A FEASIBILITY STUDY ON CONSTRUCTING A FLOOD DIVERSION CHANNEL

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Exploring the possibilities of constructing a flood diversion channel between the Mekong River and the Gulf of Thailand as measure to reduce flood risks

Master of Science Thesis Report

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This research is performed to fulfill the requirements of the Master of Science degree in Civil Engineering as set forth by Delft University of Technology, Faculty of Civil Engineering and Geosciences, Section of Hydraulic Engineering, Chair of Coastal Engineering

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Preface

This thesis concludes my Master of Sciences in Hydraulic Engineering with the specialization in the field of Coastal Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology. The graduation was carried out mostly at RoyalHaskoningDHV in Amersfoort, The Netherlands and partly at the Second Base of The Water Resource University in Ho Chi Minh City, Vietnam. The research in this thesis concerns the study on how realistic a flood diversion channel is between the Mekong River and the Gulf of Thailand as measure to reduce flood risks caused by peak discharges coming from the Mekong River.

Firstly of all, I want to thank my whole graduation committee for their interest in the subject and support during my thesis, Prof. dr. Ir. M.J.F. Stive, Ir. G.J. Schiereck Dr. Ir. B.C. van Prooijen and Ir. M. Tonneijck. I especially appreciated the meetings with Gerrit Jan Schiereck who always pushed me in the right direction during the whole course of my thesis. He has also made me well aware that models are nothing more than a tool and should therefore be treated as such. The conversations with Bram van Prooijen were always very inspiring and motivational.

I would like to thank RoyalHaskoningDHV for providing me a pleasant and comfort working environment and giving me the opportunity to visit my study area in Vietnam. In particular, I want to thank Johan Henrotte for his daily support and valuable tips. My special thanks are for Dirkjan Douma for his continues support, motivation and dedication to finalise this report. I want to also give a specially thank to Gerard Pichel. Thanks to him I got a wonderful field and boat trip, I will never forget how enthusiastic his stories were.

I also would like to thank Mr. Bao, head of the Water Resource University in Ho Chi Minh City for providing me with an excellent working space and their effort in helping me to collect data. Also I want to thank the many conversations with Mr. Mai van Cong for helping me to understanding the problems within the Delta.

Above all I would like to thank my mother Siam H. Heng and sister SuChun Lin who always supported me. A special person who I want to thank is miss Pim Kalf for giving me the confidence in finalising this thesis.

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ChuHui Lin
Delft, July 2013

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Summary

The yearly floods of the Mekong Delta caused by the Mekong River have been considered a blessing; it purifies the agricultural lands and deposits a fresh layer of silt on the surface, which keeps the delta fertile. However, the growing demand for agricultural products internationally and nationally has pushed the farmers to harvest all year long, which has lead to a situation where the floods are more of a curse than a blessing. Besides the growing agricultural demand, the continuous urbanization has also caused the yearly flood to become less accepted. Furthermore, it is expected that the flooding problems will only increase even more in future due to climate change.

A possible solution to reduce the frequency of flood risks is by constructing a flood diversion channel between the Mekong River and the Gulf of Thailand. The purpose of this flood diversion channel is to reduce the water level of the Mekong River during high water preventing it from flooding. The question is, if a flood diversion channel is a realistic measure to achieve this objective and to reduce flood risks.

A feasibility study divided into two parts has been made, to find out how realistic a flood diversion channel, as measure is to reduce flood risks. The first part of the study is to find out what the required technical conditions are for constructing a flood diversion channel. The second part of the study concentrates on the question whether the effects of sediment deposition by the flood diversion channel into the Gulf of Thailand prohibits the construction of a flood diversion channel. An impression of the flood diversion channel is given in Figure 0-1. Also several important cities and rivers of the Mekong Delta are highlighted in this figure.

Figure 0-1 An impression sketch of a diversion channel route from the Lower Mekong river to the Gulf of Thailand along with several important cities and rivers of the Mekong Delta.

The Mekong Delta can generally be described as a relatively flat area with two main river branches, the Tien River and the Hau River and more than hundreds of smaller lateral or parallel irrigation channels. Predominantly clay particles can be found in the top soil-layer of the delta. Rather low concentration levels of suspended solids are found within the Mekong River. The foreshore where the flood diversion channel debouches into the Gulf of Thailand is rather shallow and muddy. Close to the coastline where the flood diversion channel can debouche the touristic island Phu Quoc is situated, which is known for its white sandy beaches. The touristic island may not be harmed or influenced by the flood diversion channel.

The first part of the feasibility study concentrates on the required technical conditions of a diversion channel. To study the technical feasibility it is necessary to first identify the acceptable water levels of the Mekong River. A Sobek model has been used to determine the required withdrawals from the Mekong River. The found withdrawals are used as design criterions to calculate the dimensions of the flood diversion channel. Two extreme channel types have been considered: the first channel type is a shallow channel and the second type is a deep channel. For both channel types a rough cost estimate has been made to find out what the cost magnitude is for constructing a flood diversion channel. The results of the first part of the feasibility study indicate that both flood diversion channels are capable to lower the water levels of both main river branches and to reduce flood risks under current high water situations. However, when the discharge increases due to future climate changes are taken into account, the study shows that the diversion channel as measure is only suitable to lower the water level within the Hau River branch of the Mekong River and not for both branches. This is because the withdrawal necessities to lower both the river branches are too significant, additional measures are then needed. The preferred diversion channel type is to construct a deep channel. The cost analysis shows that although the initial costs of a deep channel are higher, in the long run this solution can become cheaper than a shallow channel.

The second part of the feasibility study is to find out what the consequences are if any of the sediment deposition are deposited on the foreshore close to the discharge location or near the touristic island Phu Quoc. By first identifying what kinds of sediment types are discharged into the Gulf of Thailand and what the concentration levels are, it is possible to study the coastal impact. The coastal impact is first studied using simple conservative hand calculations to identify if significant sedimentation can be expected. However, these hand calculations are based on static conditions. Therefore, a Delft3D model is used to determine what the sedimentation consequences are under dynamic conditions. The results of the second part of the

feasibility study showed that the sediment type is classified as fine silt and that the sediment concentration levels during a high water event are very low. Even with the smallest sediment size and a conservative sediment concentration level it is not possible to affect the coastal zone of the island Phu Quoc. Deposition of sediment close to the discharge location could cause an impact onto the near coastal zone. However, the current state of the near shore coastline shows that the effects of sediment deposition would most probably not prohibits the construction of the flood diversion channel. The deposition of sediment near the discharge location could even be a welcome effect of the flood diversion channel if it debouches at the Middle location, because the current coastline near the Middle location show signs of erosion.

The conclusion of this feasibility study is that a flood diversion channel can be a solution to reduce current flood risks caused by the Mekong River. However, when future climate changes are taken into account the diversion channel is only sufficient to reduce the increased flood risk of the Hau River; additional measures are necessary to also lower the water level of the Tien River. The concern of sediment deposition at Phu Quoc is unjustified. Deposition of sediment near the shore of the discharge location can even have a positive side effect for the eroding coastline. The preferred flood diversion channel is to construct a deep channel of approximately 70 km long and depending on the withdrawal necessities the width of the channel will be between the 340 and 680 meters. The flood diversion channel withdraws at Chau Doc, goes along the Vinh Te[i] channel for as long as possible and crosses the K. Tam Ngan channel to eventually discharge at the Middle location into the Gulf of Thailand see Figure 0-2.
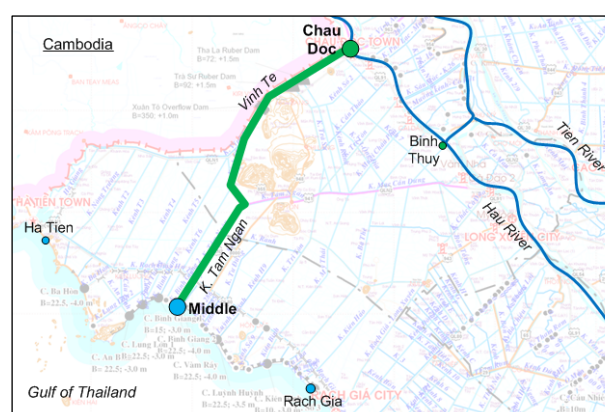

Figure 0-2 Preferred diversion channel route

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[i] *The Vinh Te channel is one of the largest existing irrigation/drainage channels within the Long Xuyen Quadrangle. The channel is located along the border between Vietnam and Cambodia. The uniqueness of this channel is that along one side of the riverbanks limited area are currently occupied by housing or industries.*

Table of Content

1.   Introduction

The Mekong delta is located at the southern tip of Vietnam (see Figure 1-1). This delta is one of the largest rice production areas in the world. The yearly floods of agricultural land caused by the Mekong River have been for years considered as a blessing for the Delta. The floodwaters purify the agricultural land leaving a fresh layer of silt behind which keeps the delta fertile, increases fishery resources, flushes out contaminated acid sulphate soils, improves navigational transport and so on.

Figure 1-1 Vietnam

However, several developments are threatening the natural balance in the Mekong Delta. These developments are gradually making the blessed yearly floods to change into a curse.   The first development is the growing demand for agricultural products in the delta. This high demand for agricultural products (e.g. rice or fruits) has pushed the farmers to increase their production capacity. Farmers used to harvest a single (rice) crop each year during the dry season, combining it with fish farming during the flood periods. Nowadays farmers are pushed to harvest at least three (rice) crops a year to cope with these growing demands. The crops harvests during the wet season are unfortunately highly vulnerable against long periods of floods. A second development is the growing population and urbanization. Flooding of people's livelihoods and infrastructures are becoming less acceptable especially in growing urban cities. The third development is the expectation of the increase of discharges coming from the Mekong River caused by climate change. The prediction is an increase of the frequency and magnitude of the seasonal high water peaks, which ultimately will affect the whole Mekong Delta and tampers any economic growth expectations.

A measure to cope with the developments in the Mekong Delta is formulated by the Dutch consultancy company RoyalHaskoningDHV. The measure is to construct a flood diversion channel between the Mekong River and the Gulf of Thailand to reduce flood risks caused by the aforementioned developments. However, it is uncertain if a flood diversion channel is a realistic option to consider as a flood risk measure. In this thesis a feasibility study is made to find out how realistic this measure is. Two elements are studied to determine the feasibility of a flood diversion channel. The first part of this feasibility study is to find out what the required technical conditions are to construct a flood diversion channel. The second part of this study is to find out whether the effects of

discharging sediment rich floodwaters into the Gulf of Thailand prohibit the construction of the flood diversion channel.

The first paragraph of this chapter provides an overview of the important features of the Mekong Delta. The problem identification and objective of this study is presented in paragraph 1.2. The final paragraph of this chapter shows the outline of this thesis.

1.1.   *Overview of the Lower Mekong Delta*

The Mekong delta is an area of approximately 3.9 million hector acres (ha). Compared to the total area of the Netherlands the size of the Mekong Delta is roughly the same. This paragraph briefly describes the outline of the Mekong delta. Figure 1-2 highlights the important features of the delta such as rivers and cities. These highlighted points are frequently referred to in this thesis.
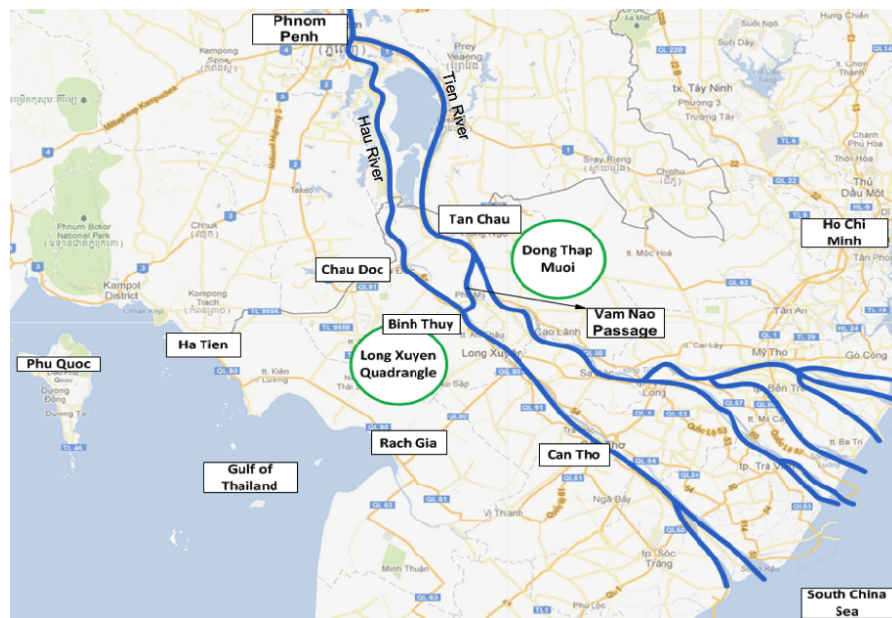

Figure 1-2 Overview of the important features of the Lower Mekong river and delta.

Lower Mekong River

The Mekong River bifurcates at the city Phnom Penh. This city, located in Cambodia is approximately 120 km upstream of the Cambodia-Vietnam border. The bifurcation of the Mekong River results in two main rivers systems:

- *Tien River*: the northern branch of the Mekong River *(also called Mekong River).*
- *Hau River*: the southern branch of the Mekong River *(also called Bassac River).*

The Mekong River enters the Mekong Delta through two river branches and crosses two cities upon entering the Delta. The northern river branch is the Tien River and flows through the city Tan Chau upon entering the Delta *(Approximately: 185.000 inhabitants,* (Wikipedia The Free Encylopedia*)). The second river branch is the Hau River and flows

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through the city Chau Doc *(Approximately: 115.000 inhabitants,* (Wikipedia The Free Encylopedia)*)*. Further downstream, the two river branches encounters the Vam Nao Passage, which re-connects the Tien River with the Hau River. This connection starts close to Tan Chau and connects with the Hau River at the city Binh Thuy. The discharge ratio between the Hau and Tien River during a high water event is approximately 20% to 80% respectively. Downstream the Vam Nao passage the discharge ratio between the two river branches becomes almost 50/50 divided. (Nguyen & Savenije, 2008).

The expectation is that Can Tho city located further downstream along the Hau River will become economically important in the future. This is due to industrialization and urbanization; which will develop the city into the largest city of the Mekong delta.

Flood plains

During the wet season high water levels caused by large discharges can overflow the Mekong River banks. The two main inundation areas are:

- *Long Xuyen Quadrangle (LXQ):* this is an area around 440.000 ha. located at the northwest of the Mekong delta.
- *Dong Thap Muoi (DTM):* is located at the north side of the Mekong delta with an area of approximately 560.000 ha *(also called Plain of Reeds).*

The combined area of these flood plains together is around 1 million ha, which is roughly 25% of the total Mekong Delta. Nowadays these two areas are predominantly used as rice cultivation areas with a production rate of two to three harvests a year.

Gulf of Thailand

The flood diversion channel debouches into the Gulf of Thailand somewhere along the coastline between Ha Tien and Rach Gia. These two cities are the larger cornerstone cities of the Long Xuyen Quadrangle area. In the two cities tourism flourishes as it serves as a passageway for boat or plane trips towards the island Phu Quoc, which is situated approximately 50km offshore of Ha Tien and 120km of Rach Gia. This offshore island Phu Quoc is very touristic and famous for its white sandy beaches.

1.2. *Problem Identification*

Developments like growing demand for agricultural products, the decreasing acceptance for flooding in urban cities and future expectations on higher discharges caused by climate change will tamper any growth perspective of the Mekong Delta. To assure further economic growth of the delta, flood control safety measures are therefore necessary.

A recommended and well-received measure is to divert the Hau River branch of the Mekong River towards the Gulf of Thailand during a high water event. The shortest way

to the Gulf of Thailand is through the Long Xuyen Quadrangle flood plain. By lowering the water level in the Mekong River flooding can be prevented. However, it is unclear if this measure is a realistic option to consider. Uncertainties exist on which dimension and route such a diversion channel should have. It is also unknown whether the effects of sedimentation caused by discharging onto the coastal zone prohibit the construction of such a flood diversion channel.

1.2.1. *Research objective and question*

The research objective of this thesis is to find out how realistic the construct a flood diversion channel is to reduce flood risks in the Mekong Delta by means of a feasibility study. Two elements are studied to determine the feasibility of a flood diversion channel. The first part of the feasibility study is by studying what the required technical conditions are of a flood diversion channel and second whether the effects of discharging sediment rich water into the Gulf of Thailand prohibit the construction of a flood diversion channel.

Based on the objective the main research question is:

How feasible is it to construct a flood diversion channel between the Mekong River and the Gulf of Thailand to reduce flood risks caused by the Mekong River?

To find an answer to the main research question four sub-questions have been formulated.

1. *What is the minimum required withdrawal of the flood diversion channel to reduce flood risks?*
2. *What is the required dimension of the flood diversion channel to withdraw the required withdrawal from the Mekong River?*
3. *What are the costs of constructing a flood diversion channel?*
4. *What is the impact of discharging sediment rich floodwater into the Gulf of Thailand?*

1.3. *Outline Thesis*

This thesis has the following structure to find answers to the sub-research questions. Chapter 2 provides an overview of the available background information of the current natural situation in the Long Xuyen Quadrangle and of the adjacent coastal zone.

In chapter 3 the first aspects of the feasibility study is researched namely the determination what the required technical conditions need to be for a flood diversion channel. The required technical condition depends on what the maximum allowable water level is within the Mekong River. The study in this chapter starts by determining what the minimum withdrawal level is using a known high peak event as design event and secondly the required withdrawal when taking future climate changes into account. These found withdrawals are then used as the design criteria for the dimensions of the

flood diversion channel. In the third paragraph of chapter 3 a rough costs estimate is made to study what the required costs are for constructing a flood diversion channel. The study performed in this chapter provides an answer to the first three sub-questions.

The intermediate conclusions that can be made based on the results of chapter 3 are:

- If the withdrawal location have influence on the required withdrawal.
- If the measure is also sufficient as flood risk control to cope with climate change.
- What the dimensions are of the considered flood diversion channel options.
- What the estimated costs are to construct a flood diversion channel.
- What the preferred flood diversion channel type is.

In chapter 4 the second aspect of the feasibility study is researched namely to find out whether the discharge of significant amount of sediment rich floodwaters into the Gulf of Thailand prohibits the construction a flood diversion channel. To determine the coastal impact it is necessary to first identify what the sediment type and concentration levels are which will be discharged into the Gulf of Thailand and second the possible discharge locations. The coastal impact is studied first by simple conservative static hand calculations to identify the expected significance of coastal sedimentation. Afterward a more detailed Delft3D model is used to determine if the expected sedimentation are found under dynamic conditions. The study performed in this chapter provides an answer to the last sub-question.

The intermediate conclusions that can be made based on the results of chapter 4 are:

- What the possible discharge locations are of the flood diversion channel.
- If the concern of sediment deposition caused by the construction of a flood diversion channel is justified.
- If near shore sedimentation caused by the flood diversion channel prohibits the construction of a flood diversion channel.
- What the preferred route and discharge location is for the determined preferred flood diversion channel type.

The final paragraph of this thesis provides the conclusions on how realistic it is to use a flood diversion channel between the Mekong River and the Gulf of Thailand as measure to reduce flood risks. Besides the conclusions the final chapter also provides several recommendations for follow-up studies.

2. Description of the Lower Mekong River and Delta area

In 1975 Galloway categorized the Mekong delta as a mainly tide-dominated system, influenced by wave and fluvial behaviour. He classified the Mekong delta somewhere in the lower middle of his graph see Figure 2-1.

The Mekong River, the Delta and the coastal area are further elaborated in this chapter to provide background information. The current natural situations are qualitatively described and,

if possible, quantitatively supported. The focus in this chapter is the west side of the

Figure 2-1 Galloway's delta classification chart

delta because the diversion channel will cross through the Long Xuyen Quadrangle and discharge in the Gulf of Thailand.

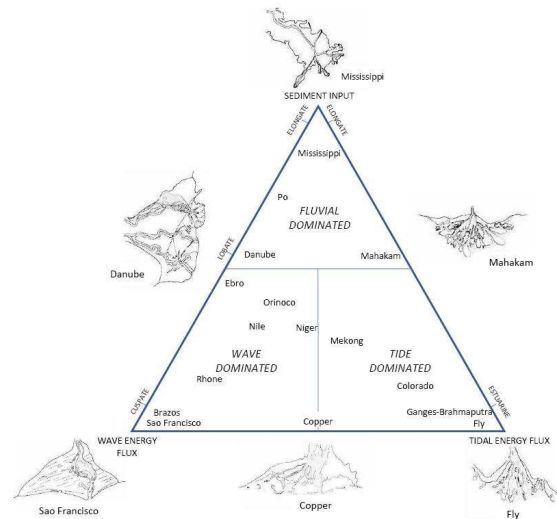This chapter is divided into two sections: the first section considers the situations on the mainland and the main river system. The second section elaborates on the western coastline of the Mekong delta.

2.1. Mainland

This paragraph provides a general outline of land use, topography and existing water infrastructure on the mainland. Additionally, a description is given of the sediment environment in the main river as well as the soil conditions in the Long Xuyen Quadrangle area. The last two sub-paragraphs of this paragraph gives information about the hydrological water flows into the Long Xuyen Quadrangle area.

2.1.1. Topography

The land elevation of the Mekong Delta varies between +0.5m to +3m relative to msl (mean sea level). In the north (-west) areas of the delta, the land elevation is around 3m above msl and decreases when travelling down towards the eastern and southern coastline (Son, 2005). Approximately 60% of the Delta is situated under the 1m topographic heights against msl. To generalize, the land elevation of the Mekong Delta decreases with the highest point in the northwest and lowest point in the southeast. There is an exception to this generalization, which is the Dong Thap Muoi area at the north side of the delta near the border of Cambodia and at the east side of the city Tan

Chau. Due to the bathtub shaped topography, it is defined as a closed inundation area. Water cannot exit the area freely therefore this area is most affected by flooding during the wet season (see paragraph 2.1.7).

The Long Xuyen Quadrangle is an open inundation area as floodwaters drains through the dense drainage channel systems towards the Gulf of Thailand. The land elevation near the Hau River is around 2m above msl and decreases rather abruptly to a topographic land level of 1.5m above msl. After the abrupt decrease the topography follow a gentle decreasing land level towards 1m above msl. Near the coastal area the land elevation decreases even more, namely to a land level of 0.5m above msl.
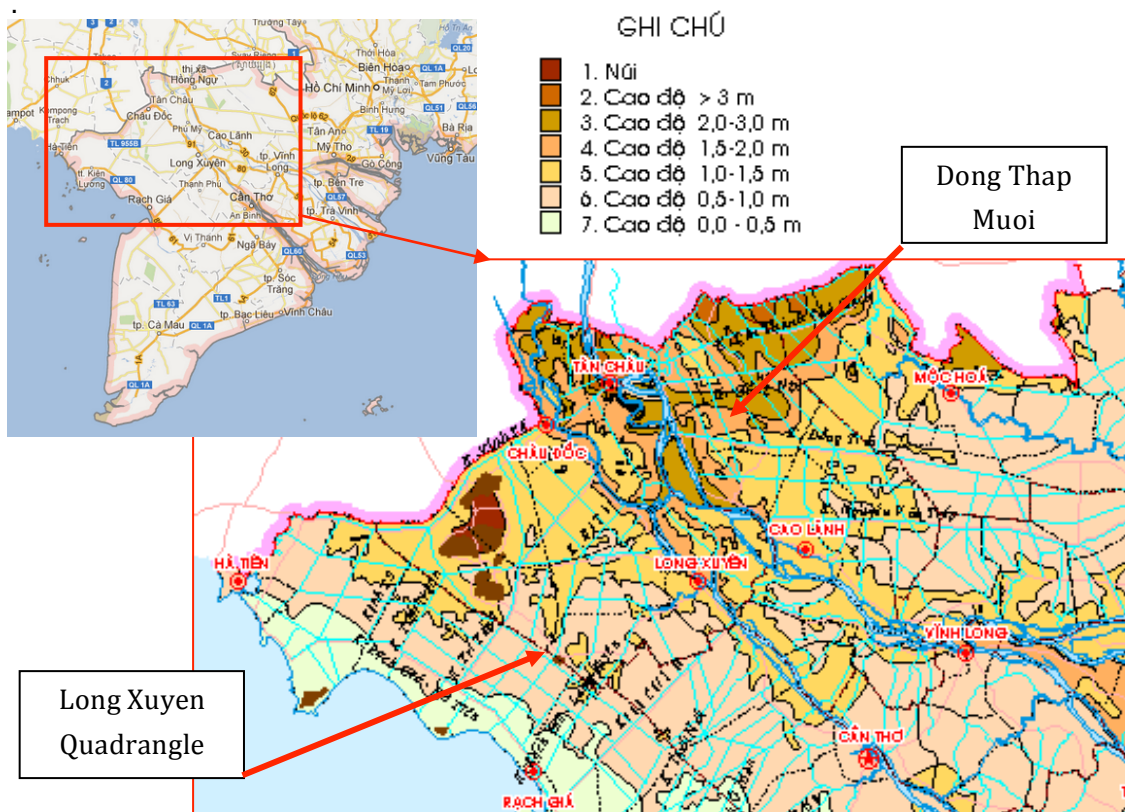

Figure 2-2 Depth topography of Long Xuyen Quadrangle and Dong Thap Muoi area

2.1.2. *Land Use*

The growing demand of land products has led to intensification of agricultural land and aquatic farming. Rice is the most predominant land cultivation product in the Mekong delta. Starting from year 2000 the frequency of production has increased from two to at least three crops of harvests a year. In some areas where only once a year crops of rice can be gathered, the farmers are combined their production with aquatic farming.

In Figure 2-3, the existing land use of the delta in 2009 is shown. Most of the land is used for rice cultivation; the light yellow colour indicates at least two harvests a year and dark yellow three harvests of rice a year. Red indicates fruit cultivation, which is more confined to the south of the flood plain areas in the lower regions of the Tien and Hau

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River. Adjacent to the coastline, at the west side of the Long Xuyen Quadrangle the area is used for brackish and salt-water aquacultures, which is indicated with the colour pink.

Throughout the two flood plains the Long Xuyen Quadrangle and Dong Thap Muoi, small green spots can be seen which indicates the production of forests. Furthermore, fresh fish farming not shown in the figure is cultivated along the upper region of the Tien and Hau River.
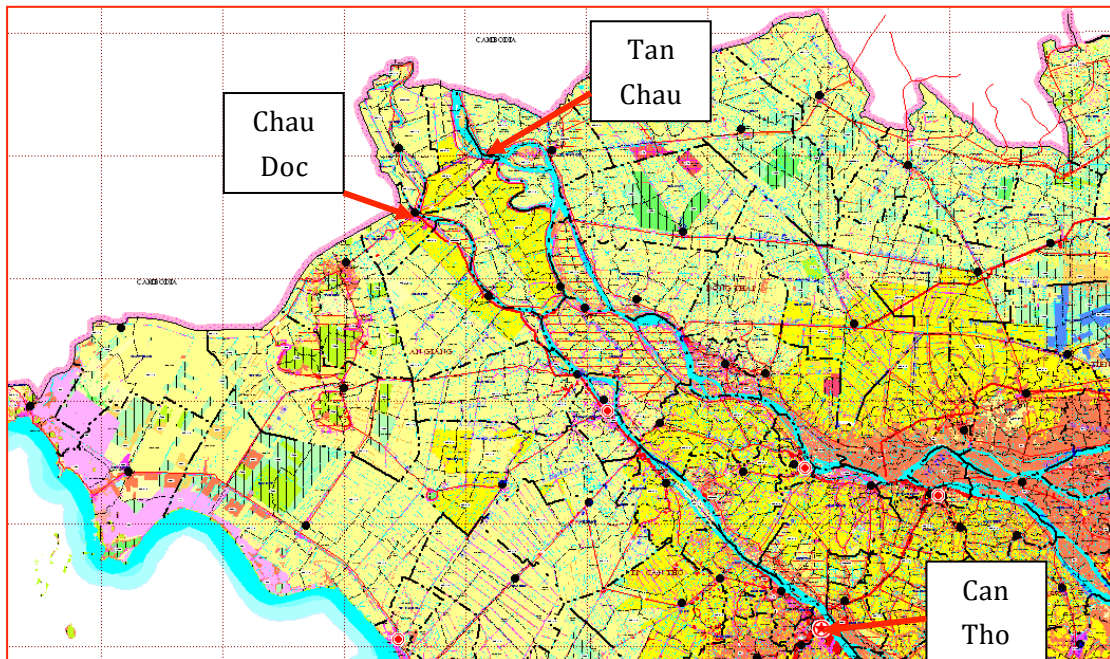

Figure 2-3 - Existing land use in year 2009

2.1.3. *Soil composition on the mainland of the Delta*

Alluvial soil types are most commonly found at the riverbanks between the Tien and Hau River. The top layer of the soil consists predominately of clay and sand throughout the Mekong delta. In general this top layer has a thickness between 20 to 50 m. Under the top layer, the soil consists of (marine sandy) clay (Son, 2005). In areas far from the main river overflow which are not drained by channels, the sediment consists of typically organic-rich mud and peat formed by local vegetation (Hashimoto, 2001)

Throughout the Mekong Delta soils are mostly contaminated with acid sulphate due to the transition from dry to wet periods. This mechanism can be explained as follows: these soils already contain acid. The soil enhances acidification in the surface layer by intense heating of the sun. When early rainfall occurs, water dissolves the toxic sulphates in the surface layer and seeps together with the rainwater into the soil spreading the toxic even more.

Farmers, use the annual high water event to replenish their agricultural land. The yearly flooding dilutes the toxic top layer. Moreover, sedimentation of fresh silt from the river

helps to cover the toxic land with fertile grounds (Son, 2005). Mild inundation is therefore not a problem; it is the high water event, which causes nuisance.

2.1.4. *Sediment Environment in the Lower Mekong River*

At the upper reaches of the Lower Mekong River, the flow velocities are relatively high compared to the middle and lower parts of the river. Therefore, the characteristics of the river bottom are relatively coarse sandy sediments. In the middle reaches of the Lower Mekong River the channel sediments are typically medium to coarse sand. Sediments in the lower reaches of the river, close to the mouth, are typically fine sand with variable admixtures of silt and clay.

