12 meter in height (Steenepoorte, 2016). To get an idea of the weight of the sluice doors in the Hau River discharge sluice, it is assumed that these doors will have the same weight per area. This would result in doors that weigh approximately 300 ton each. In the calculation below the subscript hr represents the Hau River discharge sluice and osk represents the Oosterscheldekering.

$$G_{hr} = G_{osk} \cdot \frac{L_{hr}}{L_{osk}} \cdot \frac{h_{hr}}{h_{osk}} = 480 \cdot \frac{15.529}{42} \cdot \frac{20}{12} = 295.8\ ton \tag{I.5}$$

J | Schematisation wetlands solution

To look in what extent the addition of the wetlands (see section 6.2) would help, a schematisation of the new discharge distribution in the Hau River is made visible.

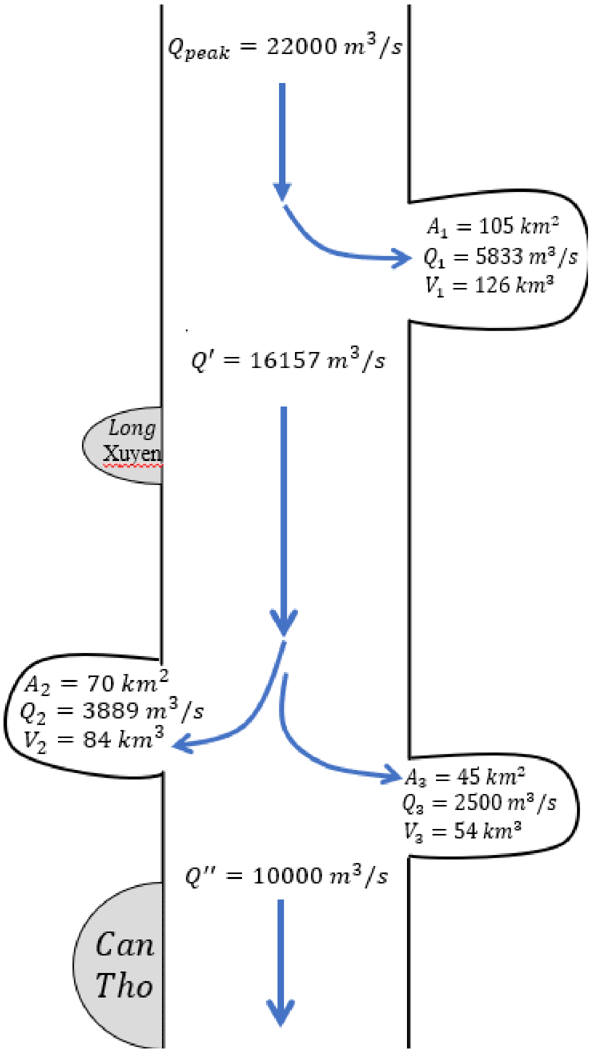


Figure J.1: Schematisation of the Hau River after reestablishing wetlands

K | Best-Worst Method

Following Rezaei (2015) within BWM at first the criteria set is determined. From this set, firstly the most important (i.e. best) w_B and least (i.e. worst) w_W important criteria are assigned. Based on the best criterion a vector is obtained which shows the importance of the Best-to-Others (a_{Bj}). Pairwise comparison is assigned from the values discussed in Saaty (2008). The other way around also a vector Others-to-Worst (a_{jW}) is determined. Based on this data and the min-max method (see equations below) the optimal weights are determined.

$$\min \max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\}$$
$$\sum_j w_j = 1$$
$$w_j \geq 0 \; \forall \; j$$

From this method the consistency of the vector (a_{Bj}) is checked by the equation below. In this equation λ is the maximum value of the equations within brackets above.

$$CR = \frac{\lambda^*}{CI}$$

In Figure K.1 the BWM method for this report is shown.

Criteria Number = 5	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Names of Criteria	Financial	Structural	Hydraulic	Transport	Socio-economic

Select the Best	Hydraulic
Select the Worst	Transport

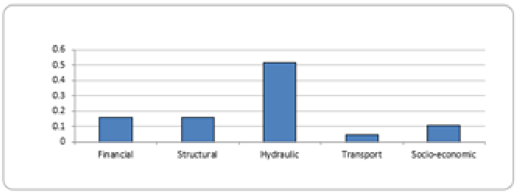
Best to Others	Financial	Structural	Hydraulic	Transport	Socio-economic
Hydraulic	4	4	1	8	6

Others to the Worst	Transport
Financial	6
Structural	6
Hydraulic	9
Transport	1
Socio-economic	4

Weights	Financial	Structural	Hydraulic	Transport	Socio-economic
	0.162162162	0.162162162	0.518918919	0.048648649	0.108108108

Ksi*	0.12972973
CR	0.029

Treshold
0.402



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Building cost	Development cost	Secondary cost	Funding opportunities