Sediment deposits near the mouth of the river are seasonal dependent. In the wet season, most suspended sediments flow out into the sea and flocculate upon encountering salt seawater. In the dry season sediment depositions occur within the river channels due to the effects of saline water intrusion.

In general the grain size decreases with an increase of distance from the river. Silt and fine sand are commonly confined to the levee crest. However, clay particles can travel extensive areas. (Hashimoto, 2001)

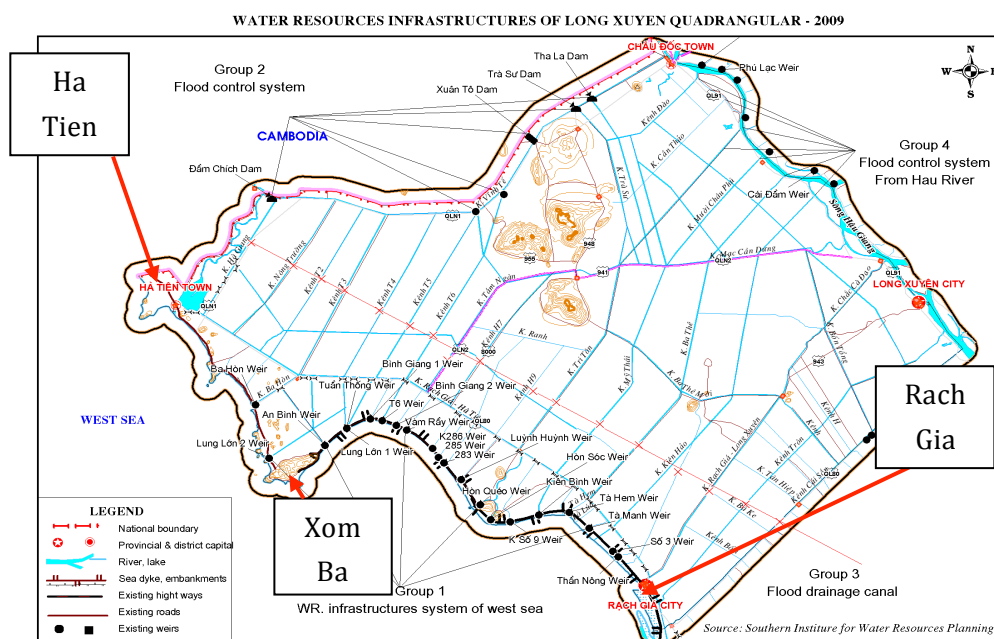## 2.1.5. *Existing Irrigation Channels*

Figure 2-4 - Existing water infrastructure in the year 2009 (Area: Long Xuyen Quadrangle)

Dense networks of irrigation channels already exist in the Mekong Delta see Figure 2-4. The cross-sectional size of these channels varies. The irrigation channels are used for fresh water supplies for agricultural purposes during the dry season. In addition, the irrigation system also serves as the main way of transporting products (mostly agricultural) to households and industries, for they are situated closely at the banks of

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these channels. These irrigation channels also serve as drainage channels during the wet period. High water events are as good as possible drained through theses irrigation channels to the Gulf of Thailand. The largest channels have a surface width of approximately 50m and a depth of approximately 4m. The average discharge of such a larger channel is approximately 250m^3/s during wet period. In appendix C.3 the diversion discharge of several existing larger channels are evaluated. It shows that the combined capacity of the existing drainage channels can divert approximately 1000m^3/s.

Small black dots in Figure 2-4 represent weirs or sluices. Sea dikes are used to protect the lower areas along the coastline between Xom Ba Tra and Rach Gia from coastal erosion. In paragraph 2.2.1 a more detailed description of the coastline can be found.

2.1.6. *Hydrological flows into the Long Xuyen Quadrangle*

Water can enter the Long Xuyen Quadrangle in several ways: by rainfall, by overflows of the Mekong River or by land overflow from the border with Cambodia. These three ways of hydrological water flows are further elaborated in this paragraph.

As mentioned, two distinct periods can be defined within the Mekong delta: the dry season, which is between November and March, and the wet season starting from May and last until September. The months May and October are the so-called transition periods in which the climate changes from wet to the dry season or visa-versa. The two distinct seasons are characterized by significant differences in the amount of rainfall and main river discharge, which in turn determines if land gets inundated due to land overflow. The change in dry and wet periods is caused by the monsoon system. The effect of the monsoon system is further explained in paragraph 2.2.2.

Rainfall

Rainfall is not evenly distributed over the delta region. The average amount of rainfall is approximately 1800mm. On the main land the precipitation is around 1400mm (blue) at the west of Long Xuyen Quadrangle a precipitation level of approximately 2000mm can be expected (indicated by yellow/orange), see Figure 2-5.

The amount of precipitation is also not evenly spread during a year. Almost 90% of the yearly precipitation pours down in 6 months, namely during the wet season

Figure 2-5 Rainfall isoline chart

which is (as mentioned earlier) between May and October. The heaviest rainfall is from July until October. Deu to the heavy rainfall an increase of the water levels occurs which
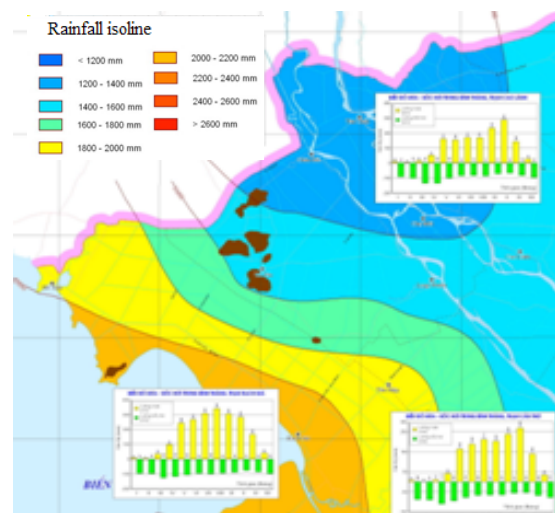
cannot flow to the south china sea in time and cause the flooding of the floodplains (Deltares & Delta-Aliance, 2011).
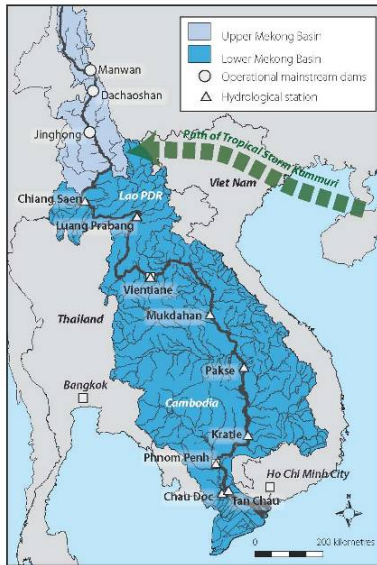
Mekong River

Figure 2-6 Catchment area Mekong River

The Mekong River has a catchment area of approximately 0.8 *10^6 km^2 (Jansen, 1979). The catchment area is almost 20 times the surface of the Netherlands.

The Mekong River Commission (MRC) which is a joint organization of the countries Cambodia, Lao PDR, Thailand and Vietnam has measured the discharge and water levels but only until the city Kratie. This city is located in Cambodia upstream the large lake Tonle Sap. The lake is of importance to the flood situation in Vietnam, because it acts as a buffer against large peak discharges. The average yearly peak discharge at Kratie is on average around 40.000m^3/s (Mekong River Commission, 2012), which is more than double the yearly average discharge at the border between Cambodia and Vietnam.

Downstream measurements are available from KOICA a Korean water institute. Figure 2-7 shows the yearly average discharge of each month based on data gathered from 1977 till 1999. The measurements are taken at the border between Cambodia and Vietnam. On average, the yearly discharge is just over 13000m^3/s.
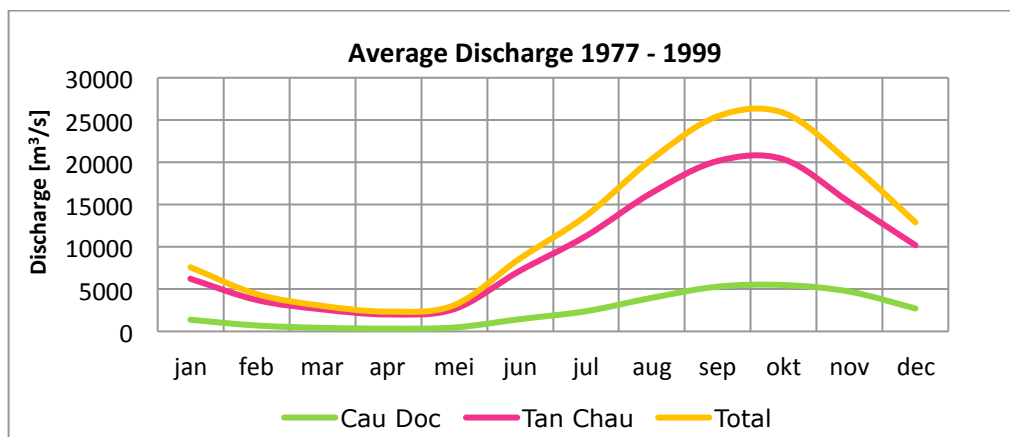

Figure 2-7 Average Mekong River Discharge 1977-1999 (MRCS & KOICA)

Approximately 2400m^3/s, which is almost 20% of the total yearly discharge flows in the Hau River through Chau Doc city. The other 80%, approximately 9800m^3/s, flows in the Tien River through Tan Chau city.

In the past the Mekong Delta has encountered extreme situations. A well-known high water situation is that of the year 2000. Peak discharges at Chau Doc and Tan Chau were measured, namely 7660 m³/s respectively 25500 m³/s during that high water event. This means that the total discharge that flows through the border was around 32500m³/s (Elizabeth Claire-Ashton, January 2005)

Land overflow

Besides rainfall and discharge from the main river system, water can also enter the Long Xuyen Quadrangle due to land overflow at the Cambodian and Vietnamese border. At the border embankments have been constructed to prevent overflow of water entering the Mekong Delta. At two locations along these embankments rubber dams have been placed to control the flood. The dams are called Tha La and Tra Su; see Figure 2-8 for pictures of the Tra Su dam.

Figure 2-8 Tra Su rubber dam. Right picture shows water flowing over the inundated rubber dam. Left picture shows the rubber dam inflated during the dry periods

Both dams are constructed on a sill. The concrete sill has an elevation of +1,50m together with the rubber dam the peak height of the dam is at +3.80m. The length of the Tha La dam is 70m for of the Tra Su dam 90m. (Hydraulic Engineering Consultants Corporation No.II) Because of political reasons Vietnam is obligated to deflate the rubber dams once a year to let floodwater from Cambodia to flow into Vietnam territory. The exact amount of discharge due to land overflow is unknown. It is also hard to determine an average discharge, because no detailed information is given on how floodwater is collected behind the dam on the territory of Cambodia.

2.1.7. *A historical flood occurrence*

In the year 2000 extreme rainfall and an early start of the wet season caused severe flooding. Large amount of water flowed uncontrolled into the two before mentioned flood plains Long Xuyen Quadrangle and Dong Thap Muoi shown in Figure 1-2. In Figure 2-9 the inundation of year 2000 is graphically shown. Based on the findings from Haruyama (Haruyama, 2011), the 2000 high water event occurs once in the 25 years, see appendix B.1 for the return period graph. The range of inundation in most areas is around 2-3m. The most heavily struck area is on the northwest side of the Dong Thap

Muoi floodplain. The inundation here was around 4m and at some locations along the border more than 5m was measured.
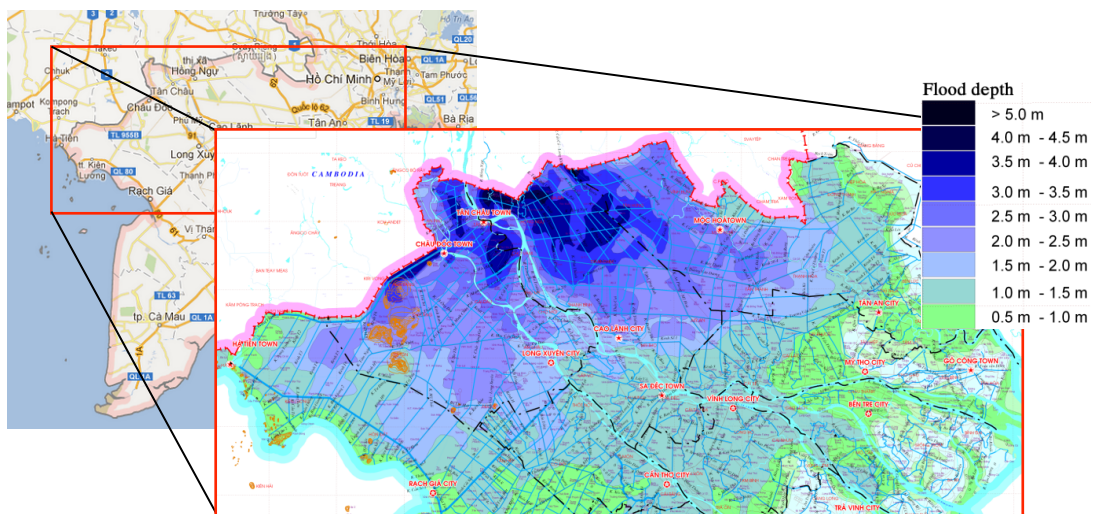

Figure 2-9 Maximum inundation flood disaster year 2000

High water event such as that of year 2000 caused lots of casualties mainly children and older people. One of the reasons for these casualties is because the ability to swim in Asian countries -despite their tropical nature- is not a common skill to be taught. Also long inundation of land causes disease to spread easily and a shortage of food and proper drink water increase the casualties related to flooding.

2.2. Coastal

The Mekong delta is situated very close to the equator, but is still on the Northern Hemisphere, see Figure 2-10. Due to the delta shape it is adjacent to two different oceans, which results in the unique situation. The east coast of the Mekong delta is adjacent to the southeast sea, whereas the west coast is adjacent to the Gulf of Thailand.

The natural coastal effects at the east coast are more dynamic than the west coast of the delta. The east part of the Mekong delta is not further elaborated because this area is beyond the scope of this thesis. On the west side, the Gulf is relative to the South East Sea rather shallow

Figure 2-10 Depth Contours Gulf of Thailand in [m] (Fang, 1998)

with the deepest point located in the middle of the Gulf, which is roughly 90m below msl.

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In the next sub-paragraphs an overview of the near shore situation is sketched out. First the coastline of interest is discussed and then the nearby offshore area. After that, a further elaboration is given on monsoons and tides influencing the west coastal area.

2.2.1.   *Coastline & adjacent offshore description*

This paragraph qualitatively describes the coastline adjacent to the Gulf of Thailand to determine which areas along that coastline should be avoided. Several site visits towards the coastline, sources like Google earth and charts have been used to formulate this quantitative description.

The shortest route for the diversion channel to discharge into the Gulf of Thailand is located somewhere between the two corner cities of Long Xuyen Quadrangle. These two cities are Ha Tien, which is the city close to the Cambodian border and Rach Gia. The coastline is approximately 110km long. The coastline counts approximately 20 irrigation channels which discharge into the Gulf. These channels are closed off from the sea by weirs or sluices to prevent salt water to penetrate into the mainland during the dry season when water supply is low. Along the coastline 5 cities are situated see Figure 2-11, re-location of these cities will be a costly option. Therefore, it is necessary to take these cities into account when designing the diversion channel. A brief description is given of the cities along the coastline from left to right.

Figure 2-11 Coastline Vietnam adjacent to the Gulf of Thailand

1. **Ha Tien**: is built around a natural river mouth close to the border with Cambodia. Small harbours for fishing boats are active in this area. The city also provides ferry services to the touristic Island Phu Quoc. *(Approximately 40.000 inhabitants,* (Wikipedia The Free Encylopedia)*)*
2. **Ba Hon**: the numbers of inhabitants in this city are unknown. Judging from Google earth this city is four times smaller than Ha Tien. It is built around a small drainage channel.

3. **Xom Ba Tra**: is a city that is situated at the tombola shaped part of the coastline between mountainous areas. Close to this city a small stone quarry is present. This city is slightly larger than Ba Hon but smaller than Ha Tien.

4. **Huynh Son**: is the smallest of the five cities. Like Ba Hon, the city is built around a drainage channel.

5. **Rach Gia**: is the capital of the Kien Giang province (this is where the flood plain Long Xuyen Quadrangle lies in). It is also the largest city of the five cities discussed here. The city has a longitudinal shape and is partly built around a river mouth. From this city it is possible to get a ferry towards Phu Quoc. This city also has a small airport. *(Approximately: 225.000 inhabitants,* (Wikipedia The Free Encylopedia)*)*

To sum up, the coastline between Ha Tien and Rach Gia can be roughly divided into two kinds of coastlines. It is the tombola shaped coast where the city Xom Ba Tra is situated which divides the coastline in these two types. On the left or west of Xom Ba Tra, low natural dunes characterize the stretch of coastline. The hinterland of this area is used for salt aquaculture activities (about 30km landwards). In front of these natural sea defences small band of sandy to muddy beaches can be found. Judging by the photo impression given in Figure 2-12 the foreshore looks quite shallow.

Figure 2-12 Photo impression coastline Ha Tien to Xom Ba Tra (source Google Earth)

The coastline between Xom Ba Tra and Rach Gia on the east or right side of Xom Ba Tra is protected with stone sea dike defences. This protection is needed, because the coastline is retreating *(personal interview Prof. Tri, Can Tho University).* The hinterland here is most commonly used for agriculture activities. Only a small band (approximately 10km or so) is used for aquatic cultivation. At the seawards side of the dike defences small mangrove rehabilitation areas have been created. The purpose of these mangrove areas are to demonstrate if planting mangroves can reduce the erosion rate of the coastline. Judging by the photo impression given in Figure 2-13 a muddy foreshore exists here.

Figure 2-13 Photo impression coastline Xom Ba Tra to Rach Gia (source Google Earth)

Offshore island Phu Quoc:

The most touristic place in this area is located 50 km away from Ha Tien offshore in the Gulf of Thailand. The name of this island is Phu Quoc and has a total land area of 574 km². The reason this city is so touristic is because it has white sandy beaches, clear seawater, some coral reefs and several natural parks. The economy drives on tourism and also on the production of its famous fish sauce and the cultivation of black peppers. The island receives about 280,000 tourists each year (Tourist Information Phu Quoc Island, 2012) & (Moreno, 2011)**.**

2.2.2. *Monsoon influence*

The Mekong Delta is located in a region affected by monsoons. This means that in this region, large sea breezes coincide with the significant difference between the heating and cooling of earth and water masses. This natural phenomenon is briefly described in the intermezzo.

Intermezzo: Monsoons

During the warm months of the year, land temperature heats up faster than that of the oceans. The difference is caused by the way (conduction or convection) elements increase in temperature. Due to the rise in temperature gasses above major land areas, like China, expand causing a low-pressure area. Over the ocean temperatures are mild which result in a high-pressure area. Sea breezes, brings moist air from the oceans towards land. Once passing over warm land the moist air rises and falls back towards the ocean. However, during the rising movement air-cools down and its ability to hold water decreases, causing rainfall overland. This is called the wet (summer) monsoon. During a dry (winter) monsoon this cycle is reversed as the land cools down faster than oceans.

For the Mekong Delta the large earth mass area is Asia, which includes areas like China. The water mass is the South East sea which includes the Gulf of Thailand. There are two distinctive monsoons; the wet (summer) monsoon which causes heavy rainfall and consequently more river discharge. The dry (winter) monsoon causes periods of draught and little rainfall. In the Mekong Delta the North-Eastern (N-E) monsoon coincide with the dry (winter) monsoon and starts from November until April. The

second monsoon is the South-Western (S-W) monsoon and coincides with the wet (summer) season and starts from May until October.

2.2.3. *Tidal characteristics at the coastline*

The Water Resource University (Second base in Ho Chi Minh City) collects and documents water level data from one tidal station, which is located in Rach Gia city. Figure 2-14 shows the measurements of the water level made in the year 2000 between 1 August and 30 October.
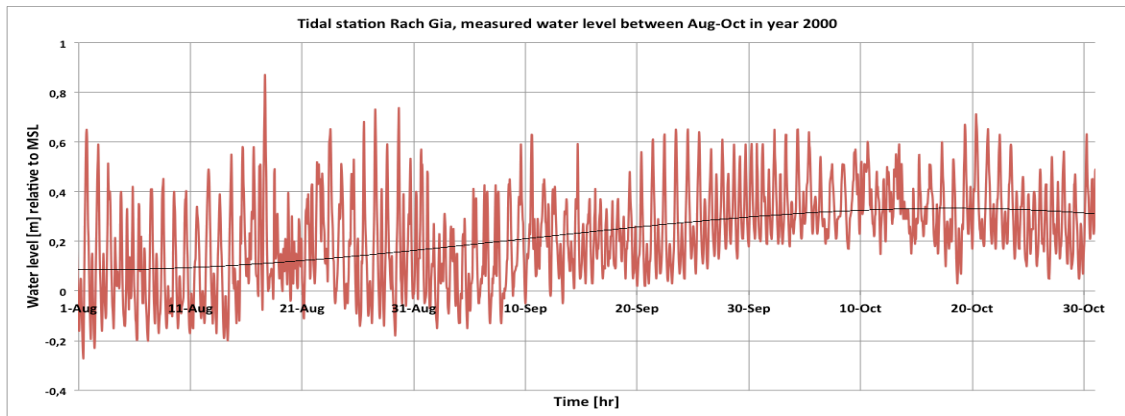

Figure 2-14 Tidal variation measured at Rach Gia in year 2000 from Aug until Oct (Source: (The Water Resource University, 2012))

A trend line is drawn through these measurements. Judging from the trend line the mean sea levels at Rach Gia are affected by a certain kind of set-up in the months August, September and October. The active monsoon system, which at this time of the year is perpendicular towards Rach Gia bay, is not the cause of this set-up in water level. Measured seasonal changes in mean sea level shows an overall decrease of the msl during the S-W monsoon months see Figure 2-15.
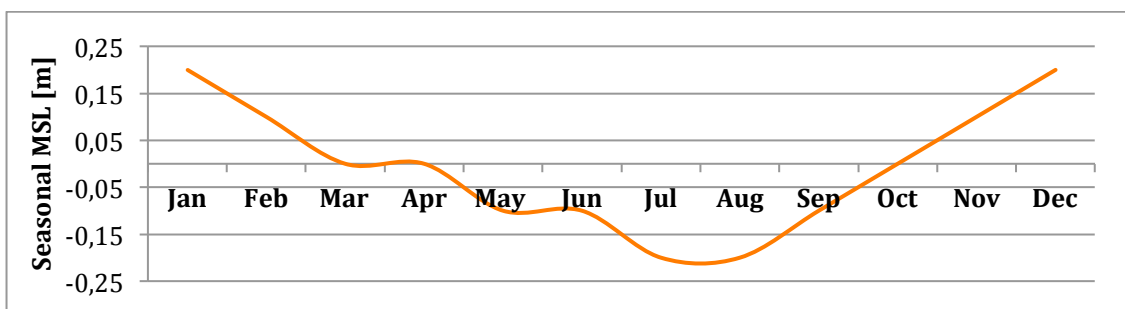

Figure 2-15 Seasonal Change of the Mean Sea Level

The reason for this decrease in water level is due to the fact that the monsoon winds are covering the whole South East Sea. Water is drawn from the relatively seen small Gulf of Thailand against the monsoon winds raging over the South East Sea. This monsoon wind causes a decrease in water level in the Gulf of Thailand. The water set-up seen in Figure 2-14 must therefore be caused by local wind set-up into the funnel shaped Rach Gia Bay.

To characterise the tide at this coastline the f-number can be calculated. This number expressed by: dividing the declination tides with the principal tides to gain a dimensionless ratio value called the f-number. Based on information gathered by two tidal stations the following f-numbers can be calculated. The tidal stations are Ha Tien and Tammassu Island somewhat 40km offshore from Rach Gia. The f-number gives a value that determines if the tide is diurnal or semi-diurnal. Values to calculate the f-number are gained from the observed values of Fang (Fang, 1998) and are based on Admiralty Charts.

The basic equation is:

$$f = \frac{K_1 + O_1}{M_2 + S_2}$$

<div align="right">(Eq. 2-1)</div>

- Ha Tien station: $f = \frac{0,26 + 0,13}{0,10 + 0,02} = 3,25$ this value is larger than 3 which mean that tide is diurnal.

- Tammassu Island station: $f = \frac{0,28 + 0,15}{0,11 + 0,06} = 2,53$ this value lie between 1,5 and 3 which means a mix type but predominantly with diurnal tides.

Both f-values confirm that the tide at the West of the Mekong delta is predominantly diurnal.

A closer look at the tidal signal during the month August is shown in Figure 2-16. During August, the tidal signal is mixed but predominantly diurnal which confirms the calculated f-number. The maximum tidal range is in the order of 1m, with 0.7m HHW and -0.2m LLW both against msl.
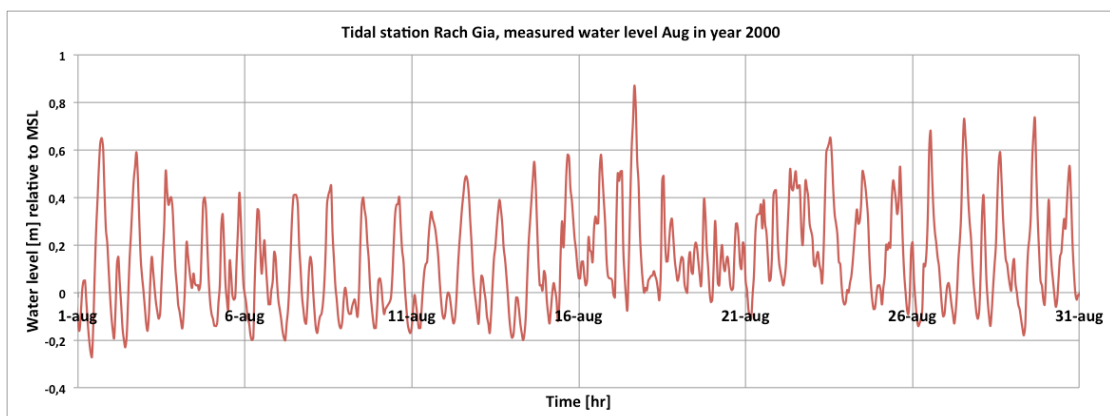

Figure 2-16 Measured water level at Rach Gia in August 2000

3. Studying the required technical conditions

The main purpose of this thesis is to determine if the construction of a flood diversion channel is a good enough measure to prevent unwanted flooding of the Mekong Delta. The first main objective of this thesis is to determine what the required technical conditions are of a flood diversion channel to reduce flood risk caused by the Mekong River. The study made in this chapter provides answer to the first three sub-questions. These question where in short: " What is the minimum required withdrawal", "What is the required dimension of the flood diversion channel" and "What are costs of constructing a flood diversion channel". The second main objective of this thesis is to determine if coastal impact would prohibit the use of a flood diversion channel which provide answer to the forth sub-questions, this second objective is studied in chapter 4.

Chapter 3 is divided into four paragraphs in which is studied if a flood diversion channel is technically seen a realistic solution to reduce flood risk caused by the Mekong River. The dimensional requirements of a flood diversion channel depends on the necessary withdrawal to lower the water level within the Mekong River to an acceptable water level of which a flooding can be prevented during a high water event. In the first paragraph of this chapter a study is made to determine what this withdrawal necessity is. Data of a recent high water event has been used and also effects of future climate changes have been taken into account that increases the discharge within the Mekong River. First, it is determined what the acceptable water level is within the Mekong River and second if withdrawal locations can have a positive influence on the withdrawal requirement. This withdrawal requirement study is made in paragraph 3.1 of this chapter and provides an answer to the first sub-question.

Based on the determined necessary withdrawal the flood diversion channel can be dimensioned. This flood diversion channels can have arbitrary dimensions however for this study two extreme dimensions are considered. Each of the extreme dimensions has a distinct advantage. The first possibility is a shallow but wide channel with the advantage that agricultural land does not get lost. The second possibility is a deep but narrow channel with the advantage that the channel can also be used as a shorter trade route between Cambodia and the Gulf of Thailand. The aim of this second paragraph is to identify what the necessary dimensional requirement is to withdraw the withdrawal requirements determined in paragraph 3.1. Paragraph 3.2 provides an answer to the second sub-question.

Following the determined withdrawal necessities and the calculated required dimensions of a flood diversion channel the cost aspect is considered. By making a rough costs estimate it is possible gain a general indication of the order of magnitude of the

project costs and to compare these costs of the two flood diversion channel types. The rough cost estimate is made in paragraph 3.3 of this chapter and provides an answer to the third sub-question.

The final paragraph sums up the main conclusions made in this chapter. The paragraph provide an intermediate conclusion on if a flood diversion channel is technically possible and which flood diversion channel type is the most realistic and preferred option to construct based on the results.

3.1. Withdrawal requirements

The withdrawal requirement depends on what the acceptable water level limit is and how significant the discharge is within the Mekong River. This paragraph consists of three sub-paragraphs.

The firsts sub-paragraph provides an overview of the available data and determines the acceptable water level limits within the Mekong River. Sub-paragraph 3.1.1 also considers how significant the influence of climate change is on the discharge in the Mekong River. Sub-paragraph 3.1.2 provides the methodology on how to determine the minimum withdrawal requirement and identifies possible withdrawal locations. Sub-paragraph 3.1.3 determines the minimum withdrawal of the flood diversion channel and the required withdrawal caused by an increase of discharge due to climate change scenarios.

3.1.1. Relevant background information

This sub-paragraph gives relevant background information of the Mekong River, which is used to determine the minimum and required withdrawal.

Available datasets

Minimal detailed data is available on water levels combined with discharges and cross-sections of the Mekong River. Therefore, an in-depth study of the possibilities of a flood diversion channel is not possible.

Discharge & Water Level

The available data on discharge coupled with water levels in the cities Chau Doc and Tan Chau are between 1996 until 2003. On average, the yearly discharge is just over 13000m^3/s. From the available data only the flood year of 2000 was an extreme high water event with a discharge of approximately 32500m^3/s at Phnom Penh and water levels of +4.8m against msl at Chau Doc and +5.02m against msl at Tan Chau. Figure 3-1 shows that the total duration of the year 2000 high water event was approximately 2 months with a peak discharge period of around 1 week.
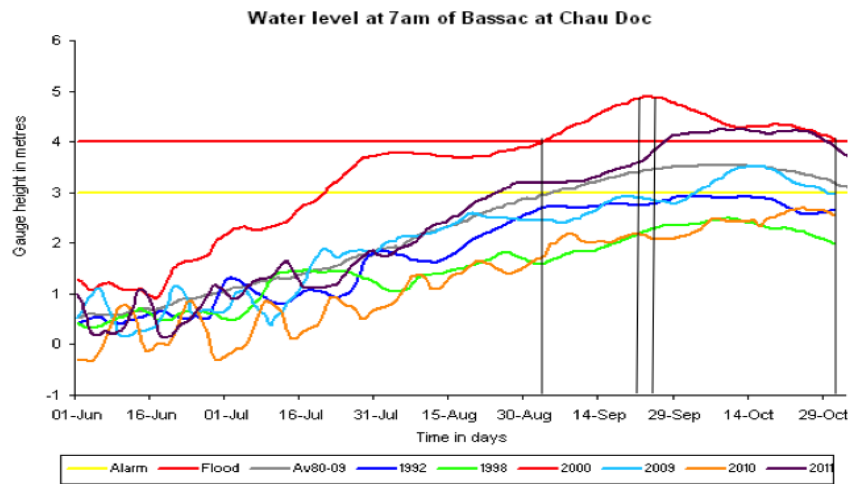
Figure 3-1 Water level in the Hau River at Chau Doc in time given by the Mekong River Commission

Studies made by Japanese researches indicated that the highest water level recorded at Chau Doc during the flood of 2000 had a return period of once in the approximately 25 years see Figure 3-2 (Haruyama, 2011). The correctness of this information is unspecified. The lack of data prohibits making own probabilistic calculations to validate the return period given by the Japanese researches.
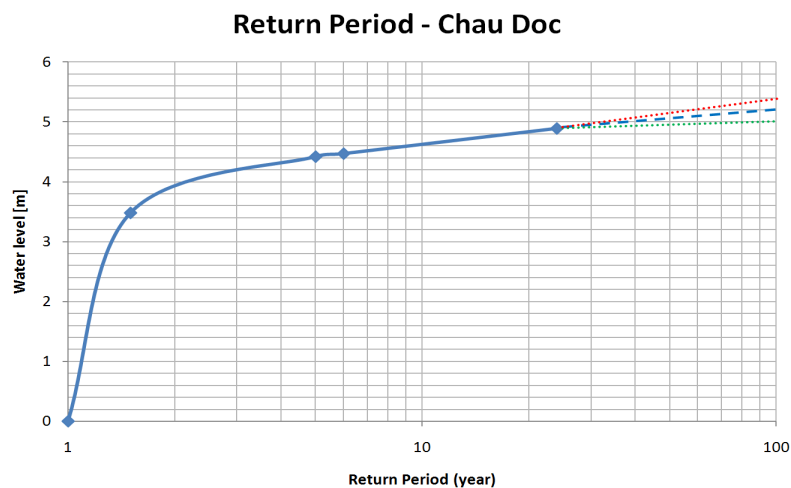

Figure 3-2 Return period based on information from Haruyama, 2011

Mekong river cross-sections and water distribution

The cross-sectional information is also minor, there are in total 5 cross-sections available and only from the upper part of the lower Mekong River. These cross-sections are given for the places Phnom Penh, Koh Khel, Neak Luong, Chau Doc and Tan Chau. What is also known is how the discharge is distributed between the Hau and Tien River during a high water event. Research made by A.D. Nguyen in 2008 showed that during a high water event the water distribution between the Hau and Tien River, just after Phnom Penh, is divided respectively 20% and 80%. After the reconnection of the Hau and Tien River by the existing Vam Nao passage the distribution among the two channels are approximately 50% and 50% (Nguyen & Savenije, 2008).

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Acceptable water levels of the Mekong River

The acceptable high water levels are the water levels whereby the necessary floods to flush the toxics from the agricultural lands are still possible. Any water levels above the acceptable water level will cause unwanted flooding of land. During the dry-season the water levels in the Mekong River fluctuates around msl. Only in the wet-season water levels in the Mekong River can reach water heights, which can cause unwanted flooding. The Mekong River Commission (MRC) has determined water level limits that are still allowed within the Mekong River. These acceptable water level are called the flood level limits by the MRC see Table 3-1. The water levels are shown in meters and are against msl. Unwanted flooding occurs if the Hau River at Chau Doc has a water level higher than 4m and if the water levels in the Tien River are higher than 4.5m at Tan Chau.

	Flood level limits [m]
Chau Doc	4
Tan Chau	4.5

Table 3-1 Flood level limits determined by the Mekong River Commission

Influence of Climate change

The concept of climate change is that due to change in climate the frequency of occurrence of a given discharge will increase. The consequence is that the extreme events would have more chance to occur. As mentioned earlier the lack of detailed information prohibits the use of probabilistic calculations to determine the discharge frequencies. However, it is possible to make a study based on expected climate change scenarios. Two future climate change scenarios are described in the Mekong Delta Plan (Dick Kevelam & Project Team, 2012). The first scenario is called the moderate scenario. This moderate scenario indicates that because of climate change high water peaks will increase with 15%. The second scenario is called the high scenario. This high scenario indicates that because of climate change high water peaks will increase with 25%. The validity of these two scenarios (15% and 25%) is unknown. Other studies made by the MRC and other institutes such as the Vietnam National Institute of Meteorology, Hydrology and Environment shows an increase between 5% and 40% of the high water peaks. While the extent of the effects of climate change are not agreed upon, a consensus exists that climate change will have a major impact on the wetness in the wet season.

The Southern Water Institute for Resources Research (SWIRR) has made flood inundation charts of the delta influenced by climate change. Figure 3-3 shows the inundation expectations of the moderate and high climate change situations. Most likely the climate change inundation figures are based on the situation of the high water event of year 2000, because the highest water event measured in that area in the last decade is that of year 2000. No further information is published on how they have determined these figures and on which discharge situation they have made their presumptions.
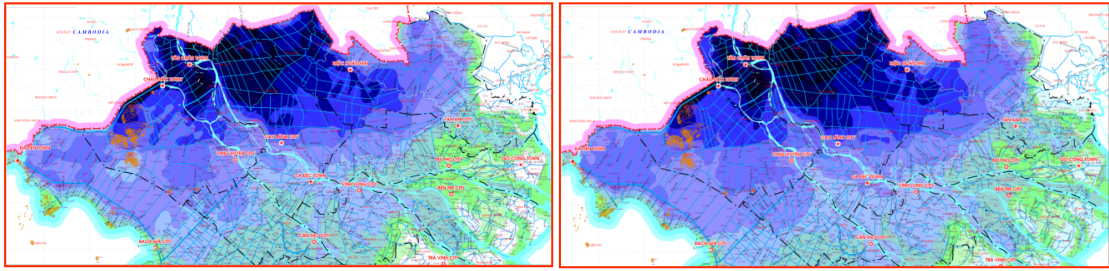
24

Figure 3-3 Maximum inundation, moderate situation (left) and high situation (right)

If the definition "high water peak" is equal to the event of year 2000, climate change will result in the following future discharge scenarios:

Most extreme peak discharge - year 2000	Discharge based on **Moderate** climate change event +15%	Discharge based on **High** climate change event +25%
32500 [m3/s]	*37375 [m3/s]*	*40625 [m3/s]*

Table 3-2 Increase of high water peak due to climate change

3.1.2. *Methodology to determine the minimum withdrawal*

This sub-paragraph gives the methodology used to determine the minimum design withdrawal of the flood diversion channel. In addition to the minimum design withdrawal this sub-paragraph also determines the necessary withdrawal for a moderate and high climate change situation.

Withdrawal locations and alternatives

The flood diversion channel withdraws from the Hau River branch of the Mekong River, with the purpose to lower the water level at the city Chau Doc and Tan Chau to an acceptable water level as described in the previous sub-paragraph. The most logical location is to withdraw as far upstream as possible, this is at Chau Doc city. However, the location Binh Thuy can have an advantage too, because it can withdraw directly from the Tien River through the existing Vam Nao passage. The withdrawal points are indicated by red dots in Figure 3-4.
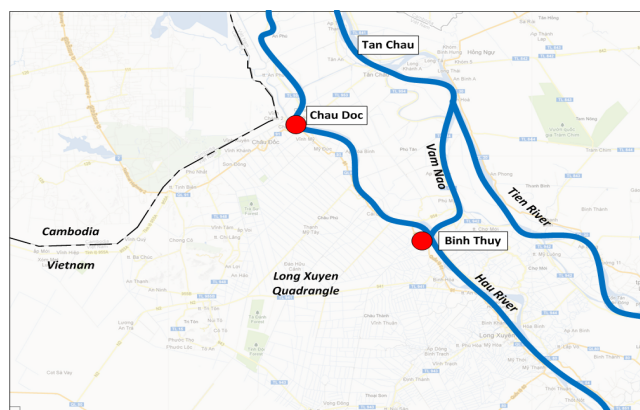

Figure 3-4 Withdrawal points location shown with the red dots

For this study three withdrawal alternatives are formulated based on two withdrawal locations. Figure 3-5 shows schematically the three withdrawal alternatives.
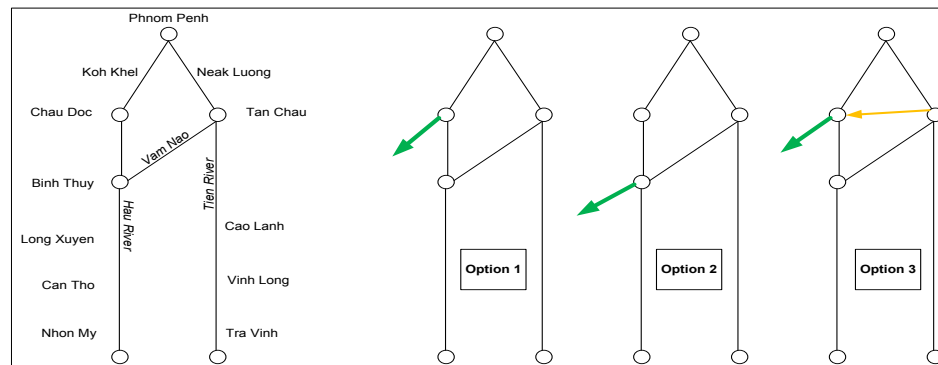

Figure 3-5 Three withdrawal alternatives based on two withdrawal points

1. The first withdrawal alternative is in theory the most beneficial solution for lowering the water level in the downstream area. The withdrawal location is located at the Chau Doc near the border with Cambodia.
2. The second withdrawal alternative is at Binh Thuy city. The reason to choose this alternative is because at this withdrawal location there is also a possibility to withdraw water from the Tien River though the natural existing Vam Nao passage. This may have beneficial results on the required amount of withdrawal.
3. The third option has the same withdrawal location as alternative one, which is at Chau Doc. In addition a construction of an extra channel between the Tien and Hau River is made. The yellow arrow in Figure 3-5 indicates the extra channel.

Mekong River model

By researching if there is a significant difference between withdrawal locations based on the three alternatives, it is possible to see if the diversion channel is bound to a specific location. Withdrawing from the Hau River will have an influence on the discharge distribution at Phnom Penh and eventually on the water level at Tan Chau.

The influence of withdrawing water at one location and the water level changing effects on the Mekong River is to broad to use simplistic static hand calculations. Therefore, a 1D Sobek model is made of the main Mekong River system to study how the water level in the Mekong River reacts on the withdrawal and if withdrawing at one location can

Figure 3-6 A schematisation of the Mekong River model

provide the necessary water level lowering to reduce flood risks. The reasons to use a 1D model is because available data are little however a rough estimation is good enough for
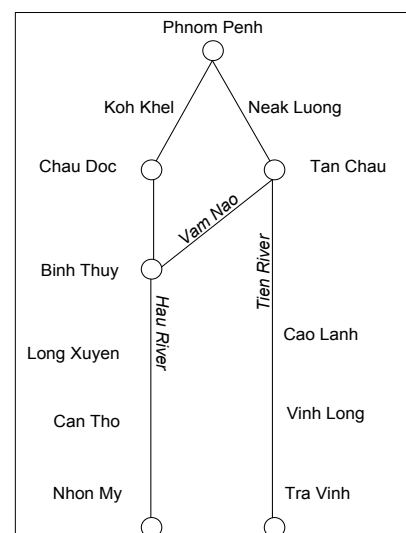
the purpose of this feasibility study. The schematization is based on the cross-sectional information gained from the website of the Mekong River Commission (MRC) and from various coarse measured hydrological data from the report made by (Tuan, Hoanh, Miller, & Sinh, 2007), see appendix B.3 for the used cross-sections.

Water levels and the specific discharge distribution between the Hau and Tien River during a high water event are used to calibrate and validate the model. By adjusting the cross-sections and the roughness parameter the model is calibrated. The dimensionless Manning's coefficient is used as a roughness parameter within this model. The choice of using Manning and not Chézy is because Manning uses the wet perimeter of the channel to base its total roughness value and therefore relating the roughness to the actual water depth. The coefficient of the Manning parameter after calibration ranges between 0,026 and 0,040 for the various channel branches in the model. The upstream discharge boundary is placed at the city Phnom Penh just after the Tonle Sap Lake. The downstream boundaries are set to be equal to msl and the nine branches of the Mekong River are simplified to only the two main river branches (Hau and Tien River). In appendix E the model set-up with the made assumptions, calibrations and validations are further explained in more detail. Figure 3-6 shows the schematization of the lower Mekong River.

The method to determine the minimum withdrawal

The method to determine if the withdrawal locations and withdrawal alternatives have a significant influence on the minimal withdrawal a withdrawal point load is used within the Mekong River model. The first withdrawal is set on an arbitrary chosen withdrawal load of $5000m^3$/s for each withdrawal alternative. The minimum withdrawal is found by incrementally lowering the discharge until the water levels at Chau Doc and Tan Chau are at the aforementioned flood level limits. The minimum design withdrawal criterion that needs to be diverted by the flood diversion channel is based on the known high water event of year 2000. To summarize, the main input parameters for the first point withdrawal load calculations are:

- The Mekong river discharge is that of year 2000 with a high water peak of $32500m^3$/s.
    - For this high water event the water level at Chau Doc was +4.80m against msl and for Tan Chau +5.02m against msl.
- The goal is to lower the water levels to the flood level limits. These limits were 4m+msl for Chau Doc and 4.5m+msl for Tan Chau.
- For the first trial run the withdrawal is set at $5000m^3$/s for each withdrawal alternative.

3.1.3.   *Determining the minimum and required withdrawal*

Figure 3-7 shows a comparison made between the three withdrawal alternatives against the reference year 2000. All the alternatives show that withdrawing 5000m³/s results in water levels that are well below the described flood level limits for Chau Doc and Tan Chau. By incrementally lowering the withdrawal volume the required minimum withdrawal can be found. The results are given in Table 3-3.
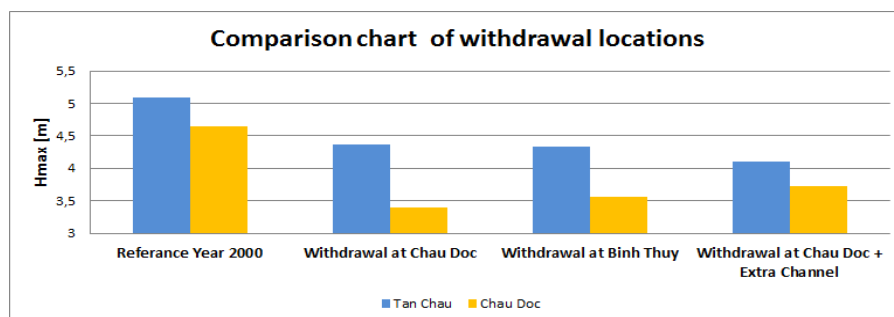

Figure 3-7 Withdrawal comparison of the 3 alternatives with the reference year 2000 (*Note: H-max starts at +3m against msl*)

	Diversion channel Discharge [m³/s]	Water level [m]	
		Chau Doc	**Tan Chau**
Alternative 1 *(Chau Doc)*	**4100**	3.6	4.5
Alternative 2 *(Binh Thuy)*	**4000**	3.8	4.5
Alternative 3 *(Chau Doc + Extra Channel)*	**3650**	3.8	4.5
Extra channel discharge	*1150*		

Table 3-3 The minimum required withdrawal to prevent flood risks caused by a high water event like that of year 2000. Results are based on trial runs starting at withdrawing 5000m³/s and incrementally lowered until both water levels are just under flood level limits.

In Table 3-3 the minimum required withdrawal, for an event like that of the year 2000, is between 3650 to 4100 m³/s to lower the water level at Chau Doc and Tan Chau to a water level just under flood level limits. The results also show that the difference in withdrawal location is not that significant. Withdrawing at Binh Thuy (alternative 2) does not have a significant advantage compared to withdrawal from Chau Doc (alternative 1). Withdrawal from Chau Doc with an additional extra channel (alternative 3) does result in a lower withdrawal necessity.

However, with respect to the coarseness of this study the small advantage of alternative 3 is negligible. Therefore, it can be concluded that withdrawing location does not have a significant influence on the necessary minimum withdrawal. What can also be concluded is that for a high water event like that of year 2000 it is required to at least withdraw 4000m³/s.

The increase of withdrawal due to Climate Change

The most conservative withdrawal is to withdraw using alternative 1, which withdraws at Chau Doc. Therefore, the withdrawal increase due to climate change is only considered at that withdrawal point. The results are shown in Table 3-4.

	Withdrawal [m^3/s]	Modelled water level at: [m]	
		Chau Doc	Tan Chau
Moderate	**6000**	***3,9***	5,1
	8000	3,5	4,8
	11000	2,7	***4,5***
High	6000	4,5	5,7
	8000	***4,0***	5,5
	16000	1,5	***4,5***

Table 3-4 The necessary withdrawals and combined water levels in case that climate change increases the discharge within the Mekong River

Two situations can be distinguished in Table 3-4. The first situation is that the withdrawal stops until the water level at Chau Doc is under the flood level limits *(at +4m against MSL)*. For a moderate situation the required discharge is 6000 m^3/s and for the high situation it is 8000 m^3/s. This is an increase of 1,5 to 2 times larger than the required discharge based on the event of year 2000. The second situation is that the withdrawal stops until the water level at Tan Chau is also under the flood level limits *(at +4.5m against MSL)*. For a moderate situation the required discharge is 11000 m^3/s and for the high situation it is 16000 m^3/s. This gives an increase of almost 3 to 4 times of the withdrawal requirement necessary to reduce flood risks cause by the year 2000 high water event.

Using a single diversion channel to withdraw 11000m^3/s to 16000m^3/s, which is equal to the current total yearly average discharge of the Mekong River is very unrealistic. So if due to climate change it is required to also lower the water level in the Tien River, additional measures need to be taken besides constructing a single diversion channel. A measure could be to construct an additional diversion channel that withdraws directly from the Tien River that crosses through the Dong Thap Muoi and discharge into the South East Sea. Researching this option or other additional measures is out of the scope of this thesis.

3.2.   Dimensional requirements

In the previous paragraph it is determined that to reduce the water level of the Mekong River to be under the flood level limits a diversion channel is needed which can at least withdraw 4000m^3/s. If climate change scenarios need to be considered as well withdrawal must be at least 6000 to 8000m^3/s and that the measure -under climate change situation- is only sufficient to lower the water level at Chau Doc. This paragraph

uses the determined withdrawals to estimate the dimensional requirements of a flood diversion channel.

The considered flood diversion channel is schematically shown in Figure 3-8. The diversion channel bifurcation at Chau Doc (location A) and debouches into the Gulf of Thailand (location A') along a straight channel axis from A to A'. The length of the diversion channel is assumed to be approximately 70km long. In the upcoming sub-paragraphs schematic longitudinal cross-sections are shown. The drawn cross-section is indicated in Figure 3-8 with a dotted line between location A (Chau Doc) and location A' (Gulf of Thailand).
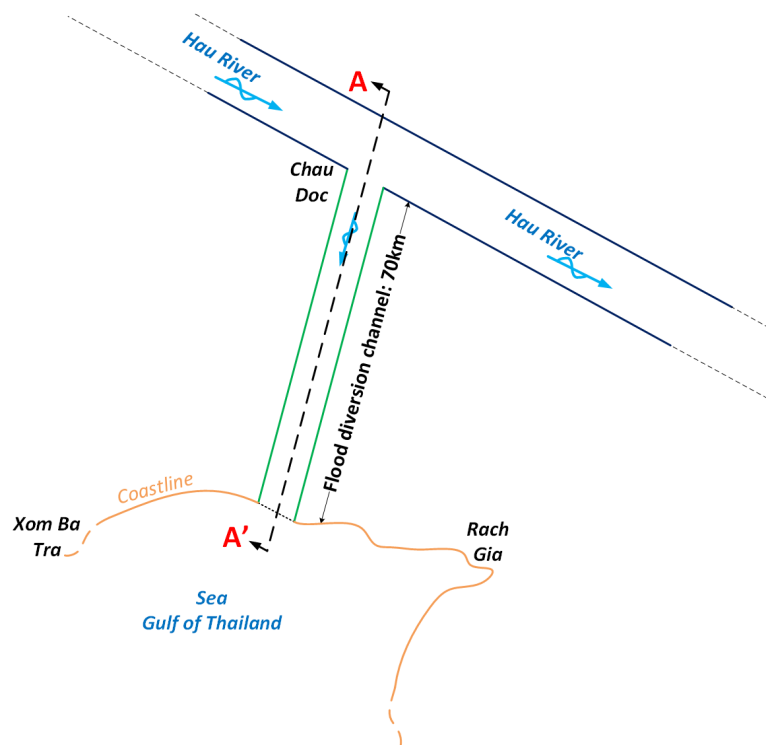
Figure 3-8 An overview of a flood diversion channel that bifurcates from the Hau River at Chau Doc (loc. A) to the Gulf of Thailand (loc. A'). The approximated length of the flood diversion channel is 70km.

This paragraph consists of three sub-paragraphs. To divert the minimum required withdrawal a variety of channel dimensions are possible. Therefore, in the firsts sub-paragraph a qualitative framework is made in deciding which channel types has the potential to be constructed and are used for further detailed calculations. In sub-paragraph 3.2.2 and 3.2.3 the required technical conditions of the chosen channel types are studied. Besides the required technical conditions, these sub-paragraphs gives the dimension of the flood diversion channel and studies what the necessities are to be taken into account during the dry-season.

3.2.1. *The considered channel types*

The landscape of the Mekong Delta consists mainly of agricultural land and is relatively flat. With exceptions of some mountainous area close to the border with Cambodia, the topographic height variation of the Mekong delta is around 2m. A proposed solution is to create a "green river" diversion channel, also known as a ground level or shallow diversion channel (NEDECO & Royal Haskoning, 1993). This shallow channel uses the existing topographical slope to divert the required floodwater towards the Gulf of Thailand. A unique advantage of constructing a shallow channel is that agricultural land will not get lost due to the construction of this channel type (no significant excavation required). The disadvantage is that the land elevation is limited with a maximum elevation of approximately 2m+msl close to the Mekong River, this small land elevation results in the situation that the width of this shallow channel will become significantly broad.

Another option is to decrease width is decreased as much as possible. Decreasing the width of the diversion channel means an increase in depth is required to still reach the minimum withdrawal capacity. The unique advantage of choosing a deep channel above a shallow channel is that with a deep channel it is possible to combine it with inland navigational activities. The disadvantage is the requirement of significant excavation and the expected loss of valuable agricultural land.

For the detailed dimensional calculations only these two (extreme) channel types are considered. The reason to only consider these two extreme channel options is because these situations have a unique advantage. These advantages are not applicable for intermediate situations. A second reason is that if it is possible to use the two extreme situations it automatically means that all the options in-between are also possible.

3.2.2. *Shallow channel dimension*

This sub-paragraph studies the possibility of constructing a flood diversion channel, which uses the excising topography as bed level. This sub-paragraph is divided in three sections. The first section determines the boundary conditions of constructing a shallow diversion channel. The second section of this sub-paragraph provides the calculations determining the minimum required dimension for a shallow channel to divert the minimum and required withdrawals determined in paragraph 3.1. The third section of this sub-paragraph studies the connections between the Mekong River and flood diversion channel and between the flood diversion channel and the Gulf of Thailand.

Boundary conditions for a shallow channel
Bed level slope

The concept of constructing a shallow channel is to use the natural and already exciting topographical slope of the Long Xuyen Quadrangle to construct a diversion channel from the Mekong River to the Gulf of Thailand. The information in sub-paragraph 2.1.1 shows

that the height differences are approximately 2m. Close to the Mekong River the land level is around 2m+msl and with an approximated channel length of 70km this gives a gentle bed slope of 2.86E-05 [-].

Roughness consideration

The shallow channel flows over the existing land topography. This topography mainly consists of agricultural land. A Manning coefficient of 0.040 is used to take this topographic roughness into account. It is taken from the studies made by Chow in 1959. The study he made shows under normal cultivations that the Manning roughness coefficient can vary between 0.030 and 0.040 depending on what is cultivated.

Floodplains	Manning	
Cultivated areas	Normal conditions	Max conditions
1. No crops	0.030	**0.040**
2. Mature row crops	0.035	0.045
3. Mature field crops	0.040	0.050

Table 3-5 Manning's coefficient for cultivated areas given by Chow, 1959

If a high water event arrives chances are that authorities would instruct farmers to clear their agricultural land. They would most probably leave an area behind which is in-between a no crop and mature row crop situation. However, agricultural activities are extensive in the Mekong delta so a Manning value of 0.040 is assumed as roughness parameter to calculate the dimensions of the shallow flood diversion channel.

Water level within the Mekong River

The previous paragraph indicates that when discharging 4000 to 8000m^3/s the water level at Chau Doc should be between +3.7m to +4m against msl. To be as conservative as possible the dimensional requirement of the flood diversion channel must withdraw the required withdrawal with a water height of +3.7m against msl within the Mekong River. Therefore, the water level of the diversion channel is dependent to the water level during high water within the Mekong River. This means that with the topographic bed level at +2m against msl a maximum water depth of 1.7m is possible within the flood diversion channel. An impression sketch is made in Figure 3-9. This figure shows that the water flows over land topography and is discharged into the sea.

Longitudinal cross-section of a shallow flood diversion channel
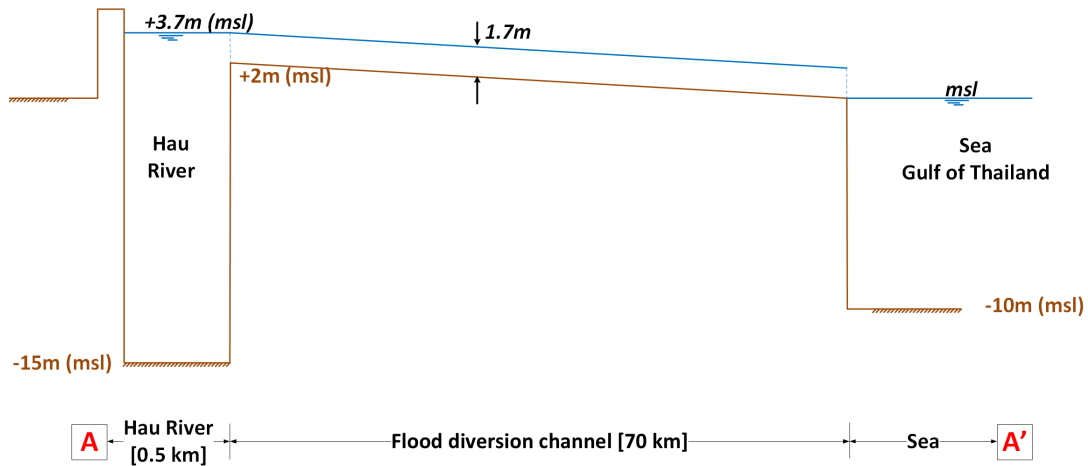

Figure 3-9 Longitudinal sketch of the shallow channel

Calculating the required width of a shallow diversion channel

The previous section described the boundary conditions of the shallow diversion channel. The necessary width of the shallow diversion channel is unknown. The diversion channel is considered to be a rectangular channel in this feasibility study. By re-writing the discharge formula it is possible to calculated the necessary width. The discharge formula is given in (Eq. 3-1).

$$Q = B * h^{3/2} * C * i^{1/2} \qquad \text{(Eq. 3-1)}$$

With:

Q = Discharge [m³/s]
B = Flow width [m]
h = Water depth [m]
C = Chézy coefficient [m$^{1/2}$/s]
i = Slope of the water surface [-]

(Eq. 3-1) can be re-written in (Eq. 3-2) with a dimensionless friction coefficient.

$$Q = B * h * \left(\frac{g*h*i}{c_f} \right)^{1/2} \qquad \text{(Eq. 3-2)}$$

With:

g = Acceleration [m/s²]
c_f = Friction coefficient [-]

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The dimensionless friction coefficient is determined with the previous quantified Manning coefficient of 0.040 with (Eq. 3-3).

$$c_f = \frac{gn^2}{h^{1/3}}$$

By using (Eq. 3-3) within (Eq. 3-2) and using a water depth of 1.7m the only unknown is the width of the channel. The calculated dimensional requirements are shown Table 3-6.

Discharge [m³/s]	Depth [m]	Width [km]
4000	1.7	12.4
6000	1.7	18.5
8000	1.7	24.7

Table 3-6 Dimensional requirements using the re-written discharge formula given in (Eq. 3-1) for a shallow channel.

The shallow variant of a flood diversion channel shows that the width of the channel must be significantly wide to be used as a possible diversion channel. The flow velocities within the diversion channel are around 0.2m/s. To bring the calculated width into perspective Figure 3-10 is made. The distance between the city Chau Doc and Binh Thuy is approximately 30km.

Figure 3-10 Shallow channels widths perspectives. The left panel is an overview of the smallest shallow channels width. The right panel zoom in on the withdrawal location.

Width reduction with some excavation

The significant required width of the flood diversion channel is a consequence of having a gentle topographic slope. For the calculation a situation was used where the water slope is equal to the existing topographic bed slope and no ground excavation is allowed.