Select the Best	Funding
Select the Worst	Secondary cost

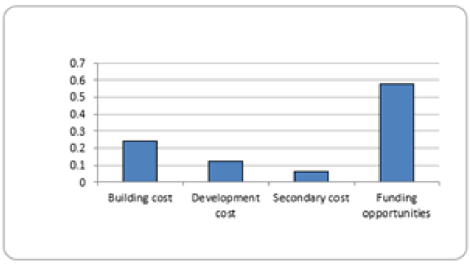
Best to Others	Building cost	Development cost	Secondary cost	Funding
Funding opportunities	3	6	7	1

Others to the Worst	Secondary cost
Building cost	6
Development cost	2
Secondary cost	1
Funding opportunities	8

Weights	Building cost	Development cost	Secondary cost	Funding
	0.238993711	0.119496855	0.062893082	0.578616352

Ksi*	0.138
CR	0.037

Treshold
0.3313



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Figure K.1: Best-Worst Method

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Flooding reduction	Salinity	Fresh water supply

Select the Best	Flooding reduction

Select the Worst	Salinity

Best to Others	Flooding reduction	Salinity	Fresh water supply
Flooding reduction	1	6	5

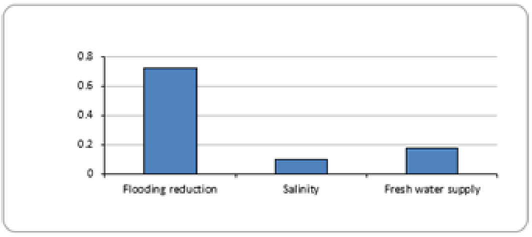
Others to the Worst	Salinity
Flooding reduction	8
Salinity	1
Fresh water supply	3

Weights	Flooding reduction	Salinity	Fresh water supply
	0.728571429	0.1	0.171428571

Ksi*	0.128571429

CR	0.043

Treshold
0.2164



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Criteria Number = 5	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Names of Criteria	Construction time	Complexity	Maintainance	Lifespan	Robustness

Select the Best	Construction time

Select the Worst	Maintainance

Best to Others	Construction time	Complexity	Maintainance	Lifespan	Robustness
Construction time	1	2	8	6	4

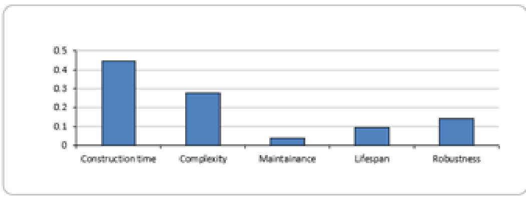
Others to the Worst	Maintainance
Construction time	8
Complexity	8
Maintainance	1
Lifespan	5
Robustness	5

Weights	Construction time	Complexity	Maintainance	Lifespan	Robustness
	0.445595855	0.279792746	0.041450777	0.093264249	0.139896373

Ksi*	0.113989637

CR	0.026

Treshold
0.402



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Travel time savings	Accessibility	Water transport

Select the Best	Travel time savings

Select the Worst	Water transport

Best to Others	Travel time savings	Accessibility	Water transport
Travel time savings	1	3	6

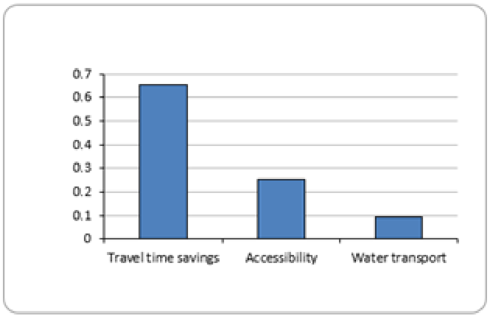
Others to the Worst	Water transport
Travel time savings	6
Accessibility	4
Water transport	1

Weights	Travel time savings	Accessibility	Water transport
	0.654545455	0.254545455	0.090909091

Ksi*	0.109090909

CR	0.036

Treshold
0.2164



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
Names of Criteria	Biodiversity	Building with nature	Tourism	Employment long term	Employment short term	Adaptation

Select the Best	Employment

Select the Worst	Tourism

Best to Others	Biodiversity	Building with nature	Tourism	Employment long term	Employment short term	Adaptation
Employment long	6	5	9	1	3	2

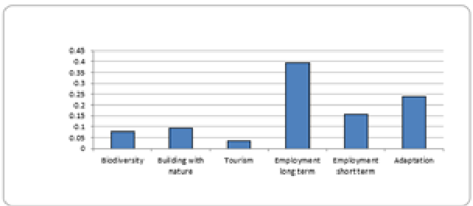
Others to the Worst	Tourism
Biodiversity	3
Building with	4
Tourism	1
Employment long	9
Employment short	7
Adaptation	8

Weights	Biodiversity	Building with nature	Tourism	Employment long term	Employment short term	Adaptation
	0.07941989	0.095303867	0.034530387	0.393646409	0.158839779	0.23825967

Ksi*	0.083

CR	0.016

Treshold
0.4225



a_{BW}	2	3	4	5	6	7	8	9*
Consistency Index (max ξ)	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23