The purpose of this additional calculation is to clarify that even with the maximum possible water slope the width of the flood diversion channel is still significantly large. The maximum water slope of 3.7/70000 = 5.28E-05[-] can be reached if excavation is allowed. This excavation is indicated with the dashed are in Figure 3-11. Using (Eq.3-2), a water depth of 1.7m and the maximum water slope results in a width requirement of

9090m to discharge 4000m/s. Although this reduces the width of the channel by approximately 3.5km the diversion channel is still significantly large. This alternative calculation is not further considered in this thesis because this option eliminates the unique advantage of a shallow channel as flood diversion channel see sub-paragraph 3.2.1.
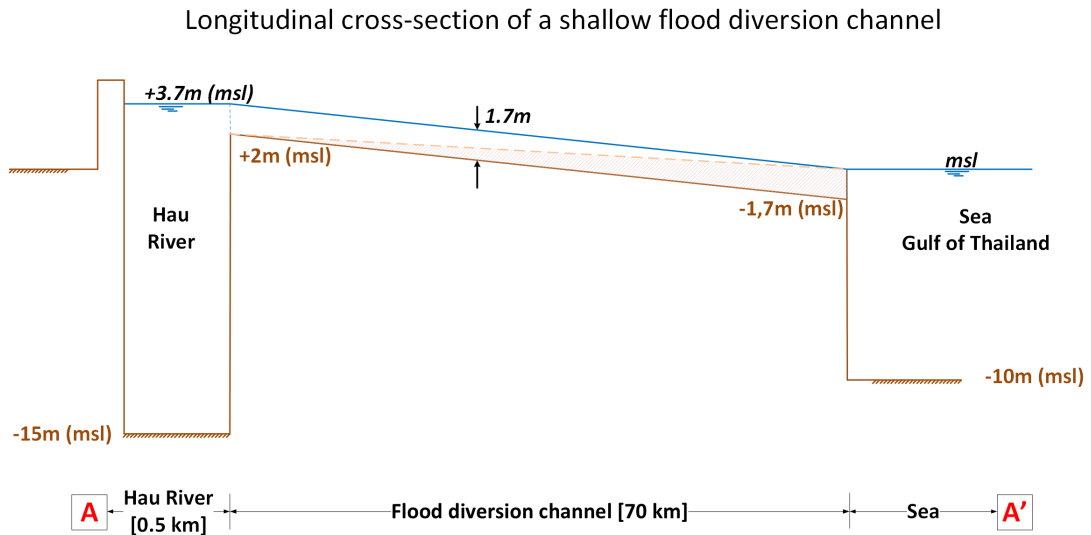
Longitudinal cross-section of a shallow flood diversion channel

Figure 3-11 Allowing excavation to get the maximum hydraulic head possible

Flood diversion channel connections using weirs

The purpose of the diversion channel is to divert high water peak events and only necessary to be flooded when a high water event occurs. Under normal yearly situations the shallow flood diversion channel should not be flooded. This section studies, which discharge level in the Mekong River will result in flooding of the diversion channel and if it is necessary to constructing a weir at the withdrawal location to prevent low discharge levels from entering the diversion channel. As a reminder, the bed level at the withdrawal point of the flood diversion channel is assumed to be at +2m above msl.

Figure 3-12 shows the modelled Q-H relationship between the discharge at Phnom Penh and the resulting water level at the city Chau Doc. This figure shows that the average yearly discharge of approximately 13000 m³/s (MRCS & KOICA) results in a minimum water level of +1.2m against msl (dashed-dotted grey arrow). This water level is below the bed level of the flood diversion channel at the withdrawal location. What the figure also indicates is that a discharge of around 18000 m³/s is the maximum discharge of the Mekong River whereby the diversion channel, which has its bed level at +2m against msl, will not get flooded (solid black arrow).

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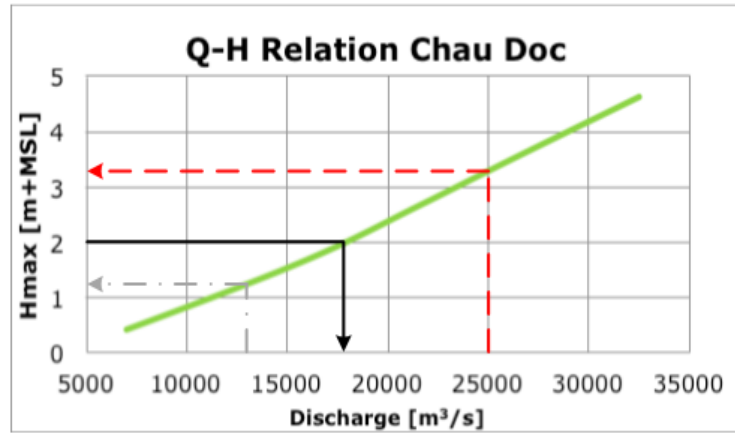
Figure 3-12 The modelled Q-H relationship at Chau Doc city

However, the yearly average "peak" discharge of the Mekong River is around 25000m³/s, see Figure 2-7. From the Q-H relationship in Figure 3-12 shows that the discharge of 25000m³/s is associated with a water level of approximately +3.3m above msl in the Mekong River (dotted red arrow). This means that considering (Eq. 3-2) a water depth of 1.3m and a width of 12.4km results in a yearly "peak" discharge is diverted to the shallow flood diversion channel of around 2500m³/s. This means that normal peak discharge will result in flooding of the shallow diversion channel. Additional measures are therefore required to prevent this yearly flooding.

Connection between Mekong River and flood diversion channel

The concept of constructing a fixed weir is studied to see if it is possible to construct a fixed weir to prevent this yearly flooding caused by the average "peak" discharge. For this approximation a rectangular weir is considered. To determine the discharge over the rectangular weir (Eq. 3-4) is used.

$$Q = f \frac{2}{3} W_s \sqrt{\frac{2}{3} g} \, (H_1 - Z_s)^{\frac{3}{2}} \qquad \qquad \text{(Eq. 3-4)}$$

With:

f = Drowned reduction factor [-]
g = Acceleration due to gravity [m/s²]
W_s =Width across flow section [m]
H_1 = Upstream energy level [m]
Z_s = Crest level of the weir [m]

The flow reduction factor is a value that reduces the discharge capability over a weir. This reduction is caused by the phenomenon called drowned flow, which is also indicated in Figure 3-13.
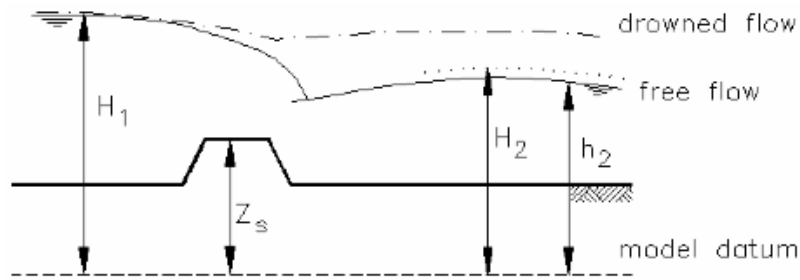
Figure 3-13 Weir drawing with the indication of what drowned flow is.

For the fixed weir within the diversion channel the flow reduction factor is set on 0.1 because the water height after the weir is almost equal to the water height within the Mekong River. By re-arranging (Eq. 3-4) the maximum weir height can be determined with the already known discharge and width across flow section. The results are given in Table 3-7. The height values are all given against msl.

Withdrawal (Q) [m³/s]	Width across flow section (W$_s$) [km]	Water height in Mekong River (H$_1$) [m]	Weir height (Z$_b$) [m]
4000	12.4	3.7	2.2
6000	18.5	3.7	2.5
8000	24.7	3.7	2.7

Table 3-7 Weir height approximation by re-arranging (Eq. 3-4) and to determine Z$_b$.

Concluding from Table 3-7 shows that fixed weir cannot be constructed at the required height to prevent the yearly average peak discharges which is approximately 25000m³/s to be diverted into the shallow channel and at the same time be low enough to discharge 4000m³/s during a high water event.

Connection between flood diversion channel and Gulf of Thailand

Considering a fixed weir between the flood diversion channel and the Gulf of Thailand will also give problems. Currently the coastline of the Long Xuyen Quadrangle is protected with sea dikes to prevent wave overtopping caused by offshore typhoon storm surges and to prevent the coastline for erosion. Removing or lowering these dikes is most probably not a realistic solution to be considered as feasible options. If a shallow channel is considered as flood diversion channel then it is necessary to remove or lower these sea dikes. By removing the sea dikes, daily tidal salt intrusion occurs that penetrates approximately 10 to 15km land inwards, until a land level that is equal to the Highest High Water, which is approximately +0.7m against msl, see sub-paragraph 2.2.3. The current sea dikes have a crest level situated at approximately 1.6 to 2m against msl. Dr. Dinh Cong San suggested that the current crest levels are to low and should be further heightened in the future to a level of approximately +3.5m against msl to prevent more severe wave overtopping to occur due to climate changes (Heiland & Prof. Dr. Schüttrumpf, 2009). Considering a fixed weir with a crest level at +3.5m above msl will

result in a retention area instead of a diversion channel. The concept of fixed weir either at the withdrawal and at discharge location is in both situations not a realistic option.

Considering flexible weir constructions

For the connections between the flood diversion channel with the Mekong River and the sea fixed weirs were considered. The results show that for the withdrawal and discharge locations a fixed weir is not a realistic option.

A theoretical possible solution to overcome these connection problems is to consider flexible weirs like rubber dams. Vietnam already has some experiences with rubber dams. The Tha La and Tra Su rubber dams are situated along the border with Cambodia. The dimension has already been given in sub-paragraph 2.1.6. As a reminder the length of the Tra Su dam is 90m long and that of Tha La is 70m long. Both dams have its crest level at 3.80m above msl. The largest rubber dam in the world is situated in China, Shandong province within the city Linyi. The total span of that rubber dam is approximately 1.1km. To overcome this length the rubber dam is divided into 16 segments each with a span of 70m.

Rubber dam retailers indicate that a rubber dam can have a typical length scale of 100m in length and 5m in height. On special request these dimensions can be enlarged to a span of 200m in length and 10m in height (Yantai Sunny Rubber Co: Rubber Dam). So it is theoretical possible to construct segmented flexible weirs to overcome these connection problems. The minimum width for the shallow flood diversion channel is 12.4km. This means that if a flexible rubber dam can be constructed it requires approximately 177 segments depending on the span per segment in this case 70m. The height of the rubber dam for the connection between the Mekong River and the flood diversion channel must be at least +3.3m against msl and is inflated during average high water events and can be deflated during low water periods. The rubber dam between the flood diversion channel and the sea must be a least +3.5m against msl to prevent waves overtopping and can only be deflated during a high water event.

A big disadvantage of this system is that if one segment fails to function flooding or salt intrusion can occur. Besides that, rubber dams are vulnerable to punctuation due to floating debris or vandalism. Many farmers and fishermen's use the (Hau) river embankments and sea dikes as trading areas or as quay wall for their fishing boat. They will most probably not consider the consequences of the possibility of punctuating the rubber dam due to their activities. Whether this is a feasible option to consider is out of the scope of this thesis. In theory this option can have potential however, because of the required length of the rubber dam this is not a practical solution.

3.2.3. *Deep channel dimension*

This sub-paragraph studies the possibility of constructing a deep and as narrow as possible flood diversion channel. This means that the depth has to increase to allow the minimum and required withdrawal to pass through. This sub-paragraph is divided into two sections. The first section again determines the boundary conditions of the deep diversion channel. The second section of this sub-paragraph provides the calculations determining the minimum required dimension for the deep channel to divert the minimum required withdrawals calculated in paragraph 3.1.

Boundary conditions of a deep channel

Roughness consideration

Different from the shallow channel this channel is excavated and always water carrying. Most probably the channel will have no vegetation or if present in a mild form. It is decided to use a Manning coefficient of 0.030 as the roughness parameter for this diversion channel. It is again taken from the studies made by Chow in 1959.

Excavated or Dredged Channels	Manning	
Earth winding and sluggish	Normal conditions	Max conditions
1. No vegetation	0.025	**0.030**
2. Grass, some weeds	**0.030**	0.033
3. Dense weeds or aquatic plants in deep channels	0.035	0.040

Table 3-8 Manning's coefficient for excavated or dredged channels given by Chow, 1959

Water level within the Mekong River

Same as in the previous sub-paragraph, when discharging 4000 to 8000m³/s the water level at Chau Doc is approximately between +3.7m to +4m against msl. To be again as conservative as possible the dimensional requirement of the flood diversion channel must withdraw the required withdrawal at a water height of +3.7m against msl within the Mekong River.

Water depth within the deep diversion channel

To construct a narrow channel it is necessary to excavate. The width of the diversion channel depends on the required excavation depth. However, the excavation depth is undetermined, especially for this feasibility study a variety of depths can be selected however, it is possible to determine a well-considered depth value.

The main reason to constructing a deep channel instead of a shallow channel is because a deep channel has the possibility to be also used for inland navigation purposes. It will be the shortest trade route between the Gulf of Thailand and cities in Cambodia like Phnom Penh. The current main types of cargos these inland navigational vessels are transporting in the Delta are rice, vegetables or wood products. The largest vessels

currently travel through the Hau River and can carry up to 5000dwt up to Phnom Penh port in Cambodia. These vessels have a maximum draught of approximately 8m (Mekong River Commission, 2010). So for the deep channel to be competitive with the Hau River, a water depth of at least 8m plus additional safety factor and under keel-clearance is necessary. A standard safety factor is 1.15 and together with a keel-clearance of 0.5m results in a total required water depth of at least 9.7m. Note that this 9.7m of water depth is required during low water periods whereby the water level at Chau Doc is around msl.

Bed level slope

High water levels in the Mekong River are reached only during high water events. The high water peak event of year 2000 lasted for approximately one week. Significant morphological changes on the initial bed level are therefore not possible. The initial bed level before a high water event occurs must be equal to the slope created under normal flow conditions. The average yearly discharge is 13000m³/s (MRCS & KOICA) and results in a water level of the Hau River at Chau Doc to be approximately 1.2m above msl. Assumed is that the bed level has the same slope as the average water level slope in uniform flow conditions. Using the average water level the initial water level slope of the diversion channel is 1.2m over a channels length of 70000m, which is equal to a slope of 1.71E-05 [-].

Calculating the required width of a deep diversion channel

As described in the previous section the initial bed level of the diversion channel is 1.71E-5[-]. The minimum water depth of the channel must be -9.7m below msl during the dry periods at the intersection between the Hau River and the flood diversion channel to be competitive with the navigational trade route through the Hau River. The water depth within the Hau River during a high water event is +3.7m against msl this means that the water depth at the withdrawal location during a high water event is 13.4m. The water depth at the mouth of the flood diversion channel is at msl. Assuming no tidal variation and using a bed slope of 1.71E-05 the water depth at the mouth is equal to -10.9m under msl. Both upstream and downstream the water depths are known. The only unknown is the necessary width of the channel.

The water surface profile of the flood diversion channel corresponds with an M2-type (concave-shaped) backwater curve see, Figure 3-14 for an impression sketch.

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Longitudinal cross-section of a deep flood diversion channel
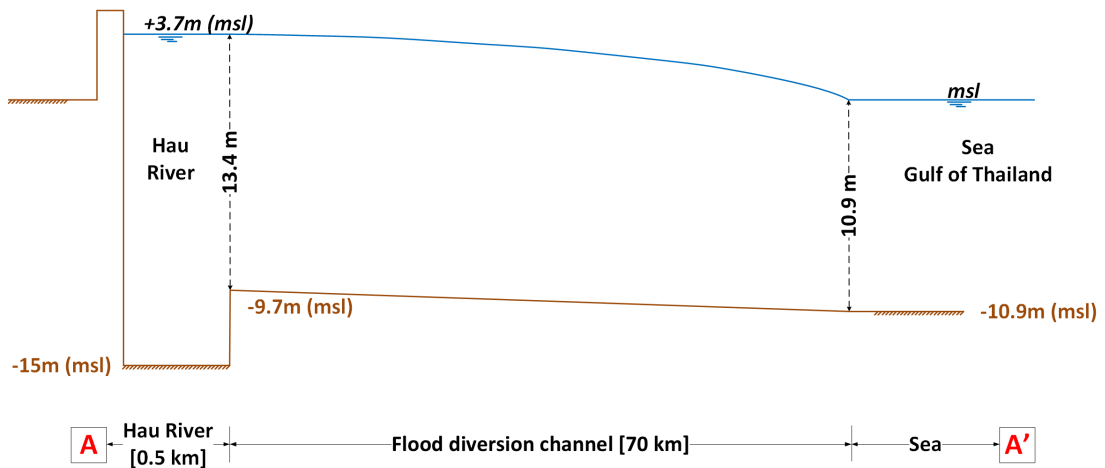
Figure 3-14 Longitudinal sketch of the back water curve within the deep channel

Using the Bélanger equation (Eq. 3-5) the course of the water surface profile can be described. By re-writing the Bélanger equation and together with the up and downstream water depth boundaries known, the required width of the channel can be iterative found.

$$\frac{dh}{dx} = i_b \left[\frac{h^3 - h_e^3}{h^3 - h_g^3}\right] = \left[\frac{h*g*i_b - \frac{g*n^2*u^2}{h^{1/3}}}{h*g - u^2}\right]$$ *(Eq. 3-5)*

The required width based on the calculated water surface profile is given in Table 3-9.

Discharge [m³/s]	Width [m]
4000	340
6000	510
8000	680

Table 3-9 Dimension results using the re-writing Bélanger equation given in (Eq. 3-5) for a deep channel.

The deep variant of a flood diversion channel shows that the width of the channel is large but in comparison between the shallow channel relatively small. Flow velocities within the diversion channel vary between 1.1 m/s close to the mouth and 0.95 m/s close to the withdrawal location. This could lead to erosion of the bed level starting at the mouth of the diversion channel. However, significant morphological changes are not expected, because an occurring high water event last for approximately two month with the peak discharge only lasting for approximately one week. Embankments are required of at least 3.7m high. Besides this, also water regulation measures need to be taken, like sluice gates at the mouth of the diversion channel. This is necessary to prevent salt-water intrusion and fresh water to be withdrawn from the Mekong River during the dry periods. A ship lock is also necessary if navigation is required between the diversion channel and the

Gulf of Thailand. Researching the construction of sluice gates and a ship lock in more detail are out of the scope of this thesis.

3.3.   *Project costs requirements*

In the previous paragraph two channel types have been calculated to withdraw the necessary floodwaters from the Mekong River. To determine which channel type is the most preferred type to be used as flood diversion channel these channels are compared to each other based on a rough cost estimate. It is not possible to provide a detailed cost scheme due to the minor information at disposal. Only an estimation of the cost magnitude is given to decide if a flood diversion channel is a realistic solution to consider and if so which of the two channel types is bet to opt for.

This paragraph is divided into four sub-paragraphs. The first sub-paragraph describes the method used to study the cost magnitude for both channel types. The second paragraph set the scope of the cost estimation and provides an artist impression of the two flood diversion channels. The third and forth sub-paragraphs determines for individual expenses the estimated unit price and required amount. The final sub-paragraph shows and discusses the total costs results. Also a conclusion is given of channel type is best to opt for based only on the costs as criteria.

3.3.1.   *Costs estimation method*

The method used to estimate the costs is derived from the Dutch governmental water organization 'Rijkswaterstaat' and is called the PRI-method (Project Ramingen Infrastructuur). This method has been used to estimate more than 700 measures for the 'Rooms for River' Projects in the Netherlands. The PRI-method distinguishes five kinds of costs. For this rough costs estimate only two types of costs are explicitly distinguished. The first type of costs is the construction costs and the second type of costs is the property costs. Other types of costs like labour, unexpected costs, permit or research costs are not explicitly distinguished. These costs are covered using a multiplication factor set on top of the construction and property costs. Van der Linde et. al. (Van der Linde, van Lier, & Prins, 2004) developed several multiplication factors. He gave a multiplication factor of 2,76 for the total construction cost and two kinds of multiplication factors for the property costs. The direct property costs like buying land are multiplied with a factor 1,11 and the indirect property costs like restitution cost for occurred damages after a high water event with a factor 1,16. The multiplication factors are specifically designed based on projects in the Netherlands. The multiplication factors for the rough costs estimation have to be taken with the mind-set of Vietnamese standards and the uncertainty in the known prices. The construction costs are multiplied by a factor 2. The reason to choose a lower value is because it is expected that the costs involving labour or arranging permit are smaller in Vietnam than within the Netherlands. For the direct property costs the multiplication factor is set on 1.2. This is

higher because uncertainty exists in the exact amount of property that has to be bought. The indirect property costs is also set higher to a factor 1.5. This is because the given multiplication factor of Van der Linde et. al. is based on restitution caused by inundation of agricultural land within the floodplains of a river. The expectation is that the indirect costs are high because a high water event flows into the shallow channel can cause damages to existing infrastructures and give more discomfort to affected farmers and their households than the Dutch considered multiplication factor.

3.3.2. Scope of costs

The previous sub-paragraph already indicated that the cost estimate will consists out of two types of expenses. The first type is the direct construction costs and secondly the property costs. Other types of costs are taken into account using multiplication factors.

This sub-paragraph distinguishes which direct construction costs and property cost there are to be taken into account for this rough costs estimate. To give an indication on which costs are taken into account and how the deep and shallow channel looks, two-impression sketch have been made. The impression sketch for a deep diversion channel is shown in Figure 3-15. The impression sketch for a shallow diversion channel is shown in Figure 3-16. Note that the impression sketches are made to give an indication on which costs are taken into account, therefore the drawings are not drawn on scale.

Deep Channel
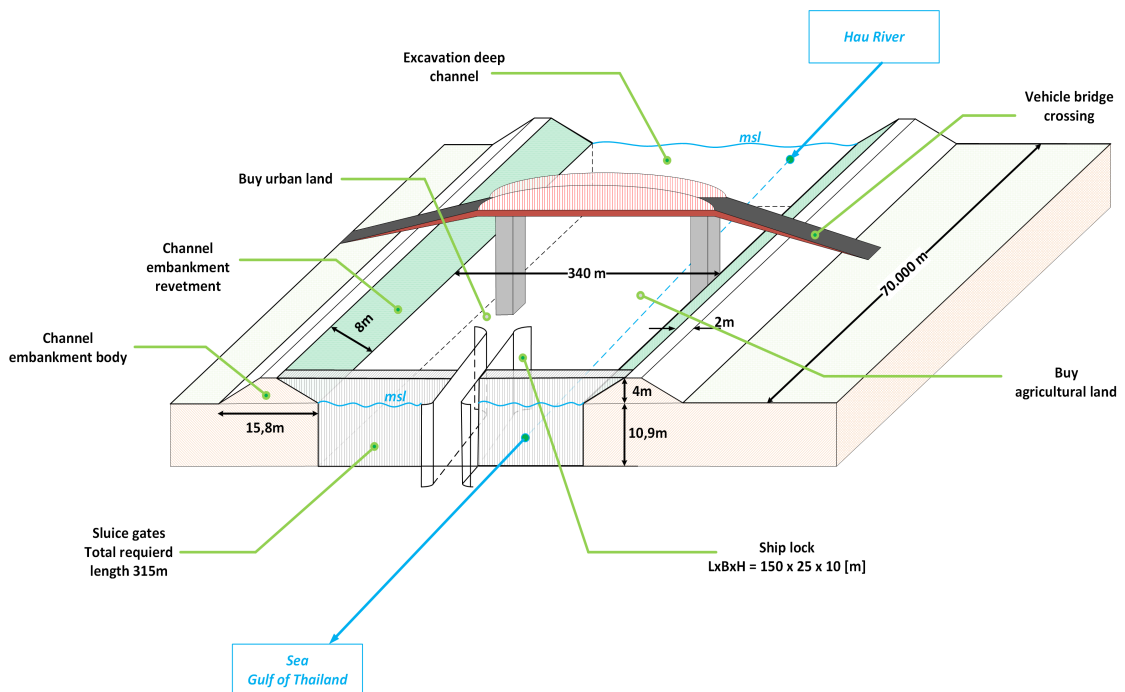
Figure 3-15 Impression sketch of the direct construction cost for a deep channel. Note: The sketch is to provide an impression, the scales are therefore not correct.

Shallow channel
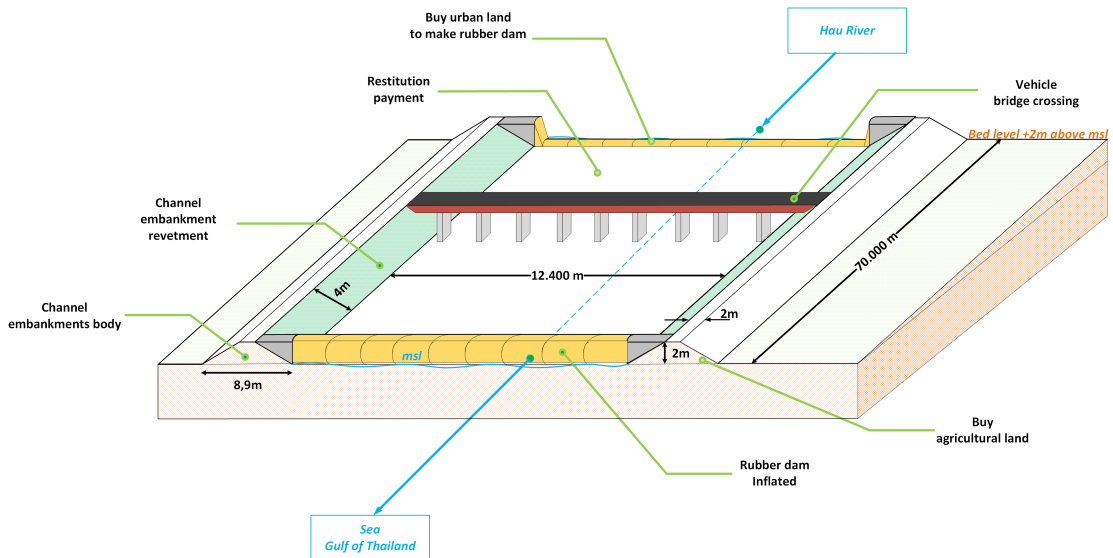
Figure 3-16 Impression sketch of the direct construction cost for a shallow channel. Note: The sketch is to provide an impression, the scales are therefore not correct.

3.3.3. *Unit price estimation*

This sub-paragraph set the estimated unit prices for constructing a flood diversion channel. Each bullet point represents an individual expense, some cost estimates are based on provided unite costs information gained from CWRCT, 2010 (Center for Water Resource Consultant and Technology Transfer, 2010). Others are estimated as good as possible by comparing them to other similar projects.

Construction costs

- Ground excavation (per m³)
    - Van der Linde set the unit costs to excavate 1m³ at 7.26 euro. A different project that involved dredging at sea was a beach nourishment project at Scheveningen (Famous city at Dutch coastline). The estimated costs were 5,90 euros per m³. These indicative excavation costs are based on the Dutch standards and excavation conditions. Exact costs figures to excavated 1m³ in Vietnam cannot be found. It is expected that the unit costs to excavate is lower than the given costs by Van der Linde or beach nourishment project because living standards in Vietnam are considered to be lower. Assumed is made that the price to excavate 1m³ range between the 3 to 5 euros so on average 4 euros per m³. However, site-specific circumstances like sailing accessibility, transport distances or sensitive environment can drive up the price. Information given in sub-paragraph 2.1.3 shows that the topsoil layer of the Mekong Delta consists of clay substances. Although, a part of the excavated soil can be used as backfill for the required channel embankments, there is still a large part

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of excavated soil that needs to be transported or stored. These circumstances may complicate the dredging process necessary to excavate a deep channel, which will result in higher costs and may increase the assumed costs even by a factor 2. So for this rough costs estimate the estimated unit price is 8 euros per cubic meter to dredged clay soil. The assumed price is combined with transportation/storage of the soil. It does not involve labour costs; this is added using the multiplication factor.

- Channel embankment (dike body per m³ and dike revetment per m²)
    - The flood diversion channel requires channel embankments. A simple embankment consists of a dike body constructed out of soil material with on the inner slope revetment to prevent erosion. The dike body is composed out of several soil types like sand and clay. CWRCT estimates the cost for several soil types per m³. They determined that black sand per cubic meter is a round 3,20 euro and yellow sand is 10,80 euro/m³. The costs of clay is not given however the Mekong delta consist mostly out of clay therefore the price of cubic clay should be relatively low. For this rough costs estimate the costs per cubic meter of clay is set on 3 euros. The average value between these three soil costs is 5.6 euros per cubic meter. For this costs estimation the unit price is set on 6 euros per cubic meter dike volume.
    - If one considers using hard structural revetments, the expenses are high because of the required length of these embankments for a flood diversion channel. The estimated price range is between 150 and 225 euros per running meter for an unspecified dike dimension (Van, Dung, Phuoc, & Du), in the same article they also have indicated that prices as high as 530 to 760 euros per running meter are not exceptional. Considering the required length of the flood diversion channels revetment a hard structural revetment is not a promising solution. A cheaper solution is to cover the dike body with a soft revetment. A newly found soft revetment is the grass type called Vetiver grass (Hengchaovanich). The price is approximately 3 euros per square meter revetment (Vu, 2007). For this rough costs estimate this soft type of revetment is used.
- Flexible weir construction (per running m)
    - The calculations made in sub-paragraph 3.2.2 did already show that a fixed weir could not be constructed high enough to prevent an average yearly peak discharge from flooding the diversion channel. Theoretically it is possible to construct a significant long (segmented) rubber dams on both the withdrawal and discharge side of the flood diversion channel. Vietnam does already have experiences with constructing and using

flexible weirs. Sub-paragraph 2.1.6 indicated two kinds of rubber dams. The Tha La, which is 70m long and has a total construction, costs of approximately 18 billion VND (720,000 euros). The Tra Su, which is 90m long and has a total construction, costs of approximately 21 billion VND (840,000 euros) (Hydraulic Engineering Consultants Corporation No.II). The given prices of the rubber dams include all made civil costs. These civil costs are besides the rubber dam also a vehicle bridge parallel to the rubber dam, a concrete sill underneath the rubber dam, a management house and the research / labour costs. For this rough costs estimation it is approximated that the construction of a rubber dam is approximately 900.000 euros per 100m. This cost is excluding labour costs because that expense is accounted for using the multiplication factor.

- A ship lock and sluice gates
  o To prevent salt water to penetrate into the deep diversion channel during normal conditions it is necessary to construct sluice gates. Beside sluice gates it is also necessary to construct a ship lock to provide a passageway for ships. Limited information can be found that can indicated what the price range is to construct these constructions. The price varies depending on the required gate dimensions, the type of gate, and required quay area of ships. A similar project, which has been executed by DHV in Ho Chi Minh City, had a price indication in the range of 80 million euros. For this rough cost estimate a more conservative amount is taken by multiplying the 80 million with an uncertainty factor of 25%. The assumed construction cost for construction the sluice gates and the ship lock is estimated to be 100 million euros for this rough costs estimate.

- Bridges
  o Both channel types require constructing bridges to provide connections for people living in the area from one side to the other side. There should be at least 3 crossings over a longitudinal channel span of 70km. Looking at bridge project in Vietnam the construction costs to construct a bridge range between the 42 to 170 million euros per bridge. The price of constructing a bridge varies depending on the required length, width and height of the bridge. Bridges like the Thuan Phuoc Bridge or the Binh Bridge with a length of approximately 1500 m, a width of 20m (4 lanes) and a clearance for ships under the bridge of 25m ranging in costs between the 42 and 45 million euros. For the rough costs estimate the price to construct a bridge is assumed to be 40 million euros. This also accounts for the bridge required for the shallow channel. Although the clearance of the bridge for the shallow channel can be small because no large ships will sail under these bridges, the significant length of the

bridge can drive up the price. Therefore, the construction cost for both bridge types is for this rough costs estimate is assumed to be 40 million euros per bridge

Property costs (direct)

- Buying agricultural land (per m²)
    - o The costs to buy agricultural land within the Netherlands are approximately 6 euros per m² as indicated by Van der Linde. CWRCT also provided a unit price to buy agricultural land in Vietnam. They provided a lower unit price of 4 euros per m². The unit price for this costs estimate is set on the provided CWRCT unit price of 4 euros per m² of agricultural land.
- Buying urban land (per household)
    - o To estimate a payment per household a comparison has been made on gross domestic product (GDP) at purchasing power per parity per capita (PPP) between the Netherlands and Vietnam. The calculated value shows how much money would be needed to purchase the same goods and services in two different countries. The GDP (PPP) of the Netherlands is indexed at 42.194 and that of Vietnam at 3548 (index has been taken in 2012 from the World Bank database (The World Bank)). The ratio between the two GDP (PPP) indexes is approximately 12. With this ratio it is possible to estimate what the price is of an average house in Vietnam. An average house in the Netherlands is approximately 150000 euros. Using the ratio factor of 12 shows that an average house in Vietnam is approximately 12000 euros. However, the average price is based an average house in the Netherlands. Households along the channel banks and in agricultural areas are often constructed out of wood with corrugated sheet see Figure 3-17. These houses will most probably not be of high value. A different view to the costs per household is by looking an article in the local newspaper of Vietnam (News VietNamNet, 2012). The government provided financial aid to households that were required to re-locate because riverbank erosion led to unsafe situations. The payment per household was between 28 and 32 million VND. This is approximately 1200 euros.

        The considered flood diversion channel will cross through mostly agricultural land and areas where only small cities are located. The re-location costs should therefore be in the range between 1200 and 12000 euros. To be more conservative with this costs expenditure and considering the value of company to be higher and the necessary enforcement of people to re-location the payment per

household/company is assumed to be equal to 8000 euros for this rough costs estimation.

Figure 3-17 People living along a river channel in the Kien Giang province

Property costs (indirect)

- Restitution payment (per m²)
  - These payments are costs that have to be paid if damages occur. Van der Linde used a restitution payment of 2 euros per m² for agricultural land. To estimate the required restitution payment for Vietnam it is necessary to know what is damage during a flood event. Flooding occurs mainly over agricultural land that cultivates rice. Besides agricultural land also housing and infrastructure can get damaged due to flooding. The yield of rice per m² is approximately 1kg. The estimated value per kg rice is 5000 VND this means a price of approximately 0,20 euros/m². However, the restitution payment is not only to compensate failed harvests but also to compensate for damage occurred onto housing and infrastructure. The restitution payment is therefore increased an assumed value of 0,8 euro/m². For this rough cost estimate the assumed restitution payment is set on 1 euro per m². This value covers every restitution payment for damage occurring on agricultural land, households, companies and infrastructures.

3.3.4. *Unit amounts estimations*

The previous sub-paragraph showed the approximated expenditures. Some expenditure is given per unit volume. This sub-paragraph determines the required amount of each unit volume to eventually determine the total cost.

Construction costs

- Ground excavation (per m³)
  - Excavation of ground is only required for the deep channel option.

- - - The volume is calculated as the required excavation to construct a deep channel minus the already existing irrigation channel.

    340m*9.7m*70000m – 50m*5m*70000m = 213.360.000m^3
- Channel embankment (dike body per m^3 and dike revetment per m^2)
  - The channel embankments are different from each other in dike volume and required revetment area. The embankments are considered as trapezoidal constructions with a crest that is 2m wide and a additional freeboard of 30cm and with a 30-degree slope see Figure 3-18 There are 2 channel embankments one on both sides of the flood diversion channel see Figure 3-15 and Figure 3-16.
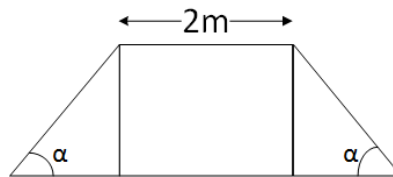
Figure 3-18 Channel embankments dimensional estimation

  - - Shallow channel embankment volume:

      2*(2m*70000m*5.4m)=1.512.000m^3
    - Deep channel embankment volume:

      2*(4m*70000m*8.9m)=4.984.200m^3
  - The revetment is only necessary on the inner slope of the embankment. With the considered trapezoidal construction and 30-degree slope results in the following revetment areas.
    - Shallow channel revetment area:

      2*(4m*70000m)= 560.000 m^2
    - Deep channel revetment area:

      2*(8m*70000m)=1.120.000 m^2
- Flexible rubber dam (per 100m)
  - The flexible dam is required only for the shallow channel. The dam should be placed at the withdrawal and debouching location of the shallow diversion channel. The width of the shallow diversion channel is calculated to be 12.400m this means in total approximately 250 segments of 100m flexible rubber dams are required.
- Bridges
  - As earlier mentioned both channel types requires the construction of bridges. The absolute minimal required bridges over the diversion channels are assumed to be three. The deep channel requires three bridges each estimated to be 40 million euros. The shallow channel only requires one bridge of 40 million euros. The reason for that is because the costs for constructing a flexible rubber dam already have the construction costs for building a bridge alongside the flexible dam in it.

Property costs (direct)

- Buying agricultural land (per m²)
    - The shallow channel requires agricultural land to construct the channel embankments. The deep channel also requires agricultural land for the channel embankments plus the width of the excavated flood diversion channel.
        - Shallow channel agricultural land: 9.8m*70000m=560.000 m²
        - Deep channel agricultural land: (16.8m+340m)*70000m = 24.976.200 m²
- Buying urban land (per household)
    - Urban development in Vietnam is often constructed as ribbon development (Dutch: lint bebouwing) along the irrigation channels. The reason for this is because the waterways are the main forms to transport products. The degree of clustering highly depends on the location. The ribbon development along the Hau River is significantly clustered besides that also small clustered neighbourhoods packed with housings can been found. This can be seen in Figure 3-19 top right aerial photo. The amount of households is approximately to be 50 per 100m of shallow flood diversion channels width.
        - Shallow channel: 50*124=6200 households

The ribbon development along the irrigation channels in the heart of the Long Xuyen Quadrangle are significantly more clustered than the ribbon development along the irrigation channels closer to the border with Cambodia see Figure 3-19 lower three aerial pictures.

Figure 3-19 Ribbon development clustering along waterways within the Long Xuyen Quadrangle

For a deep channel it is possible to choose the route with the least amount of relocation or alter the route to prevent unnecessary relocation. The following estimation is made for the deep channel; approximately 15 households are situated per 100 m of deep flood diversion channel.

- ▪ Deep channel: 15*700=10.500 households

Property costs (indirect)

- • Restitution payment (per m²)
  - ○ The restitution payment for damage is only required for the shallow channel option.
    - ▪ The total area is 12400m*70000m = 868.000.000 m².

3.3.5. *Costs results and discussion*

In Table 3-10 and Table 3-11 the total rough costs estimation for a shallow and deep channel are given. The first noticeable conclusion is that the costs difference is approximately 2.2 billion euros with the advantage for a shallow diversion channel. The biggest cost for the deep channel is the excavation of the channel; this expense covers almost half of the total construction costs expenses. However, the property costs for a deep channel is relatively small. For the shallow channel it is the other way around. The costs covering the total construction cost are relative small but the property costs are high, this has to do with the returning restitution payment.

Cost of constructions	Unit	Amount of units	Cost per unit	Cost in VND [10^9]	Cost in Euro [10^6]
Ground excavations					
Flexible weirs	100m	250	€ 900.000	€ 5.625	€ 225,0
Channel embankment body	m3	1.512.000	€ 6	€ 227	€ 9
Channel embankment revetments	m2	560.000	€ 3	€ 42	€ 2
Ship lock + Sluice gates construction					
Bridges	piece	1	€ 40.000.000		€ 40
Sub-total construction cost					
Multiply factor of 2,0				VND 11.788	€ 552
Cost of purchasing land					
Buying agriculture land	m2	560.000	€ 4	€ 56	€ 2
Restitution payment	m2	868.000.000	€ 1	€ 21.700	€ 868
Buying urban land	p.h.	6.200	€ 8.000	€ 1.240	€ 50
Sub-total					
Multiply factor of 1,2 and 1,5				VND 34.105	€ 1.364
Total:				**VND 45.893**	**€ 1.916**

Table 3-10 Cost estimation for a Shallow diversion channel

				Deep Channel			
Cost of constructions	Unit	Amount of units	Cost per unit	Cost in VND [10^9]		Cost in Euro [10^6]	
Ground excavations	m3	213.360.000	€ 8	VND	42.672	€	1.707
Felxible weirs							
Channel embankment body	m3	4.984.000	€ 6	VND	748	€	30
Channel embankment revetments	m2	1.120.000	€ 3	VND	84	€	3
Ship lock + Sluice gates construction	piece	1	€ 80.000.000	VND	2.500	€	100
Bridges	piece	3	€ 40.000.000	VND	3.000	€	120
Sub-total construction cost with multiply factor of 2,0				VND	98.007	€	3.920
Cost of purchasing land							
Buying agriculture land	m2	24.976.000	€ 4	VND	2.498	€	100
Restitution payment							
Buying urban land	p.h.	10.500	€ 8.000	VND	2.100	€	84
Sub-total Multiply factor of 1,2				VND	5.517	€	221
Total:				VND	103.524	€	4.141

Table 3-11 Cost estimation for a Deep diversion channel

Discussion

Although the initial cost of a shallow channel is significantly smaller than a deep channel the disadvantage of considering a shallow channel is the returning restitution payment, which is an expenditure that covers flood damages and agricultural losses after a flooding has occurred. The break-even point upon where the shallow channel becomes more expensive is after 2 high water events have occurred, this is shown in Table 3-12.

	Shallow channel Cost in Euro [10^6]	
Initial costs	€	609
Returning costs	€	1.302
Replacement rubber sheet costs	€	200
Initial total costs	€	609
First high water event	€	1.911
Replacement Rubber sheet	€	2.111
Second high water events	€	3.413
Replacement Rubber sheet	€	3.613
Third high water events	€	4.915

Table 3-12 The increasing costs for a shallow channel. After the second high water events every following event will result in a situation where the deep channel is becoming the cheaper solution.

Both flood diversion channels are designed to divert a high water event like that of year 2000. According to Haruyama, 2011 the event of 2000 had a return period of once in the approximately 25 years (Haruyama, 2011). Besides the restitution payment, the rubber sheets used in the flexible weirs may deteriorate overtime therefore these sheets need to be replaced after several years. An average design lifetime of these rubber sheets are approximately 20 to 25 years. So if a flood event occurs every 25 years then it means that after 50 years the deep channel has become the cheaper solution. However, if the effects of climate changes are taken into account, which increases the frequency of occurrence than the expected return periods of succeeding high water events will decrease. This will

result in a situation where the break-even point can be reaching far quicker than the assumed 50 years.

Besides becoming the cheaper solution in the long run, an additional advantage is that the deep channel has a way to earn back the expenditures. The main reason of constructing a deep channel was that it could be used for multiple purposes. The first one is to divert a high water event; the second one is providing a shorter trade route between Cambodia and the Gulf of Thailand. By placing taxes on the use of the newly created inland waterway the expenditures can be earned back in the long run from the private sector. This advantage of generating income is only possible if a deep channel is considered. A small advantage for considering a deep channel, which can partly lower the initial expenditure, is that the excavated soil can be partially used as backfilling for the required channel embankments. A second option for the excavated soil is that it can be used to heighten low situated areas or strengthen the river embankments along the Hau River. The third option is to sell the soil if possible.

Conclusion

The costs between a deep channel and shallow channel differ from each other approximately with a factor 2. With this rough cost estimate it is not possible to exactly indicate what the required costs will be. However, what can be concluded is that the initial cheaper solution may not be the best solution in the long run. The cost estimation shows that a shallow channel is a short-term solution. The problem of a shallow channel is not the initial construction costs, because these costs are relatively low. The problem lies in the high returning restitution payments, which have to be paid after each high water event.

Although a deep channel has a high initial construction costs it does not have these returning restitution payment as expenditure. Furthermore, an advantage of a deep channel is that a deep channel has several benefits to reduce the initial construction costs, by generating tax income or reusing the excavated sand as backfilling for land elevation. These advantages are not possible if a shallow channel is constructed.

3.4. Conclusion on the required technical conditions

In the previous paragraphs the required withdrawals, dimensions and costs estimates are made for a flood diversion channel. The main findings in the previous paragraphs of this chapter are first summarised and then discussed. Based on that the preferred channel type will be chosen.

Withdrawal

The acceptable water level limits are 4m+msl at Chau Doc and 4.5m+msl at Than Chau. The provided water levels include the necessary flooding for farmers to purify their agricultural lands. The outcome of the withdrawal study shows that the withdrawal location does not have significant impact on reducing the withdrawal requirement.. The minimum withdrawal is approximately 4000m^3/s to be able to prevent flooding caused by a high water event like that of year 2000. To mitigate the effects of climate changes as well, a single diversion channel shows not to be a suitable solution to prevent both cities Chau Doc and Tan Chau from flooding. In this case a single flood diversion channel is only able to lower the water level in the Hau River. If climate changes are taken into account the withdrawal requirement increases to 6000m^3/s in a moderate climate change situation and in a high climate change situation to 8000m^3/s. If the Tien River needs to be lower during climate change situations as well, additional measures are necessary to take.

Dimension

Shallow:
The natural topographic slope of the Long Xuyen Quadrangle determines the shallow channels dimension. This results in a significantly wide flood diversion channel. Especially when climate changes are taken into account almost half of the Long Xuyen Quadrangle must be used as flood diversion channel. An additional calculation is made that allowed additional excavation to get a maximum water slope (hydraulic head). The result is a reduction of the width by approximately 3.5km. Although the width of the diversion channel is smaller it is still significantly wide. If a shallow channel is considered additional connection measures between the Mekong River and the flood diversion channel and the sea are required. Based on the findings, constructing a fixed weir is not possible. In theory a flexible weir like a rubber dam can be an option however, from a practical point of view this option is not a realistic solution. The disadvantage is the required significant length of the weir, because if one segment of the rubber dam fails flooding or salt intrusion may occur. An advantage of constructing a shallow channel is the relatively low initial costs and almost no loss of agricultural land.

However, a shallow channel can become more expensive in the long run because of the returning restitution payments.

Deep:
The minimum required ships draught determines the dimensions of the deep channels. The result is a relative narrow channel with high embankments to be able to divert the required discharge. It is also required to construct sluice gates and a ship lock to prevent salt water from intruding into the diversion channel during low water periods. By constructing a deep channel agricultural land will get lost and the costs for a deep channel is significantly higher than the initial costs to construct a shallow channel. However, the advantage of creating a deep channel is that a shorter trade route is then possible between the Gulf of Thailand and Cambodia. With this trade route the initial high construction costs can be earned back by placing taxes on vessels that wants to use the deep channel as waterway.

The preferred channel type

The most preferred channel type is to construct a deep channel and not the initially cheaper shallow channel. The reason to choose for this channel type is because the purpose of considering a flood diversion channel is to prevent land from inundation. Although a shallow channel does reduce flood risks the land used for the shallow channel will get inundated for a long period of time during a high water event. The diversion channel with a width of at least 12.4km is inundated with a depth of approximately 1.7m for at least a week if a high water event like that of year 2000 is considered. Besides inundation of agricultural land also expected expanding urban cities are flooded which results in a high discomfort for the population within the shallow diversion channel area. Another argument to not consider a shallow flood diversion channel is based on the safety aspects. The ability to swim is still is not a common skill to be taught in Vietnam (Asia). Despite that people are living in the tropical almost three-quarters of children across Asia does not know how to swim therefore inundation of land could result in unnecessary casualties (Globalnation In Quirer, 2011). The biggest disadvantage of considering a deep channel is the high initial construction costs however, the initial investments can be earned back in several ways and a deep channel can become the cheaper solution in the long run. One of the main used arguments to not consider a deep channel as flood risk measure is the loss of valuable agricultural land. However this argument is not strong because, when calculating the maximum required area for a deep channel the agricultural land loss is approximately 1% relative to the total area of the Long Xuyen Quadrangle. *[Max required channel area: 680m*70000m = 4760 ha. The total Long Xuyen Quadrangle area is approximately 440.000 ha.]*.

4. Studying the possible coastal impact

The previous chapter showed that it is technical possible to design a flood diversion channel to reduce flood risks caused by the Mekong River. The conclusion of the previous chapter is that the most preferred channel type is to construct a deep flood diversion channel that can withdraw 4000 to 8000m³/s.

The second objective of this thesis is to find out if discharging the withdrawn floodwaters into the Gulf of Thailand prohibits the construction of a flood diversion channel. The reason to study this coastal impact behaviour is because there is a concern that discharging significant sediment rich floodwaters into the Gulf of Thailand will damage the white sandy beaches of touristic coastal zone of Phu Quoc. The study made in this chapter provides an answer to the final sub-questions, which is: "What is the impact of discharging sediment rich floodwaters into the Gulf of Thailand".

This chapter is divided into four paragraphs to find out if sediment deposition prohibits the construction of a flood diversion channel. To determine what the coastal impact can be it is necessary to first determine what kind of sediment type and concentration level is discharged by the flood diversion channel into the Gulf of Thailand. Furthermore, it is necessary to determine at which location along the coastline the flood diversion channel can discharges into the Gulf of Thailand. The study made in paragraph 4.1 provides an answer to both questions.

Based on the expected amount of sediment, which could be discharged into the Gulf of Thailand as well as the chosen discharge locations, the impact on the coastal zone can be determined. The second paragraph uses static hand calculations to identify what the expected sediment depositional behaviour will be. The study in sub-paragraph 4.2.1 determine how far a single grain cell can travel before it gets deposit onto the seabed floor and in sub-paragraph 4.2.2 the significance of bed level increase is determined due to the deposition of sediment. The conclusion made in paragraph 4.2 can provide a good indication if the impact of sedimentation could cause problems close to the coastline where the flood diversion channel debouches. Furthermore, it can provide an answer to if the concern of sediment reaching the island Phu Quoc is justified. The island is situated approximately 50 km away from the coastal city Ha Tien.

The calculations made in paragraph 4.2 are based on steady assumptions where as mechanisms as erosion, bed level variation or differences in flow velocities are not taken into account. To study if the before mentioned mechanisms do have a significant influence a coastal model is made to simulate the sediment depositional behaviour. The study made in paragraph 4.3 provides a visual picture of what the deposition at the near shore and offshore locations will be.

The final paragraph of this chapter sums up the main conclusions made in the previous three paragraphs and provide the intermediate conclusion if the effect of sedimentation prohibit the construction of a flood diversion channel. The final paragraph also indicates which route and discharge location of the flood diversion channel is the most preferred option.

4.1. Sediment information and possible discharge locations

To study the coastal impact it is necessary to find out what is transported through the flood diversion channel. Furthermore, it is necessary to select the possible discharge locations. This paragraph is divided into three sub-paragraphs.

The first sub-paragraph gives an overview of the available information about the sediment type and concentration level in the Mekong River. In this sub-paragraph attention is also given to the influence of an increased sediment concentration level due to sediment pick-up by the flow within the flood diversion channel. Sub-paragraphs 4.1.2 and 4.1.3 determines which discharge locations have the potential for the flood diversion channel to debouch. The study starts by studying the potential discharge locations along the coastline without re-locating existing urban cities. Sub-paragraph 4.1.3 studies the shortest possible routes between the Mekong River and the previous determined discharge locations. The possible discharge location is then selected to be used for the detailed coastal impact studies in paragraph 4.2 and 4.3.

4.1.1. Available sediment data

The available data on sediment types and the concentration levels of sediment within the Mekong River are low. This sub-paragraph first describes the available sediment data. After that a calculation is made to determine how the sediment is transported through the flood diversion channel. The final section of this sub-paragraph describes what the possible sediment concentration level increase is due to bed level erosion of the flood diversion channel.

Suspended material found within the Mekong River

Renaud & Kuenzer 2012 has collected several recent studies of the Mekong Delta. In their collection a study was available on the total suspended solid (TSS) in the lower Mekong River during high water events. The sampling location was situated close to the Cambodian-Vietnamese border adjacent to the Tien River branch. The first sampling location is called An Long, which is located at the junction with the Tien River. The second sampling location is called T2 and is located more land inwards than the sampling location An Long. Both sampling locations are within the study area indicated in the right panel of Figure 4-1.

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The measured TSS concentration during the wet-season of year 2009 is shown in the left panel of Figure 4-1. The provided data shows a rather low TSS concentration level with a peak of around 200mg/l in the beginning of October.
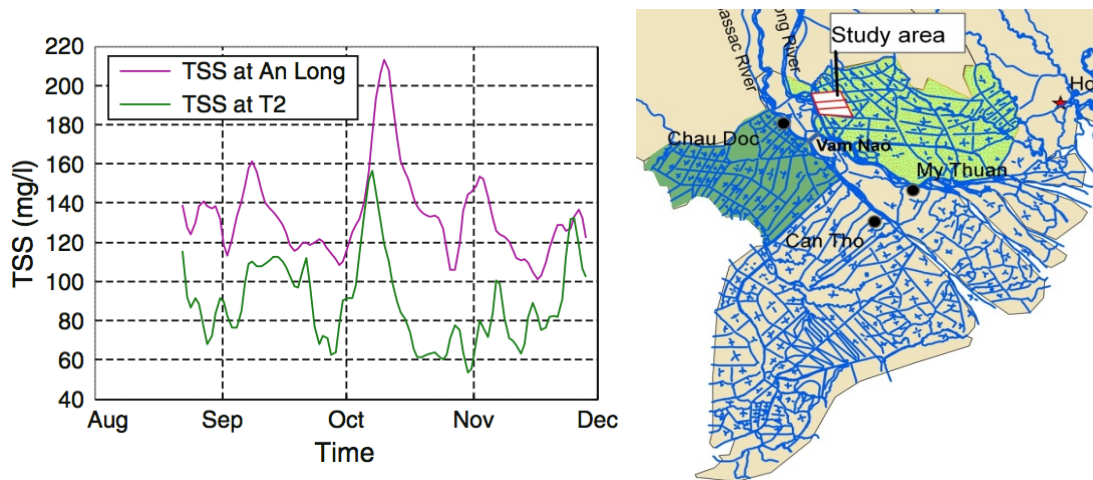
Figure 4-1 Left panel: Citation of (Renaud & Kuenzer, 2012): "TSS concentration at An Long (close to the junction of the Mekong) and T2 (further land inwards) of flood season 2009." This is within the study area shown in the right panel.
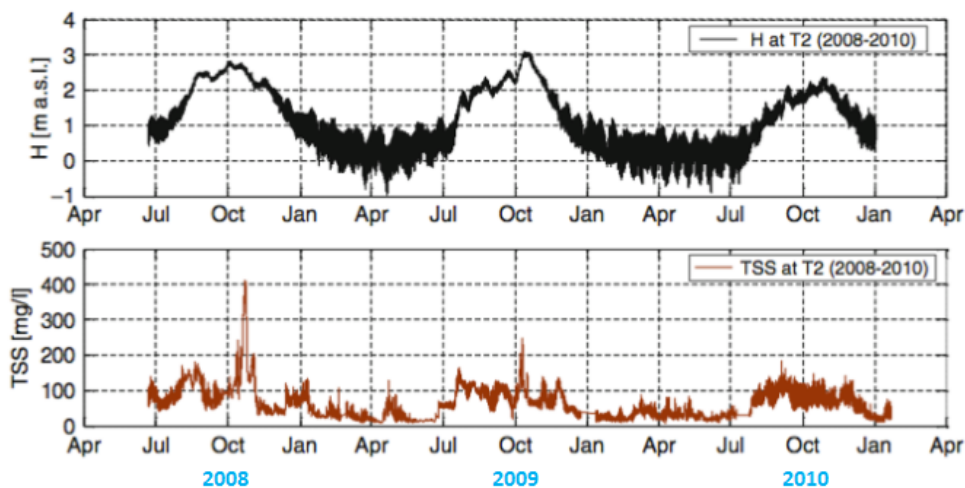
Figure 4-2 The TSS concentration and water level at location TSS for three consecutive flood seasons (2008 – 2010) at location T2. (Renaud & Kuenzer, 2012)

Figure 4-2 shows three consecutive flood seasons (2008 – 2010) at location T2. In 2008 the TSS concentration level had its peak at 400mg/l with the longest high water event while in 2010 the high water event was small which resulted in a very low TSS concentration level approximately 100mg/l. Therefore, it is possible to conclude that the TSS peak is controlled by the flood magnitude, the duration of the flood and the rainfall in the Mekong basin.

A different study made by the Mekong River Commission (MRC) showed that the TSS concentration level does not vary significantly in the upper region of the Mekong River. The tests were conducted in Laos at the city Luang Prabang (1) and the city Vientiane

(2), which lies upstream the Mekong River, see Figure 4-3. Location (3) in Figure 4-3 is the study location of the collected studies of Renaud & Kuenzer 2012

Figure 4-3 Total suspended solids sampling location in the Mekong River (left) and the Mekong River (right)

The samplings of the MCR have been taken made far upstream the Mekong River. The analysis of the samplings gives an indication of the reason why the TSS concentration level had dropped significantly. The commission took samples between 1985 till 2007 see Figure 4-4 (Mekong River Commission, 2007). The figure shows that the total suspended solid decreased over the years, to eventually a TSS level of approximately 250mg/l in the year 2007. A noticeable drop in TSS level was around 1992, which corresponds with the construction of the hydropower dam called 'Manwan' upstream the Mekong River in China. Measurements made by the MRC at Vientiane stated that the average concentration of TSS even drops to around 200mg/l. At the moment already 30 hydropower dams are scattered all over the Mekong River. The prediction is that the TSS level in the lower Mekong River will decrease even more in the future due to the on-going constructions of more hydropower dams.
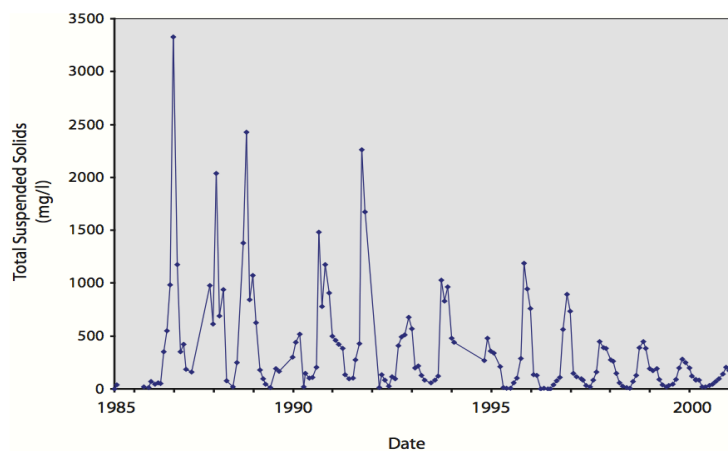
Figure 4-4 TSS concentration over time at Luang Prabang (1)

Sediment type found in flood plain

Together with the TSS study close to the Cambodian-Vietnamese border Nguyen Nghai Hung 2011 has also conducted measurements on sediment types delivered by the Mekong River. He has studied which types of sediment are being deposited through the existing irrigation channels into the floodplain compartments (his study area is the same area as where the TSS concentration levels are found, see right panel Figure 4-1). For his study he measured the mean sediment types during dry and wet periods. His findings show that the median dispersed sediment particle size (D_{50}) is around 10 to $15\mu m$. He has also made estimations regarding the flocculated grains went the sediment comes in contact with salt seawater. He has indicated that the flocculated grain size would be 3 to 4 times larger than the median of the dispersed grain size. Furthermore, he has concluded that the turbidity during dry seasons is around 50mg/l and 200mg/l during the wet seasons (Hung, 2011).

Wash load transport from the Mekong River

The previous section shows that the concentration of the total suspended solids within the Mekong River is approximately 200mg/l. The findings of Hung (Hung, 2011) indicate that the median dispersed sediment particle size (D_{50}) is around 10 to $15\mu m$.

But, in what form are these sediment particles being transported from the Mekong River to the Gulf of Thailand? The Rouse number, which is a non-dimensional number, can indicate how sediment is transported in a fluid. It gives the ratio between the downward settling velocity (w_s) and the upward velocity on the grain represented by (κu_*). For more details on the used equations see appendix C.4. For a Rouse number > 2.5 (or $w_s/u_* > 1$) all transport is bed load. Based on the classification of the "American Geographical Union" the sediment size described by Hung (Hung, 2011), is fine silt. By setting the bed roughness as a constant of 60 m$^{1/2}$/s and the flow velocity at 0.5 m/s the calculated Rouse number of a sediment size of $15\mu m$ is approximately 0.003[-]. In Figure 4-5 the relationship between the sediment sizes and Rouse numbers are given. Note that a Rouse number smaller than 0.8[-], means that sediment is transports all as wash loads.
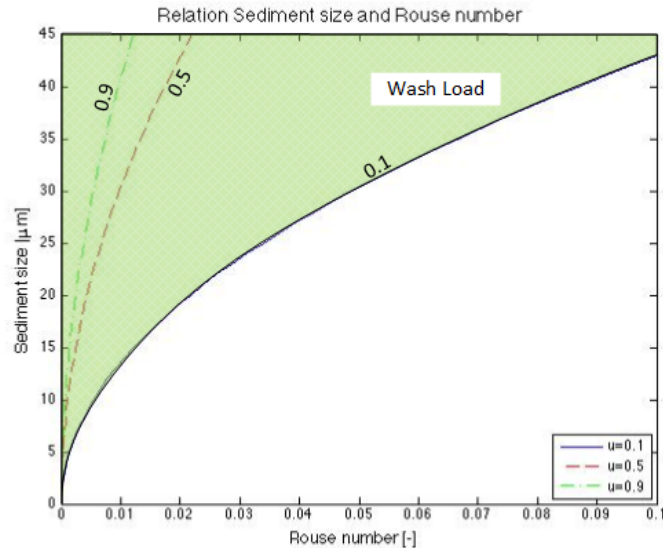
Figure 4-5 Relationship between sediment size and rouse number given a constant bed roughness of 60 [m$^{1/2}$/s]
Note: that the shown Rouse number is between the 0 and 0.1 [-]. The sediment sizes are between 0 and 45[μm].
See appendix C.4 for the full sediment range between 0 and 250[μm] and with the corresponding Rouse number.
The given u is in [m/s].

Wash load is carried within the water column and therefore moves with the mean velocity of the main stream. Because the calculated Rouse number is almost equal to 0 (i.e. the settling velocity is far less than the turbulent mixing velocity), it is possible to conclude that the concentration profile of the sediment is perfectly uniformly distributed over the vertical water column. Water withdrawn by the diversion channel is only from the upper part of the Mekong River as seen in Figure 3-14. This is therefore most likely only wash load with a concentration of 200mg/l.

Concentration increase caused by sediment pickup within the diversion channel

Currently the concentration level of the total suspended sediment is approximately 200mg/l. However, with the construction of a new diversion channel the concentration level will undoubtedly increase, due to the fact that sediment particles will also be picked up from the channels bed of newly constructed diversion channels. Unfortunately there is no information on what kind of particles sizes can be found in the diversion channel. In sub-paragraph 2.1.3 is described that the first 20-50 meters of the topsoil layer of the Mekong delta predominantly consists out of clay particles and sand (Son, 2005).

Large sand particles have a grain size larger than 62 μm. If they have not already been deposited within the channel the sand particles would most probably be deposited immediately in the deeper waters of the sea. If finer particles are picked up within the diversion channel the TSS concentration level could increase. However, with the limited amount of information it is not possible to give a clear pick-up rate to specify the exact increase of the concentration. It is undoubtedly that due to a newly constructed channel the sediment concentration level will be higher than the concentration level found by

Nguyen Nghai Hung in his study of 2011. To be able to do a relevant coastal impact study a significant high and thus conservative concentration level is being used for the calculations in this thesis to determine if sediment concentration level could in a way prohibit the construction of a diversion channel. The concentration is set to 2.5 times higher than the given 200mg/l. So the assumed concentration level is 500mg/l.

4.1.2. *Discharge locations of the diversion channel*

This sub-paragraph studies at which location along the coastline of Vietnam it is possible for the flood diversion channel to discharge. The Long Xuyen Quadrangle coastline that is adjacent to the Gulf of Thailand is approximately 110km long. The stretch of the coastline starts from the city Ha Tien near the border with Cambodia to the city Rach Gia. The touristic island Phu Quoc is located approximately 50km offshore from the city Ha Tien.

As already explained in sub-paragraph 2.2.1 the coastline of Vietnam adjacent to the Gulf of Thailand has five important coastal cities. Re-locating a city would be an expensive operation. Therefore, it is best to search for a discharge location somewhere in between the cities where the area is still less developed and uncultured. Small fishing boats generally uses the foreshores between the coastline cities. No vulnerable touristic beaches are situated at the near coastline of Vietnam. Furthermore, based on information gained from Reefbase project (ReefBase, 2013) that provides an online database of existing coral reefs, no coral reefs exists along the coastline between Ha Tien and Rach Gia and also not at the east side of the Island Phu Quoc. As mentioned before between the cities Xom Ba Tra and Rach Gia the coastline is protected with sea dikes. In front of these sea dikes mangrove rehabilitation areas can be found. The purpose of replanting these mangrove forests in front of the sea dikes is to reduce the on-going erosion of the current coastline. Studies using shoreline video assessment shows significant signs of coastal erosion see Figure 4-6 (Cuong (GIZ) & Brown, 2012).

Figure 4-6 Coastal erosion indication between the Ha Tien and Rach Gia. Red = High potential increase erosion, Yellow = signs of erosion and green = stable areas.

The cities Ha Tien and Rach Gia are a bit touristic, though it mainly serves as passageway cities (either by plane or boat) to Phu Quoc Island. The island Phu Quoc is an area known for its white sandy beaches. Harming these beaches will damage the economic potential of this island. Therefore impacts on this area must be taken into account when deciding to construct a diversion channel or not.

Three discharge locations are selected based on the criteria that cities should not be relocated. Blue diamonds in Figure 4-7 indicate the three possible locations. An overview of the coastline bathymetry is given in Figure 4-8.

Figure 4-7 Possible discharge locations

The **first** location lies south from the city Ha Tien.

- Amongst the three locations this location is closest to the border to Cambodia. The foreshore is rather shallow in comparison to the other two locations. The depths are roughly -2m to -4m against msl. The concern to choose this location as the discharge point is that this location lies closest to the touristic beaches of Phu Quoc.

The **second** location is in between the two cities Xom Ba Tra and Huynh Son.

- This location is located in the middle of the 110km coastline and will further be named 'the Middle location' in this thesis. A narrow band of shallow foreshore in front of the coastline is being used as a rehabilitation area for mangroves. Further offshore this shallow band of foreshore changes into a small bay area. The deepest point of the bay is around -12m below msl.

The **third** location is just above the city Rach Gia.

- This city is within the funnel shaped land created by the coastline of Long Xuyen Quadrangle and the Ca Mau peninsula. (Ca Mau peninsula is the distinctive point shape of the whole Mekong Delta.) The near shore area in front of Rach Gia is called Rach Gia Bay. The depth of the bay adjacent to the city is deep, roughly -

18m below msl. Further offshore, a wide ridge is noticeable with depths ranging from -2m to -4m below msl.
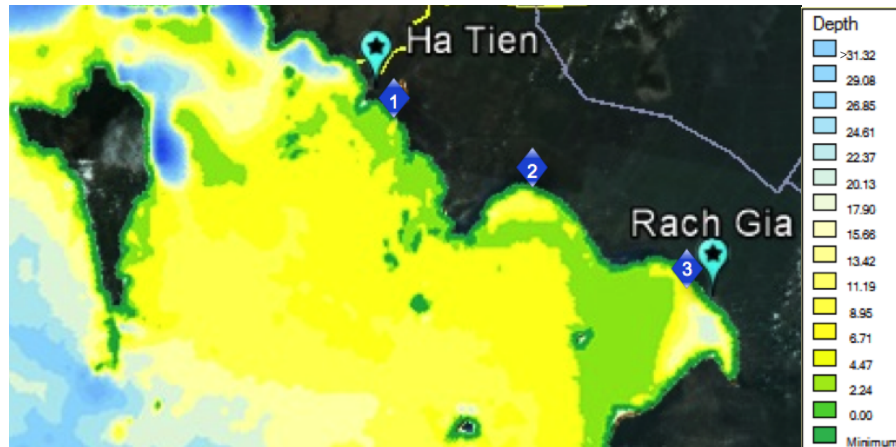
Figure 4-8 Depth contours of the foreshore adjacent to the coastline of Long Xuyen Quadrangle

4.1.3. *Route of the diversion channel*

In the previous sub-paragraph three possible discharge locations have been selected. In this sub-paragraph the discharge locations are coupled with the possible routes of the flood diversion channel. The aim of this sub-paragraph is to find out which discharge locations is the most preferable for the flood diversion channel to debouch into the Gulf of Thailand.

There are numerous routes possible for the deep diversion channel. However, connecting the deep channel with the many already exciting irrigation channels could reduce the required excavation. When taking the existing irrigation channels into account and also the already in sub-paragraph 4.1.2 defined discharge locations of the channel, four distinct channel routes can be identified see Figure 4-9.
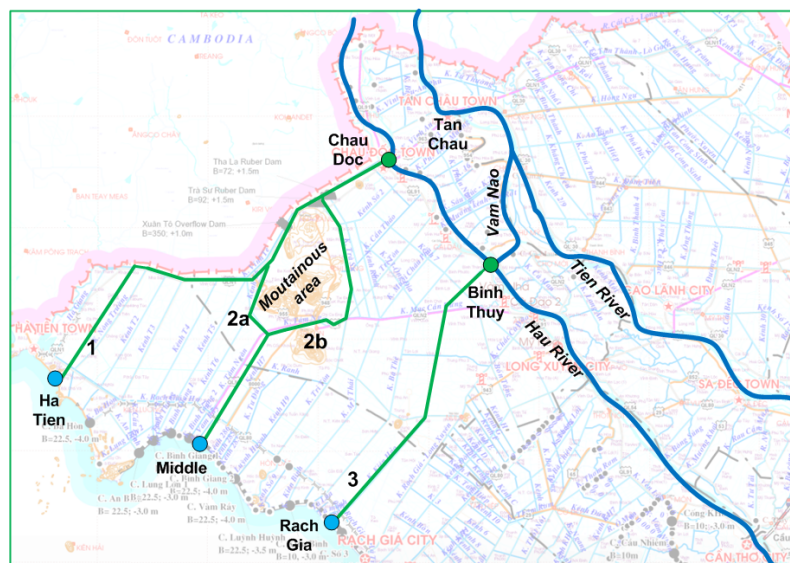
Figure 4-9 Possible deep channel routes combined with existing irrigation channels

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Route 1 starts at the withdrawal point Chau Doc, travels for most of its length with the Vinh Te channel and then makes a sharp turn towards the discharge location Ha Tien using the Ha Giang channel. Based on aerial photos there are a few housing along Ha Giang channel. The length of this route is approximately 85km. The advantage of using this route is that for most of its length it uses the Vinh Te channel. The Vinh Te channel is the most preferred channel to expand because a little to no housing exist along the channel banks closest to the border with Cambodia. The little to no housing area is the result of a political agreement to let the borderland overflow. The Vietnamese authorities are confined to comply with this agreement each year. A close-up of an aerial photo of the Vinh Te channel is shown in Figure 4-10. In this figure it can be seen that the area closest to the border of Cambodia is almost not inhabited.

Figure 4-10 Close up of the Vinh Te channel close to the Cambodia border and Chau Doc city

Route 2(a, b) also uses the withdrawal point of Chau Doc and follows at the beginning the Vinh Te channel. Near the mountainous area close to Cambodia the route bifurcates into either route 2a or route 2b. After passing the mountainous area either routes will enter the K. Tam Ngan channel and eventually discharge at the Middle location into the Gulf of Thailand. The K. Tam Ngan channel does have some housing and industries along its channel. The length of the diversion channel will be approximately 70km for option 2a and 80km for option 2b.

Route 3 is the only channel that has it withdrawal point at Binh Thuy. This diversion channel follows through one exciting drainage channel namely the Kien Hao channel. It discharges just above Rach Gia city. This option is also the shortest one with a length of approximately 60km. The big disadvantage of this option is that it passes through the heart of the Long Xuyen Quadrangle in which a lot of housing and industries are located

along both sides of the channel banks. An aerial impression of the channels is given of the three possible routes in Figure 4-11.

Figure 4-11 Aerial photos of the existing drainage channels

Intermediate conclusion

The sediment transported to the Gulf of Thailand has a sediment size between 10 to 15μm and the assumed conservative concentration level is set on 500mg/l. Based on the findings of sub-paragraphs 4.1.2 and 4.1.3 three discharge locations and 4 possible flood diversion routes are determined. A summary of these routes is given in Table 4-1.

	Discharge location	Route length	Re-location
Route 1	Ha Tien	85km	Low
Route 2a	Middle	70km	Low/Medium
Route 2b	Middle	80km	Medium
Route 3	Rach Gia	60km	High

Table 4-1 Main conclusion based on discharge location and route option

- The shortest route is route 3. However, the disadvantage of this option is that the flood diversion channel crosses through the heart of the Long Xuyen Quadrangle. Many households and industries are located in this area. Due to the lack of feasibility of this option, this route will not be further considered as possible route for the flood diversion channel.
- The second shortest route is option 2a. Compared only to 2b, route 2a has more benefits than route 2b; it is shorter than 2b and have less re-location

requirements because route 2a uses more of the Vinh Te channel which is less inhabited than the area along which route 2b travels.

- The longest flood diversion route is route 1 and this is also the disadvantage of choosing this option. However, the advantage is that by using this route little re-location is necessary because most of the flood diversion channel goes over the Vinh Te channel.

Considering the above only two routes are attractive enough for the construction of the diversions channel, namely route 1 and route 2a. Discharging from Rach Gia is not an option because of the high amount of re-location activities, which need to be taken. This leaves Ha Tien and the Middle location open to choose as possible discharge location.

4.2. *Coastal impact using hand calculations*

In the previous paragraph it is first identified that the sediment size is between the 10 and 15μm and second that it is transported as wash load to the Gulf of Thailand. Furthermore, the sediment concentration level is approximately 200mg/l. However, due to the newly constructed channel, the concentration level will undoubtedly increase because sediment is picked up from the channels bed by the flow. As mentioned earlier the assumed conservative sediment concentration level is set on 500mg/l.

This paragraph consists of two sub-paragraphs to find out what will happen if sediment rich water is discharged into the Gulf of Thailand. Sub-paragraph 4.2.1 considers a simple fall velocity calculation to determine the maximum travel distance of a sediment particle. Sub-paragraph 4.2.2 provides a balance calculation to consider what the bed level increase is if only sediment deposition is taken into account. The calculations in the first sub-paragraphs can provide a firm indication if the concern of sediment deposition at Phu Quoc island is justified. The calculation in the second-paragraph can show if problems can be expected due to near shore sedimentation.

4.2.1. *Maximum travel distance sediment particle*

The previous paragraph has indicated with the Rouse number that the fine silt sediment coming from the Mekong River is transported as wash load and flows in that condition towards the Gulf of Thailand. Once in the Gulf of Thailand the flow velocities decrease causing the fine particles to settle. By considering a situation where no other mechanisms can alter the settling path such as currents, waves or other turbulent mixing mechanisms the distance that a particle can travel can be determined. The travel distance is than only dependent on the size of the grain and the horizontal flow velocity, such as in the case of a sand trap.

To get a first indication of the maximum travel distance of a particle the adaptation length is approximated using the equations presented by Galappatti and Vreugdenhil, 1985 (De Vriend, 2009).

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$$L_a = \frac{\overline{u_f} \cdot h}{w_s} \qquad\qquad (Eq.\ 4\text{-}1)$$

With:

$\overline{u_f}$ = *Mean flow velocity [m/s]*

h = *Water depth [m]*

w_s = *Fall velocity [m/s]*

For this first approximation the assumption is made that the mean flow velocity is equal to that of the tidal currents. These tidal currents are small ranging between 0.1 and 0.4m/s. The water depth close to the shore is between the 8 and 9 m below msl. For this indicative study the water depth is fixed at 8.5m. Figure 4-12 shows that the adaptation lengths with particle sizes of 10 μm can reach distances of almost 40 km; particle sizes of 15 μm can reach almost 17 km.
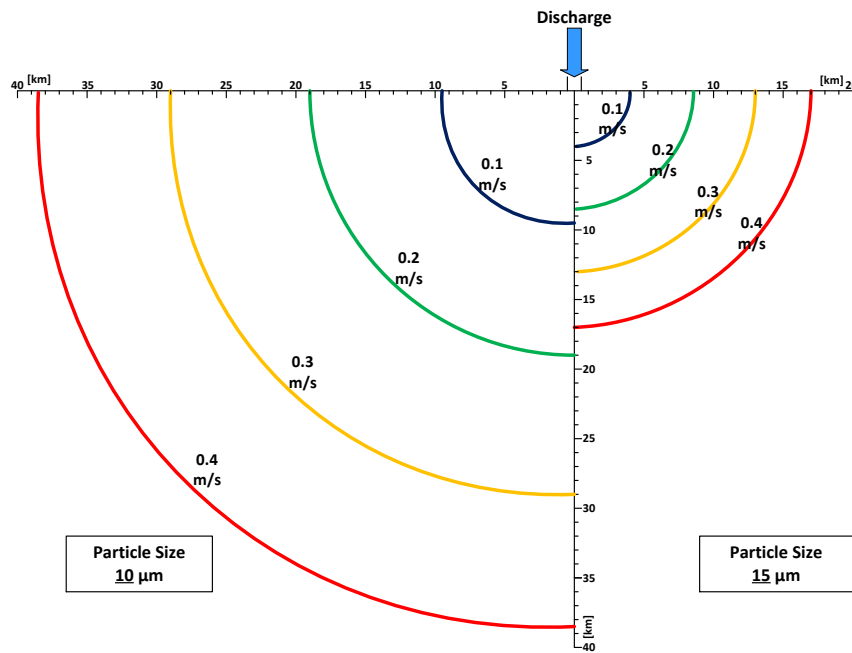
Figure 4-12 The maximum adaptation length based on the particle size 10 (left) and 15 (right) [μm]. The lengths are given in [km]. The used water depth is equal to the deep channel 8.5[m]

The adaptation length calculated in Figure 4-12 only applies for situations whereby a grain size does not flocculate. Cohesive sediments have the potential to flocculate into larger aggregates, which are called flocs. Hung (2011) suggested that flocs would have sizes of 3 to 4 times the median particle size when coming into contact with salt seawater. This means with a floc increase of 3 times the $D_{50,}$ the size of the floc is than approximately between the 30 to 45 μm. Using these particle sizes the following adaptation lengths can be found, see Figure 4-13.
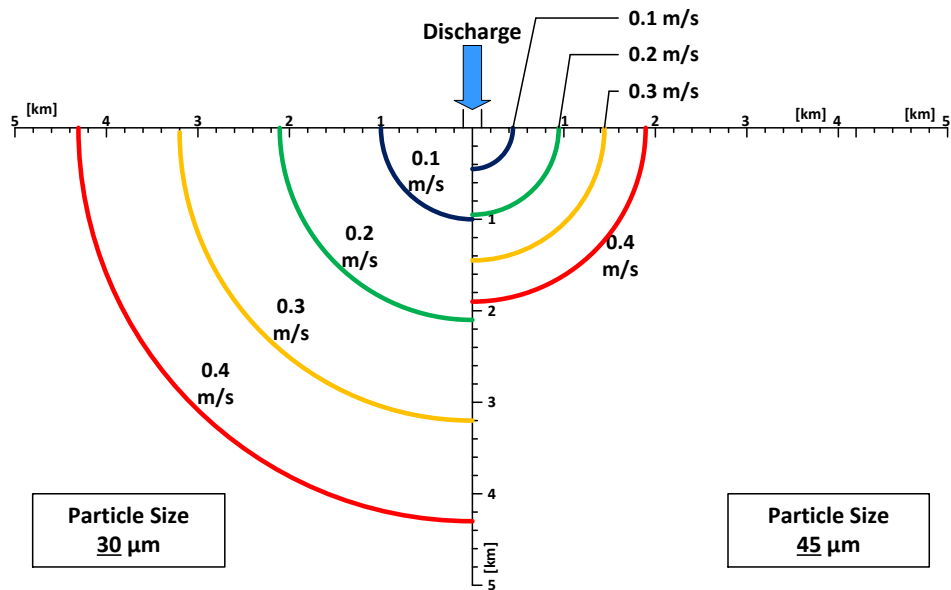
Figure 4-13 The maximum adaptation length based on particle sizes 30 (left) and 45 (right) [μm]. The lengths are given in [km]. The used water depth is equal to the deep channel 8.5[m]. Note: the difference in length scale with Figure 4-12

The adaptation length shown in Figure 4-13 indicates that due to an increase of particle size the travel distance decreases significantly. The maximum travel distance is approximately 4,5 km for a particle size of 30 μm and almost 2 km for a particle size of 45 μm.

4.2.2. *Balance calculation for increase of bed level*

The previous sub-paragraph shows to what extend a grain particle can travel. In this paragraph an indication is given if near shore bed level increase due to settling of sediment particles could cause near shore coastal problems. For this study it is assumed that the bed level is horizontal, that no erosion occurs and that the concentration level of sediment is spread evenly over the seabed. The balance calculation considers a basin where a fixed sediment concentration level is discharged into over a predefined time period.

The increasing bed level can be calculated by using the following balance equation.

$$\delta = \frac{Q_r * C_r * t_d}{A * \rho * (1-p)}$$
(Eq. 4-2)

With:

      Q_r *= River discharge [m³/s]*

      C_r *= Concentration [kg/m³]*

      t_d *= Discharge time [s]*

      A *= Bed level surface [m²]*

      ρ *= Specific density sediment [2650 kg/m³]*

      p *= Porosity [40%]*

The surface area of half circle is used which is associated with the adaptation length of a particle size of $15\mu m$ and an average flow velocity of 2.5m/s resulting in a maximum travel distance of approximately 10km calculated with the adaptation length from sub-paragraph 4.2.1. A schematic drawing is made in Figure 4-14 to give an indication of the considered sedimentation surface area.
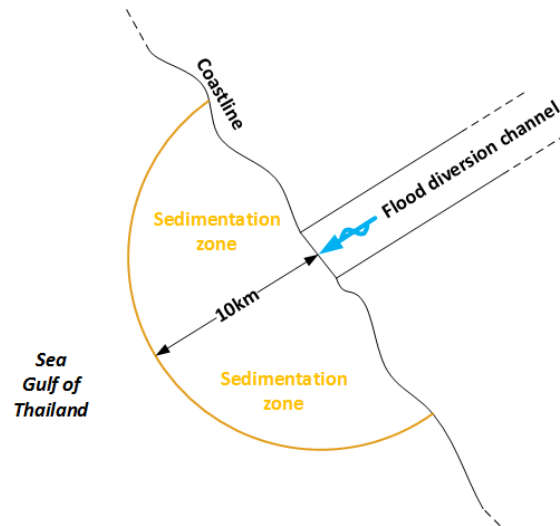
Figure 4-14 Surface area used to calculate the bed level increase

The river discharge is set at 4000m³/s and the concentration levels of 200 and 500mg/l are being used. The increase of bed level depends on the duration of the total discharge. Figure 3-1 shows the relationship of the water level at Chau Doc in the course of time. The highest water level curve (indicated with a red line) is the high water event of year 2000. The total duration of the 2000 high water event was almost 2 months in which a peak discharge period occurred of almost 1 week. This high water event can be schematized using a trapezoidal shaped discharge pattern, see Figure 4-15.
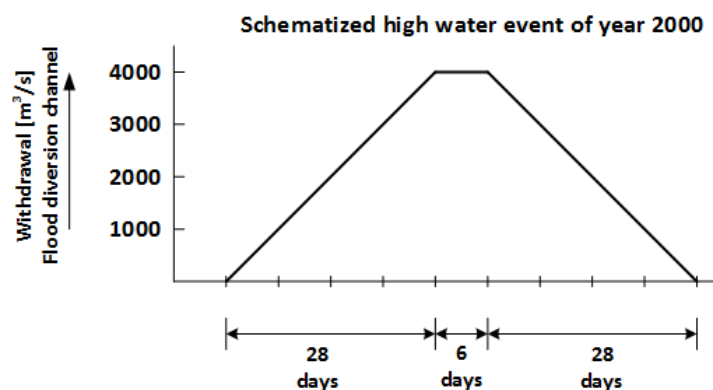
Figure 4-15 Schematized high water event of year 2000

In the first 28 days the diversion channel needs to withdraw water from the Mekong River starting from 0m³/s to the highest withdrawal required of 4000m³/s. When the maximum withdrawal is reached the flood diversion channel withdraws constantly 4000m³/s for 6 days. From day 34 the withdrawal decreases linear from 4000m³/s to

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0m³/s again spread over 28 days. Since it is assumed that the high water event is linearized as a trapezoidal it is also possible to say that for 30 days in a row a withdrawal has occurred of 4000m³/s. The amount of withdrawal is assumed to be equal to the discharge from the flood diversion channel into the Gulf of Thailand.

By using the balance equation (Eq. 4-2) and the made assumptions it is possible to approximate the bed level increase. The results are shown in Table 4-2.

Concentration levels [mg/l]	Mass of concentration [kg]	Bed level increase [cm]
200	$2.07 * 10^9$	0.83
500	$5.18 * 10^9$	2.08

Table 4-2 Balance calculation of bed level increase

The table shows that the bed level increases with approximately 1 to 2 cm over the whole bed level depending on which TSS concentration is used. Looking at the bed level increase this is rather significant and can result in a near shore sedimentation problem.

Intermediate conclusion

Galappatti shows that with sediment sizes between 10 to $15\mu m$ combined with the considered mean flow velocities will not result in a significant sediment deposition at Phu Quoc. Even under the most conservative conditions with the largest radius for a sediment size of $10\mu m$ with a constant 0.4m/s mean flow velocity the travel distance will have a adaptation length of 40km, which is still 10km away from the white sandy beaches of Phu Quoc. Thus, the concern of having a significant impact of sediment at the near shore of Phu Quoc is therefore most probably unjustified.

However, a sedimentation impact problem could occur close to the mouth of the diversion channel. Based on the balance calculation the total bed level will increases approximately 1 to 2 cm during a high water event depending on the chosen discharged sediment concentration level. This increase seems small but in reality the deposition is not equally deposited onto the sea bottom. The expectation is that the deposition will be higher close to the mouth of the diversion channel and will gradually decrease with an increasing distance from the mouth. This could lead to sedimentation problem at the near coastal zone.

To find out if the concern of sediment deposition at Phu Quoc is really not justified and to find out how significant the near shore deposition is a coastal model is made in paragraph 4.3.

4.3.   Coastal impact using computer simulations

To study how the near shore bed level changes due to deposition and erosion a coastal area model has been made. The first sub-paragraph describes briefly how the model has been set-up. Sub-paragraph 4.3.2 describes which simulation runs have been made to determine if sediment deposition can reach the island Phu Quoc and how significant sedimentation can occur near shore. Sub-paragraph 4.3.3 provides the results of the made coastal simulations.

4.3.1.   Coastal area model

For this study the two-dimensional horizontal advection-diffusion model (2DH) has been used, which can be selected within the modelling environment of Delft3D. The schematization uses bathymetry data, which is provided on the online service General Bathymetric Chart of the Oceans (GEBCO). Tidal data has been gained from the online service TPXO. Wind and wave influences are not taken into account in this feasibility study. Tidal predictions of Ha Tien and Kam Pong Som (a coastal city in Cambodia) are used to calibrate the model.

The model has been calibrated by adjusting the roughness of the bed and local constrictions. Water level measurements at Rach Gia are used to validate the model. The diffusion parameter has been selected using a Smagorisky type of approximation that multiplies a constant with the velocity gradient over a horizontal grid cell and the square of the length of a grid cell. The used diffusion parameter is selected to be equal to 30m^2/s. It is important to understand that inaccuracy will occur due to the simplification and assumptions within the schematization. However, for this feasibility study, knowing the influence zone of the dispersion is more important to known than having a full detailed coastal model. In appendix G, the model set-up with the made assumptions, calibration and validation is explained in more detail. In Figure 4-16 the schematization is shown of the coastal zone. The red dotted box indicates the area of interest.
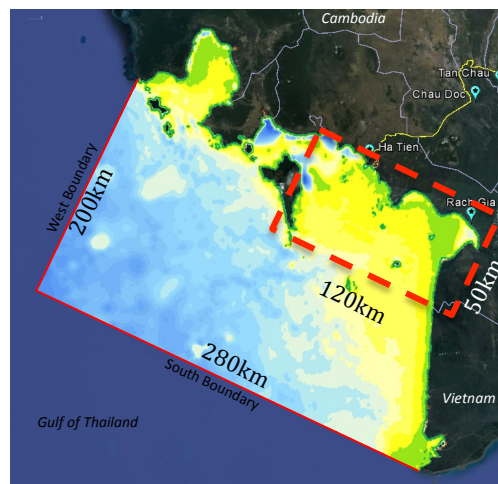
Figure 4-16 Delft3D model area, with bathymetry contours

4.3.2. *Set-up of simulation runs*

This sub-paragraph determines the boundary conditions for setting up the simulation runs. There are two questions to be answered using the coastal simulation:

1. Will sedimentation of fine sediment result in a significant effect at the near coastal zone of Phu Quoc?
2. How significant can sediment deposition be at the near shore?

The simulation runs are both made using the cohesive sediment settings in Delft3D. For these runs, flocculation of cohesive sediments is not taken into account. To be conservative both simulation runs uses a sediment concentration of 500mg/l and a discharge rate of 8000m³/s. The discharge location that can cause the most sedimentation impact is by debouching at discharge location Ha Tien because this location is the closest to Phu Quoc. The computational runs discharging from the Middle locations can be found in appendix H.2. The computational runs will be stopped after five months of computational runtime when no significant changes in bed levels have been noticeable.

The first computational set-up is made to find out if there could be an effect noticeable at Phu Quoc. These boundary conditions are referred to as Method A.

- The sediment type as aforementioned are between 10 to 15 μm. The smaller the sediment type is the lower the fall velocity will be and therefore the larger the travel distance will be. The model run uses a fall velocity corresponding to a sediment type of $10\mu m$, which has approximately a fall velocity of 0.1mm/s.
- The critical bed shear stress for erosion is set rather low at 0.08N/m². How smaller the critical bed shear stress to induce erosion is, the larger the erosion rate will be and thus the higher the sediment dispersion will be. The reason to choose 0.08N/m² is because the tidal currents induce rather low bed shear stresses. These bed shear stresses are between the 0 to approximately 0.1 N/m². If choosing a high critical bed shear stress no erosion would occur once a sediment particle has settled.

The second computational set-up is made to find out if there could be an effect noticeable close to the discharge location. These boundary conditions are referred to as Method B.

- The model run uses a fall velocity corresponding to a sediment type of $15\mu m$, which has approximately a fall velocity of 0.25mm/s.
- The critical bed shear for erosion is first set on the default value of 0.5N/m². This means no tidal erosion can occur (Method B1). A second run uses a bed shear stress of 0.08N/m² to induce erosion (Method B2).

4.3.3. *Results and conclusions of simulation runs*

This sub-paragraph is divided into two sections. The first section shows the results based on the boundary conditions of Method A. The first model run has been made to find out if there could be a noticeable sediment deposition effect at Phu Quoc Island. The second section shows the results based on the boundary conditions of Method B. These model runs have been made to find out how significant the near shore sediment deposition can be.

Results using Method A
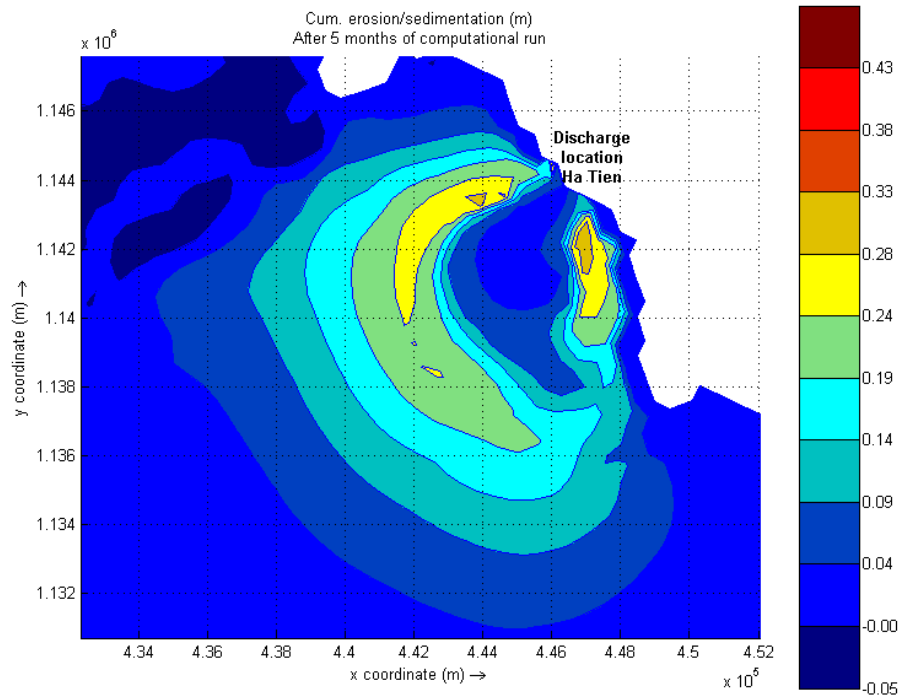
Figure 4-17 Simulation run with boundary conditions (A) with the discharge location Ha Tien. The figure shows the cumulative erosion or sedimentation against the initial bed level in m.

The sediment dispersion under the conditions of Method A is shown in Figure 4-17. In the previous paragraph the maximum travel distance of a single grain of $10\mu m$ is approximated to be 40km under the most conservative situation. The computational result shows that the dispersion length is confined to a length of approximately 14km starting from the discharge location. The reason for a smaller maximum travel distance could be, because the velocity gradient is not constantly 0.4m/s and also the travel route will not constantly be directed towards Phu Quoc, see Figure 4-18. The figure shows the modelled depth average velocities at an observation point approximately 5km away from the discharge location Ha Tien. The depth average flow velocity alternates between 0.1 to 0.3 m/s. The direction of the combined depth velocities alternates along the coastline, see Figure 4-18 left panel.
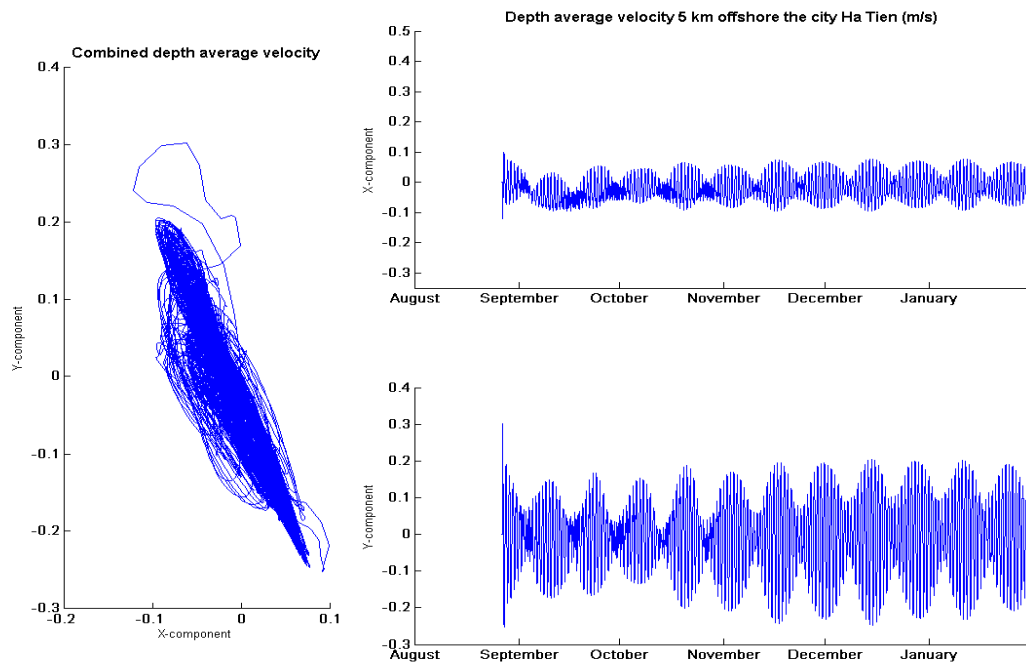
Figure 4-18 The depth average flow velocities in m/s. The left panel shows the depth average flow velocity gradient within the observed grid cell. The right panels show the depth average flow velocity in x- and y-direction

Conclusion: Method A

Based on the hand calculations and model results using Method A, it is possible to determine that sediment debouching (even from the closest discharge location Ha Tien) will not cause the feared sediment depositional impacts on the white sandy beaches of Phu Quoc. Also, the model has been set-up as conservative as possible therefore the occurrence of flocculation has not been taken into account for. If flocculation were also taken into account the sediment deposition will only be more confined to the discharge location.

Besides that the calculations and model results indicates that Phu Quoc will not be harmed by the dispersion of sediment from the flood diversion channel the current natural coastline between Ha Tien and Rach Gia also indicates that the sedimentation concern is most likely not possible. Currently approximately twenty smaller irrigation/drainage channels are already debouching into the Gulf of Thailand between Ha Tien and Rach Gia. Besides that the coastline at the moment is sandy to muddy, see sub-paragraph 2.2.1 these already existing natural muddy situations do not show signs of disturbing the coastline of Phu Quoc.

Results using Method B

The first computational run uses Method B1. This method neglects the possibility of erosion induced by the tidal currents. The results are shown in Figure 4-19.
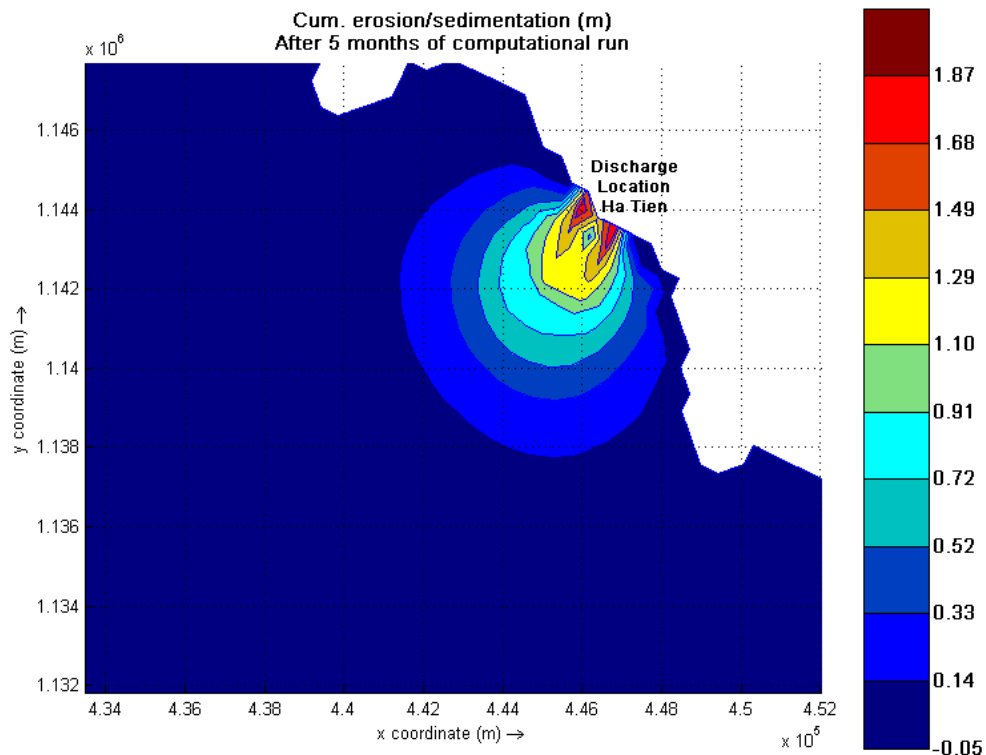
Figure 4-19 Simulation run with boundary conditions (B) and with the critical bed shear stress set on 0.5N/m².
The figure shows the cumulative erosion or sedimentation against the initial bed level in m.

Figure 4-19 shows an almost symmetrically sediment deposition pattern. The travel distance is confined within a stretch of approximately 6km. Based on the calculations made in sub-paragraph 4.2.2 it can be concluded that if sediment deposition is spread evenly over the whole bed level the increase in bed level is approximately 2cm. The model result shows that near to the mouth of the flood diversion channel spots can be found with significant bed level increases, which are approximately 1.7m high. The bed level gradually decreases with an increase distance from the mouth.

The second computational run uses Method B2. This method does involve the possibility for sediment to be eroded by the tidal current see Figure 4-20. The computational run shows that the travel distance has a stretch of approximately 10km. The bed level increase close to the mouth of the discharge location has spots that are approximately 0.90m. The deposition gradually decreases with an increasing distance starting from the discharge location.
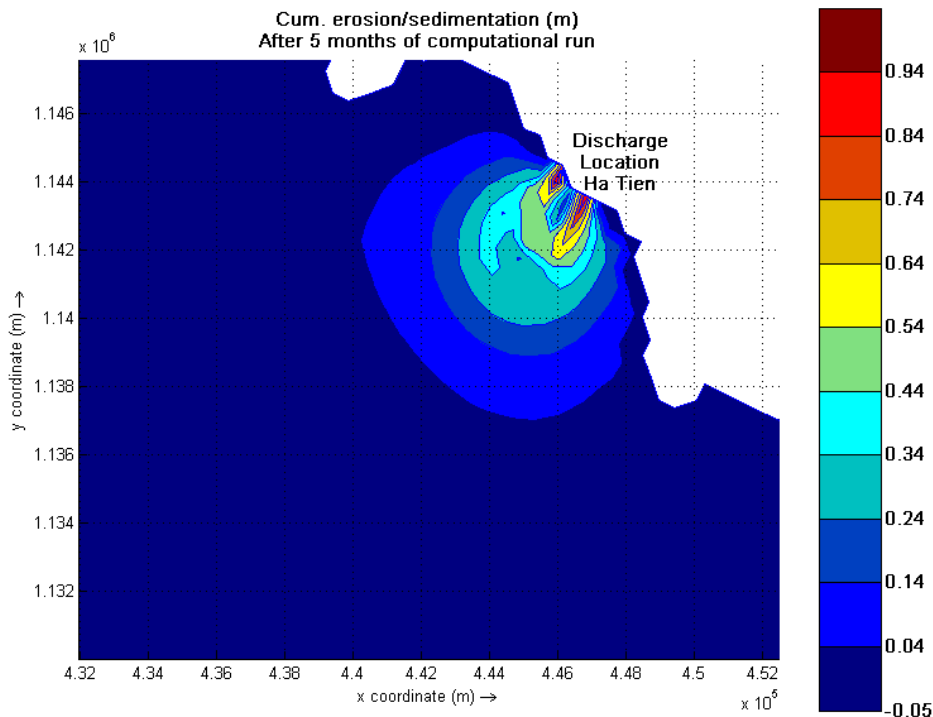
*Figure 4-20 Simulation run with boundary conditions (B) and with the critical bed shear stress set on 0.08N/m².
The figure shows the cumulative erosion or sedimentation against the initial bed level in m.*

Conclusion: Method B

The model results found with method B are in line with the expectations based on the hand calculations made in sub-paragraph 4.2.2. The model results do indeed show that sedimentation problems can occur close to the discharge location. Method B1 is a conservative model run. However, if flocculation is taken into account larger flocs are deposited closer to the near coastal zone and therefore in line with the model outcome of B1. Higher bed shear stresses are then required to erode the larger floc sizes. Method B2 does allow already deposited sediment to erode. The sediment deposition is still confined to the discharge location. However, the sedimentation is less significant than in the situation if erosion is not taken into account.

Based on the model results it is not possible to indicate the exact amount of bed level increase caused by the debouching flood diversion channel. In reality other mechanisms can alter the amount of sediment deposition or erosion. If flocculation of cohesive sediment occurs, the fall velocity will increases and therefore more sediment will be deposit closer to the flood diversion channels mouth. A mechanism that can cause more erosion is for example (waves induced) long shore currents. Most probably the sedimentation at the discharge location will be transported with the long shore current along the coastline.

The results show that it is rather certain that sedimentation will occur at the near coastal zone. However, this sedimentation does not have to be a reason to prohibit the construction of a flood diversion channel. From an environmental point of view the

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impact of sediment deposition onto the near coastal zone is negligible because along the whole coastline no coral reefs or popular touristic beaches are situated. Discharging from the Middle location can even have a positive side effect. At the moment the coastline between Xom Ba Tra and Rach Gia small spots of mangrove rehabilitation areas are situated. These mangroves areas are not used to protect against storms/typhoons but to prevent the coastline from eroding see Figure 4-6. The advantage of discharging at the Middle location is that the extra deposition of sediment at the near coastal zone can be helpful to reduce the on-going erosion of the coastline, see sub-paragraph 2.2.1.

4.4. *Conclusion on the possible coastal impact*

The study made in the previous paragraphs finds out if due to the discharge of the flood diversion channel a significant deposition of sediment is possible at the Island Phu Quoc or at the near coastal zone around the discharge location. The main findings in the previous paragraphs of this chapter are first summarised and then discussed. Based on that the preferred channel route and discharge location will be chosen.

Sediment information and discharge location

From studies made by Nguyen Nghai Hung (2011) it is possible to indicated that the sediment type within the Mekong River are between the 10 to 15μm with a concentration level of approximately 200mg/l. The concentration level of sediment will most probably increase due to the pick-up of sediment within the newly constructed flood diversion channel. Therefore, the concentration level is set to a conservative level of 500mg/l.

The study on potential discharge locations shows that the choice Rach Gia as location will result in the highest re-location activities. Therefore, this discharge location is not suitable as possible discharge location and is therefore not further considered as a possible discharge location option. The other discharge locations Ha Tien and Middle location do have the potential to be used as discharge location.

Hand calculations

The first calculations have been made to find out what the maximum travel distance is for a single grain cell considering a constant mean flow velocity and water depth. The most conservative situation to gain as much travel distance is to consider the smallest possible sediment size of 10μm with the maximum possible flow velocity. The maximum travel distance is then approximated to be 40km. With this simple calculation it is already possible to say that significant sedimentation caused by discharging into the Gulf of Thailand cannot reach Phu Quoc Island which is located 50 km away from Ha Tien. Furthermore, if flocculation and fluctuating flow velocities are taken into account the maximum travel distance will then decrease even more.

The second made hand calculation is to find out how much the seabed will increase due to discharging sediment rich floodwaters. The most conservative situation is to take reasonable high sediment concentration level associated with a small depositional area. Therefore, a concentration level of 500mg/l is used with a radius of 10 km. The radius is is associated with the maximum travel distance of a $15\mu m$ particle that travels with the average flow velocity of 2.5m/s. By discharging 4000m³/s for 30 days the bed level increases with approximately 2cm over the considered seabed area (a half circle). With this simple hand calculation it is possible to say that there is a possibility that sediment deposition at the near coastal zone can cause significant sedimentation.

Computational runs

The outcome of the computer models does confirm the already expected results based on the aforementioned hand calculations. For the first model run a conservative situation is used to find out if sedimentation deposition can affect the island Phu Quoc. The conservative situation was a sediment size equal to $10\mu m$, a discharge rate of 8000m³/s and a sediment concentration level of 500mg/l with sediment that does not flocculate. The model run shows that the sediment deposition is confined to a depositional length of approximately 14km from the discharge location. This means that even when taking a conservative situation as considered in the first model run shows that sediment deposition near Phu Quoc Island cannot occur.

The second computational run is to find out what the impact can be close to the discharge location. The second model is set-up using a sediment size of $15\mu m$, a discharge rate of 8000m³/s and a sediment concentration of 500mg/l. Two situations have been considered: one without erosion and one with erosion. The one without the possibility of erosion does show a significant increase of the bed level close to the discharge location with spots of approximately 1.7m of bed level increase. The second model run in which erosion is taken into account for shows that the sedimentation will spread along the coastline. The highest spots are approximately 90cm close to the discharge location.

The outcome of the second model results cannot provide the exact bed level increase because mechanisms like sediment flocculation and waves induced sediment transport have not been taken into account for. These mechanisms can alter the erosion and deposition impact. However, the near coastal sedimentation does not have to be a reason to prohibit the construction of a flood diversion channel. The current natural environment of the coastline does not prohibit the deposition of additional sediment. Besides, if the discharge location is situated at the Middle location the sedimentation could even be helpful to stop the on-going erosion of the coastline between Xom Ba Tra and Rach Gia.

Preferred channel route and discharge location

The study shows that even under a conservative situation the concern of sedimentation effects at Phu Quoc is unjustified and will most likely not occur. The sediment deposition study does show that significant sedimentation can occur close to the discharge location.

Discharging at Ha Tien has the benefit that the least amount of re-location activities is needed. However, the route of the diversion channel starting from Chau Doc and discharging at Ha Tien is 85km and therefore longer than the diversion channel discharging at the Middle location which is 70km. The disadvantage to discharge at the Middle location is however that more re-location activities are required. Considering both options, the most preferred discharge location for the flood diversion channel is – to my opinion – to debouch at the Middle location. This is due to the fact that discharging at this location will have an addition advantage to the environment, namely it can help in supplying sediment to the on-going erosion of the coastline between the cities Xom Ba Tra and Rach Gia. Considering these benefits the preferred discharge location for the flood diversion channel is to debouch at the Middle location using route option 2a.

5.   Conclusions & Recommendations

This chapter concludes the findings of the feasibility study. In the second half of this chapter the recommendations are given for follow-up studies. The objective of this research was to find out how realistic it is to construct a flood diversion channel as measure to reduce flood risks in the Mekong Delta.

The main research question was:

How feasible is it to construct a flood diversion channel between the Mekong River and the Gulf of Thailand to reduce flood risks caused by the Mekong River?

To find an answer to the main research question four sub-questions have been formulated.

1. *What is the minimum required withdrawal of the flood diversion channel to reduce flood risks?*
2. *What is the required dimension of the flood diversion channel to withdraw the required withdrawal from the Mekong River?*
3. *What are the costs of constructing a flood diversion channel?*
4. *What is the impact of discharging sediment rich floodwater into the Gulf of Thailand?*

5.1.   Conclusion

The growing demand for rice products nationally and internationally has pushed the farmers to also harvest agricultural products during the wet season. The yearly returning flood, which was a blessing is gradually becoming unwanted. In addition to that the growing population and urbanization decreases the acceptance for the yearly floods. Future expectations on climate changes indicate that flooding problems will only increase and eventually affect the whole Mekong Delta. A possible solution to cope with flooding is to construct a flood diversion channel between the Mekong River and the Gulf of Thailand. The study made in this thesis is to find out if a flood diversion channel is a realistic solution to be considered as flood risk measure.

The study shows that a shallow or deep diversion channel can indeed lower the water levels in both main river branches in the Mekong Delta considering a flood situation as that of the year 2000 with a withdrawal necessity of approximately $4000 m^3/s$. The location of withdrawal does not have a significant influence on the required withdrawal. The diversion channel does show that if climate change situations are taken into account, it will only be capable to lower the water level in the Hau River. The withdrawal requirement increases from $4000 m^3/s$ to $6000 m^3/s$ in a moderate climate change situation and it will increase to $8000 m^3/s$ in a high climate change situation. However, to

mitigate the effects of future climate change for both river branches the results show that a single flood diversion channel as measure is not sufficient enough. To also reduce flood risk induced by the Tien River it is best to also consider taking additional measures. If additional measures are not taken, the withdrawal necessity of a single flood diversion channel at the Hau River will become unrealistically high. The withdrawal becomes almost equal to the yearly average discharge of the Mekong River.

Two alternative diversion channels have been researched; an extremely wide but shallow channel and a deep but relatively narrow channel. The route of the shallow channel is bound to the existing topographic slope. In order to withdraw 4000m^3/s the width of the shallow channel must be at least 12.4km wide. The significant width of the shallow channel is however not the only disadvantage of this construction but also the discomfort of having a large area inundated with approximately 1.7m water depth for a long period of time during a high water event. In the case of a deep channel the depth of the channel needs to be at least 9.7m to be competitive as trade route with Phnom Penh against the Hau River. The corresponding width is 340m in order to withdraw 4000m^3/s. Both channel types require additional hydraulic structures to prevent inundation or salt intrusion at the discharge location of the flood diversion channel. The shallow channel requires flexible weirs (rubber dams) and the deep channel requires sluice gates and a ship lock to provide a passage between the sea and flood diversion channel.

A rough cost estimate was made to determine the costs involved when constructing a deep or shallow channel. The study showed that a shallow channel is significantly cheaper to construct. However, the shallow channel has a continuous returning expense. This expense is the payment for damage due to floodwaters affecting farmers or households during a high water event. The costs, also called the restitution payment, will eventually make the shallow channel the more expensive solution in the long run. The break-even point is reached after two succeeding high water event has occurred. Every following high water event results in a situation where it is better to have constructed a deep channel. The biggest part of the initial costs to construct a deep channel is due to the excavation of the channel. Although the initial high costs make the deep channel less attractive there are possibilities to lower these cost or to generate income from a deep channel. It is possible to re-use the surplus of excavated soil or to collect additional income by placing taxes for the usage of the newly made navigational trade route with Cambodia. These advantages are not possible if a shallow channel is considered.

Sediment deposition impact studies show that the concern of harming the coastal zone at Phu Quoc Island is unjustified. The travel distance of even the finest sediment particle is confined to approximately 14km from the discharge location. However, sediment deposition close to the discharge location can be significant. It is not possible to determine the exact bed level increase based on the calculated results because mechanisms like sediment flocculation and waves induced sediment transports are not

taken into account for in this study. Although the exact near coastal impact cannot be determined, what can be concluded based on the calculations is that the sedimentation at the near coastal zone does not have to prohibit the construction of the flood diversion channel. This is because the near coastal zone does not have any coral reefs or popular touristic beaches. Besides, the current coastline near the Middle discharge location shows signs of an eroding coastline thus supplying additional sediment by debouching at this location can be a welcoming positive effect on the coastline.

Considering the results of this feasibility study it is possible to determine the preferred diversion channel. The most preferred flood diversion channel is to construct a deep channel of approximately 70 km long and depending on the withdrawal necessities the width of the channel will be between the 340 and 680 meters. The flood diversion channel withdraws at Chau Doc, goes along the Vinh Te channel for as long as possible and crosses the K. Tam Ngan channel to eventually discharges at the Middle location into the Gulf of Thailand, see Figure 5-1.
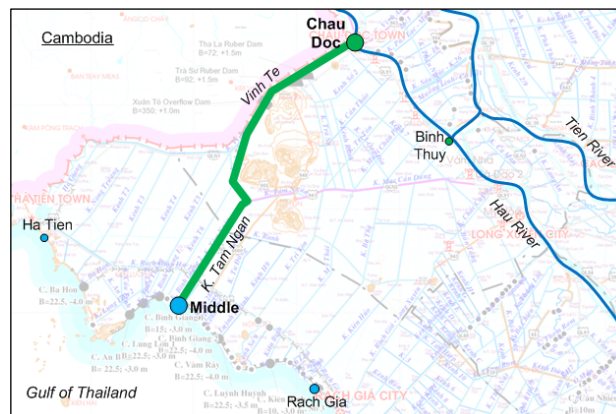
Figure 5-1 Preferred diversion channel route

5.2. Recommendations

A diversion channel from the Mekong River to the Gulf of Thailand has been researched in the previous chapters. Assumptions and simplifications have been made to come to the above given conclusions. In the following, recommendations are given for follow-up studies.

General recommendation

Probabilistic approach:

- A moderate and high climate change scenarios were taken into account by applying a percentage on a known high water discharge. It is recommended that for a follow up study probabilistic discharge calculations need to be performed to determine the design discharge levels.

Land overflow from Cambodia and Rainfall:

- The requirement of the diversion channel is now based only on diverting water from the Mekong River. Follow up studies should also account for the yearly land overflow from Cambodia and the extensive rainfall over land.

Taking periodic measurements:

- The availability of data is little and does not always seem reliable. The calibrations of both hydrodynamic models are based on the limited available information. More measurements can lead to the possibility of extensive calibration and therefore enhances the confidences in the models. It is recommended to start own measurements on water levels and discharge levels.

Methodology recommendation

Enhancing river model with additional side channels:

- The Mekong River is schematized as if it is build out of two large branches with an additional channel in between. The model is calibrated with the available data and after validation the model does give reasonable results. However, the Mekong delta consists of hundreds of smaller channels, which are all linked to each other. These channels have a unique buffering effect. The schematised model lacks in representing these channels. The model also lacks the ability to represent how these smaller channels alter the hydro- and morph-dynamics once a diversion channel has been implemented.

Implementing additional open boundaries in coastal model:

- The coastal model is set-up with a closed coastline system. It therefore lacks the ability to represent the inflow of fresh water coming from the debouching smaller irrigation channels. In reality approximately twenty small channels discharges into the sea along the coastline between Ha Tien and Rach Gia. In addition to those smaller channels one larger channel discharge directly into the funnel shaped bay at the south of Rach Gia city see Figure 5-2. These channels have not been represented in the model but they can alter the behaviour of the coastal model.
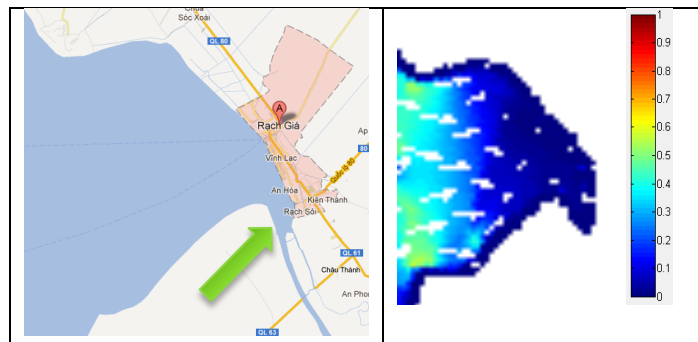
Figure 5-2 Funnel shaped bay in front of Rach Gia. The left picture is an aerial picture of the funnel. Right picture is a depth-average flow velocity during flood tide.

Using more realistic cross-sections or curved grid cells instead of the assumed rectangular shapes:

- The river model could be enhanced with real cross-sectional variation and river bends. Rectangular cross-sections are used to schematize the flood diversion channel. In practice an excavated channel of almost 10m deep cannot be perfectly rectangular. The channel shape would come closer to a trapezoidal shaped cross-section. The calculations made in the feasibility study on the required width is therefore a under estimation. For follow-up studies it is recommended to consider more realistically shaped cross-sections.
- The coastal model could be enhanced with curvilinear cells to remove the errors made close to the coastline. Even better is to make use of unstructured grid cells, therefore giving more detailed resolutions to the areas that matter like near the entrance of the discharge location. It is also recommended to decrease the grid size to gain more resolutions. It has to be kept in mind that by introducing more details the computational run time would increase significantly.

Sedimentation in the flood diversion channel and the requirement for maintenance dredging

- The feasibility study has only considered the possibility of sediment deposition onto the coastal zone. It is assumed that sediment from the Mekong river travels as fully suspended wash load to the Gulf of Thailand. However, the significance of

sedimentation during normal conditions in the deep flood diversion channel is not considered in this thesis. For follow up studies the significance of sedimentation within the flood diversion channel must be studied and it is recommended to also study the required maintenance dredging to retain the required navigational depth. In addition to the maintenance dredging it is also required to study if the return costs outweighs the advantages of having a deep flood diversion channel.

Coupling River and Coastal:

- Enhancing the coastal model with a diversion channel can indicate what the interactions are between the diversion channel and coastal hydro- and morph-dynamics: like the effect of saltwater intrusion or sedimentation blockage due to sedimentation at the near shore. The conclusion made in paragraphs 4.2 and 4.3 did indicate the possibility of sedimentation at the location where the flood diversion channel debouches. This could lead to blockage of the passage between the flood diversion channel and the Gulf of Thailand. By coupling the river and coastal model these effects can be studied.

Sediment flocculation:

- By considering density differences of the salt seawater and fresh river water in the coastal model, it becomes possible to physically induce how sediment is flocculating. This adjustment of the model can provide a better indication on how sediment is deposited at the near coastal zone. The expectation is that more sedimentation occurs closer to the discharge location due to this flocculation mechanism.

Waves and wind:

- The affects of wind and waves are not considered in the model. This mechanism can alter the sediment dispersal behaviour. Most probably the sediment dispersion coming from the flood diversion channel will be transported along the coastline.

Tidal influence:

- The dimensions of the diversion channel are calculated without the influence of the tide at the channels mouths. Due to neglecting of tidal variations the required width of the flood diversion channel is possibly higher than what is calculated in this feasibility study.

<u>Unconsidered alternatives</u>

- The study made in this thesis focus only on the feasibility of a single flood diversion channel. However, there are several alternatives, which could lead to a reduction of the required withdrawal level and/or the reduction of the required dimension of the flood diversion channel.
  - One of the alternatives is to consider widening or deepening the main river branches Tien and Hau and therefore reducing the necessary withdrawal level of the flood diversion channel.
  - A second alternative is to construct several small flood diversion channels or to consider constructing two separate flood diversion channels. One that withdraws from the Tien River and one from the Hau River.
  - Another alternative is to consider a diversion channel that combines a deep channel *(Dutch: zomerbed)* with shallow floodplains *(Dutch: winterbed).* The advantage is that during normal situations the (smaller) deep channel is used as navigational route and the floodplains can be used to cultivate agricultural products. When a high water event occurs the shallow floodplains are temporary used to increase the drainage capacity of the flood diversion channel. By combining a deep channel with shallow floodplains the initial costs to construct a deep channel are reduced because less excavation activities are required. Besides that, also less restitution payments are required because the floodplains are smaller and with proper management the floodplains can be a restricted area to construct buildings. This could result in a reduction of the assumed restitution payment, because only loss of agricultural products (which are relatively cheap) has to be cover by this costs expense. The disadvantage is that with combining the diversion channels it is also necessary to construct both a ship lock/sluice gates and flexible weirs. However, excavation and restitution payments are the highest costs expenses in the rough costs estimate, so to reduce these expenses is most probably more beneficial than the disadvantage of constructing both flood defences.

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Appendix

A.   Mekong Delta Plan

In history several institutes and companies have already looked at the possibility of diversion discharging the Mekong delta. This paragraph serves as platform to elaborate what is known on diversion discharging the Mekong River prior to setting up this thesis.

NEDECO: Master Plan for the Mekong Delta (1993)

The idea of discharging the Mekong River to the Gulf of Thailand started within the Master Plan for the Mekong Delta by NEDECO written in 1993. For this master plan a (sub) reports have been made to research this possibility with the idea that if flood production is increasing in the future more flood control is needed. A given option is to create a diversion channel, which crosses the Long Xuyen Quadrangle from the Main River towards the Gulf of Thailand. The advice given in the NEDECO report is that extensive full flood control is better undertaken at regional scale i.e. rising embankments (roads) or closing off primary channels. However, if is also told that regional protection in the long run is better to extend cross-borders.

Unfortunately this (sub)-report is lost in time. Detailed calculated information and assumptions are unknown. However, experts in Vietnam say that the idea of having the diversion channel is stopped because the calculated dimensions where unacceptable.

Mekong River Commission: Basin Development Report (2005)

Within the Mekong River Commission Basin Development Report in 2005 again the idea came up to drain towards the west sea. This idea does coincide with the outcome of this prefeasibility study. They also had the idea to drain using the Vinh Te channel by enlarging the bottom width of the channel and to enlarge the flood plains along the Vinh Te channel to a possible discharge during flood situation of 1940m^3/s (used flood in 1961). Judging from that report they still need to conduct a feasibility study on this idea.

Mekong Delta Plan by DHV and partners (2012)

Funded by Nla agency Partners for Water Program the Mekong Delta Plan project is set-up. In cooperation with; Royal Haskoning, Deltares, Waganingen University, Rebel Group and Unesco-IHE. DHV provides advisory service and strategic guidance for developing the Mekong Delta. This joint partnership provides firm recommendation on water management and climate change adaptations in relation with the user functions in the delta and guidance for further (sub) regional planning and formulation of investments.

The advisory service and strategic guidance are based on economic growth or stagnation scenarios. Overview of these scenarios is given in Figure A-1.

- If there is economic stagnation the unemployment rate will increase. People will live in slums that are scatter all over the delta; most probably land cultivation products become the most dominating land use. It results in a situation where Food-Security is key.
- If there is economic growth, it can again go two ways. Either an intensification of agro-businesses or an intensification of industries. Strategically seen spatial planning is key in this situation.

The above mentions possible future scenarios can be reached by using measurements as a tool to steer towards the desired scenario. Some measurements are good for one scenario but not suitable for another scenario. However, there are measurements that are robust enough. Meaning that by using these measurements it is beneficial to each scenario. For more detail on all the kinds of measurements see (Dick Kevelam & Project Team, 2012).

One robust measurement is creating a diversion channel between the Hau River and the Gulf of Thailand. To deal with inundation during the wet season caused by high peak discharges. The aim of this thesis is to research the feasibility of constructing such diversion channel.
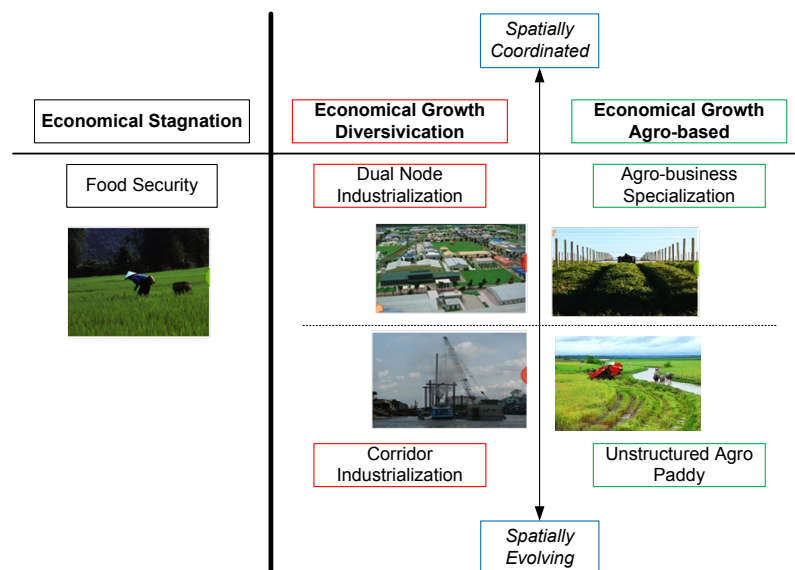
Figure A-1 Mekong Delta Plan Scenarios

B.   Additional Information

B.1.   *Return period*

The return period is made on the information given by (Haruyama, 2011). These where Japanese researches who also did investigations on the Mekong River. Unfortunately the return period graph was limited to 5 quantitative values. The correctness of the information is not known. The lack of data prohibits making an own probabilistic approach. The graph showed that a water level of 4.80m+msl is equal to approximately 1 in 25 year.
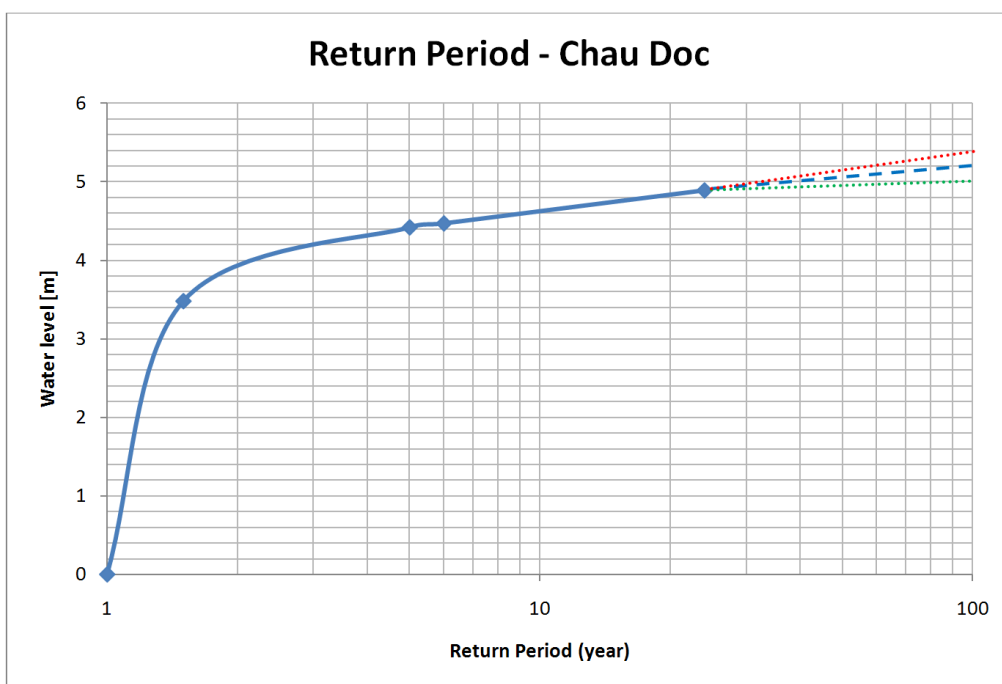
Figure B-1 Return period based on information gained from (Haruyama, 2011)

B.2. *Wind and wave data*

The collected data on wind and waves are model predictions based on 22992 model records collected between 1992 and 2010 (Argoss, 2012). During the N-E monsoon, the wind direction is, as specified, mainly from northeast/east direction. Likewise, during the S-W monsoon, the wind direction is mainly from west/southwest direction. In Figure B-2 two wind roses are shown.
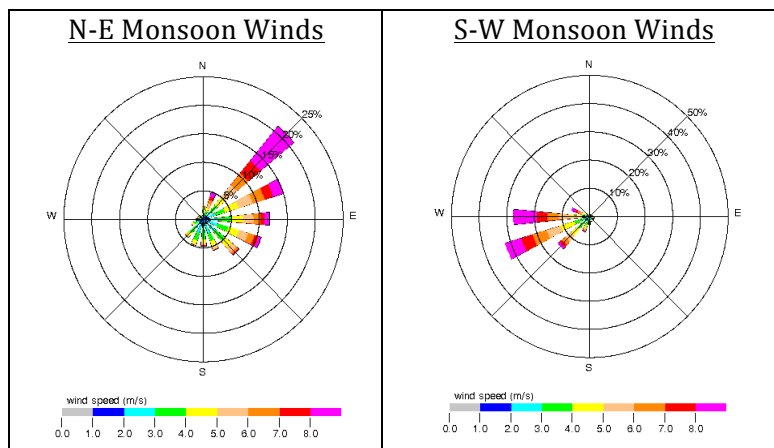
Figure B-2 Wind Rose of Monsoons (Argoss, 2012)

Waves near the coast of Thailand coincide with the dominant wind directions. These waves vary between 0.5-2.5m. A peak is seen from the southeast directed towards the northwest during the N-E monsoon period. This peak is caused by distanced storms. The range of these swell waves is at maximum 1m.
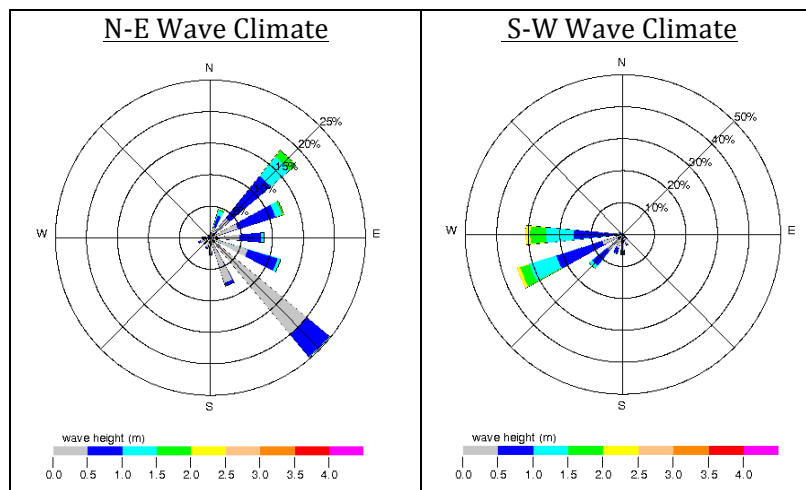
Figure B-3 Wave Rose of Monsoons (Argoss, 2012)

B.3. Cross-sections main river system

At the moment of making the Sobek model these five cross-sections where available. Cross-sectional information given by the MRC website is used.
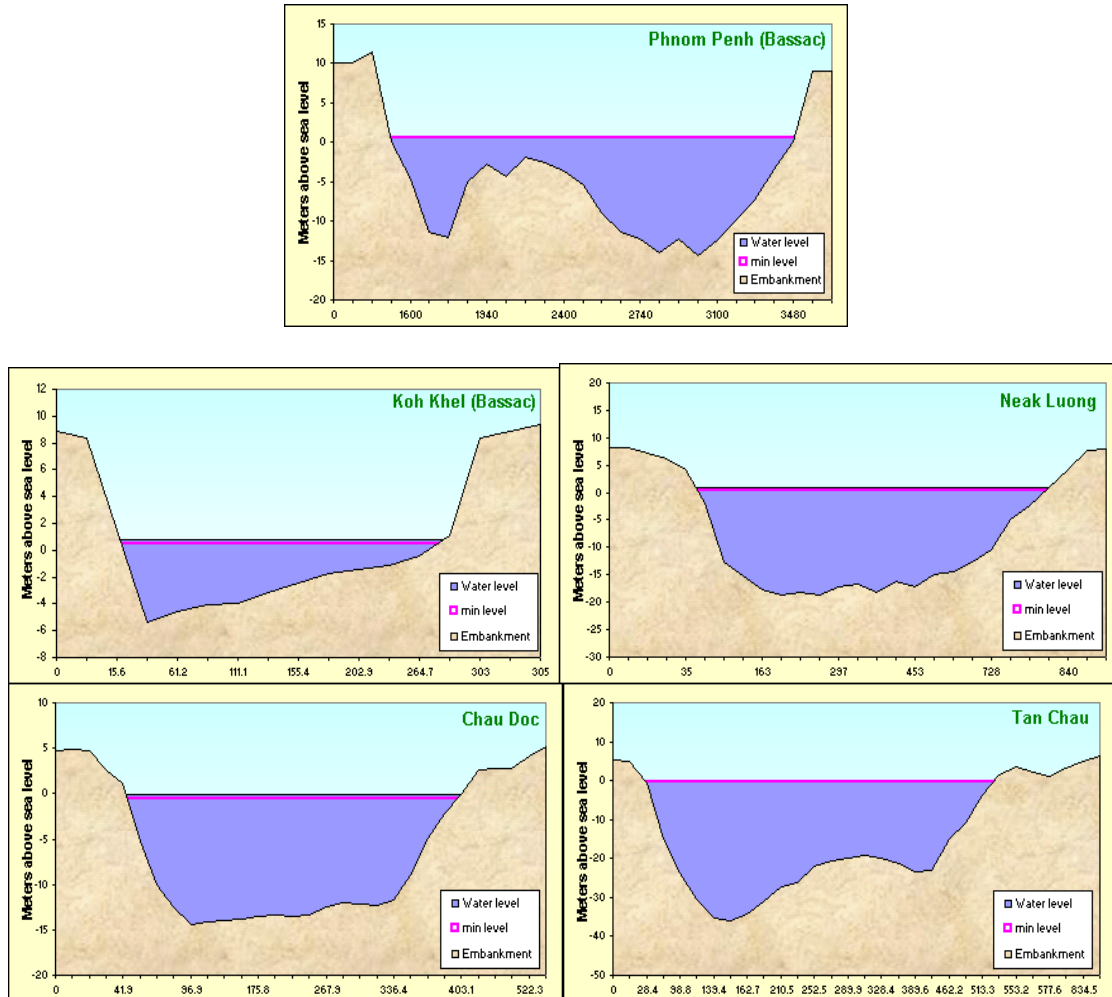
Figure B-4 Corss-sections used in Sobek model

After the trip towards Ho Chi Minh City more cross-sectional information is gain. The available cross-sections of the lower Mekong River is given in Figure B-5. Although this information is gained, the extra cross-sections are not implemented into the already made Sobek model. The reason for this is because adding more cross-sections would not significantly improve the made 1D model. However, it is placed into the appendix as extra reference material for possible follow-up studies. The y-axis is the depth against mean sea level in [m] and on the x-axis the width of the cross-section is given in [m]. A number indicates the coloured lines, which correspond with the distance between the measured cross-section and the starting point of mentioned channel measured in [km].

Hau River
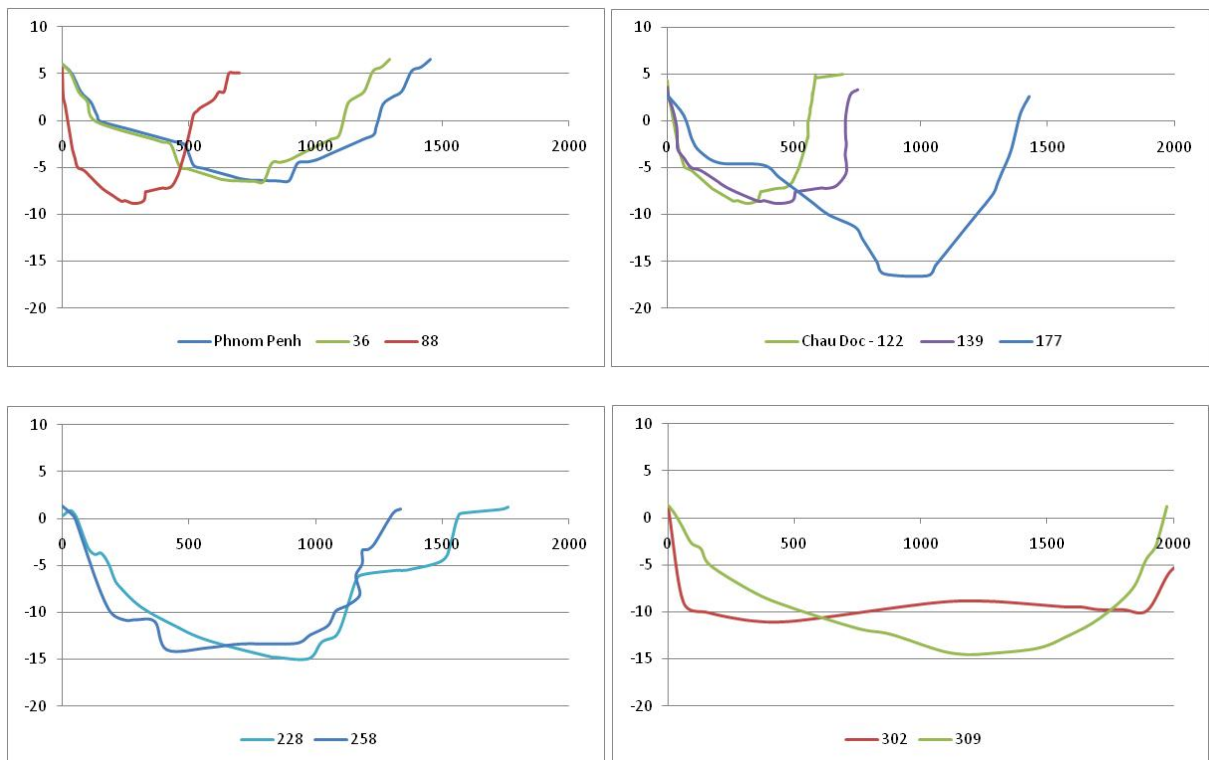
Tien River
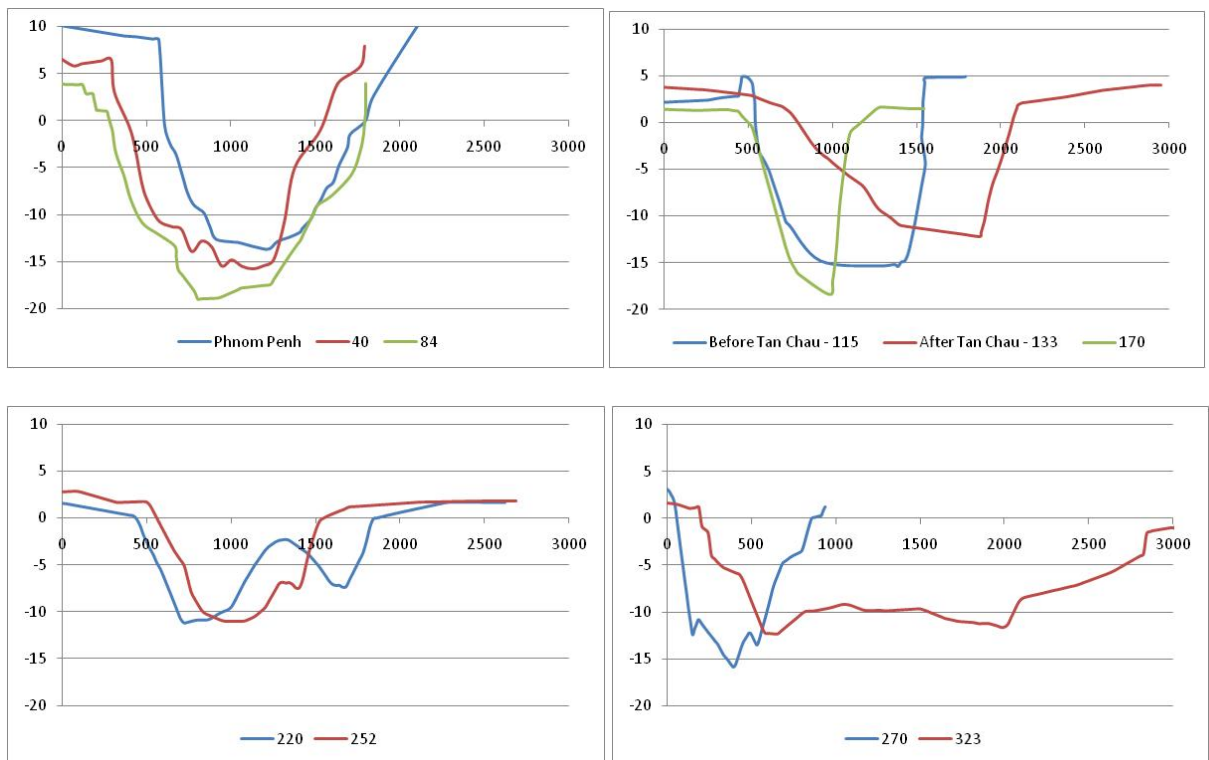
Figure B-5 Cross-sections Lower Main Mekong River

In Figure B-6 the cross-sectional information based on the Vinh Te channel, which lies close to the border of Cambodia and Vietnam is given.
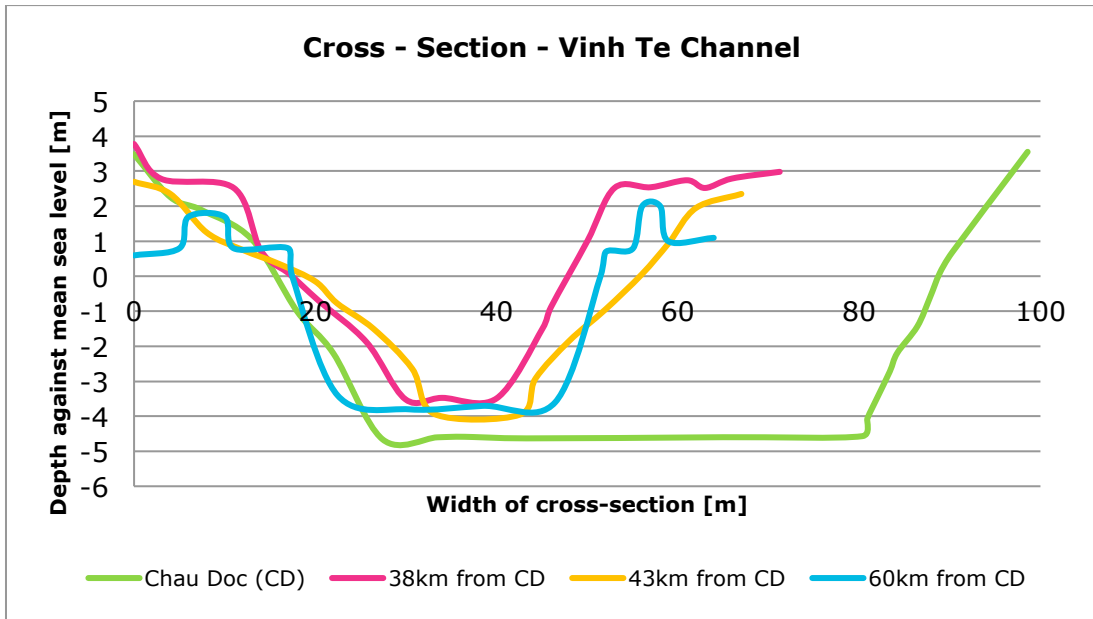
Figure B-6 Cross-section Vinh Te Channel

The green line is at the attachment point, quickly after that attachment point at Chau Doc the width stabilise itself around a surface width of 70m.

C. Preliminary calculations

C.1. Diversion channel weir calculations

To consider this the Bernoulli equation for rectangular weirs is used.

$$Q = f W_s \sqrt{g} \left(\frac{2}{3}\right)^{\frac{3}{2}} (H_1 - Z_s)^{\frac{3}{2}}$$
(Eq. C-1)

With:

f	= Drowned reduction factor [-]
g	= Acceleration due to gravity [m/s²]
W_s	=Width across flow section [m]
H_1	= Upstream energy level [m]
Z_s	= Crest level of the weir [m]

The amount of discharge over the weir mostly depends on the height of the weir and on the width across flow section. For further elaboration on the above equation a referral is made towards the technical manual of Sobek.

To determine the required weir height depends on which discharge capacity the main rivers can clear. At the average yearly discharge based on (MRCS & KOICA) which is around 13000 m³/s results in a minimum water height at Chau Doc of 1.2m. However year 1998 was the lowest peak water level recorder at Tan Chau in the time between 1997 and 2000. The water level for that year at Tan Chau equals to 2.8m and for Chau Doc 2.5m. Both are far beneath the flood level limits. In Figure C-1 a linear Q-H relationship is given at Chau Doc.
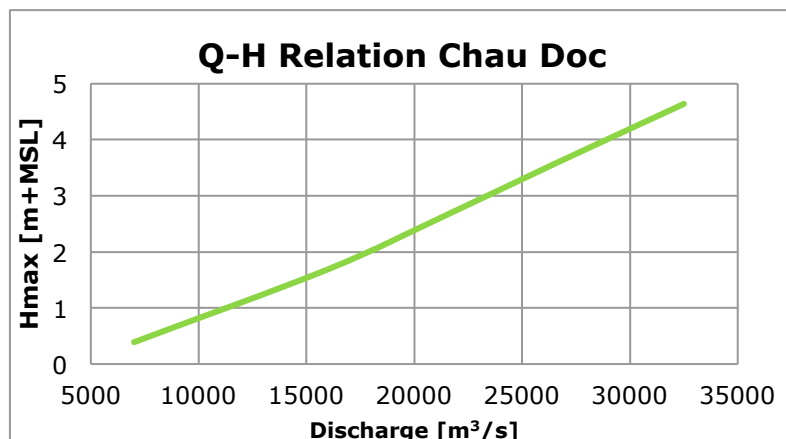
Figure C-1 Q-H Relation Chau Doc

Concluding from the figure above, it is wise to set the weir height at least at 2.5m. To prevent discharges, as that of 1998 to also discharge via the diversion channel. Of course it is possible to go higher. However, with the same diversion channel depth a higher weir

height crest results in a larger width across flow section to discharge an equal amount ($4000m^3/s$) needed to lower the water level in the main river system. A drawback in implementing a weir is that the discharge now highly depends on the dimensions given to that weir. The dimensions of the diversion channel can only negatively influence the discharge over the weir due to the occurrence of the situation called drowned flow. For a deep channel this drowned flow problem is not of any concern.

C.2. *Inundation volume year 2000 and retention area*

The possibility to store water until the high peak wave is over is looked at in this paragraph using a very crude method. The idea is to store water within a retention area and that that area has the same depth everywhere. First the inundation volume from 2000 is evaluated; afterwards the required area if a retention area is used.

In paragraph 2.1.7 Figure 2-9, the flooding of year 2000 is shown. The most heavily struck areas were the flood plains Long Xuyen Quadrangle (440.000 ha) and the Dong Thap Muoi (560.000 ha) area. The combined area of these two flood plains is around 1 million ha. This is somewhat 25% of the total Mekong Delta, which is approximately 3.9 million ha.

The water level in het main river system rises above flood level limit in the year 2000 from the beginning of September till the end of October this is approximately 60 days based on the graph shown in Figure 3-1. Seen from Figure 2-9 the inundation depth varies between the 2.5m to 1m relative to MSL for the Long Xuyen Quadrangle and 4m to 2m relative to MSL for the Dong Thap Muoi area.
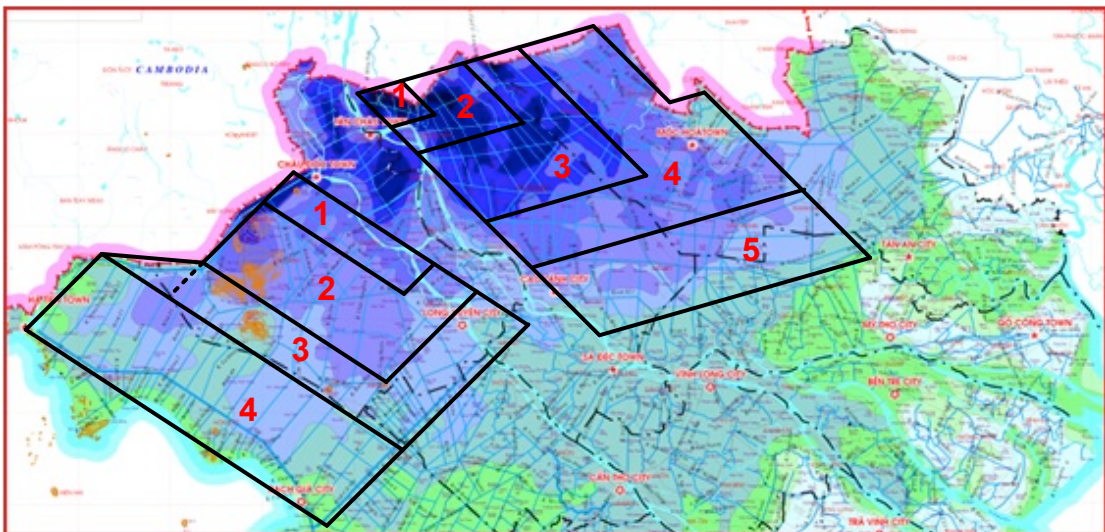
Figure C-2 Segmenting the Long Xuyen Quadragle and Dong Thap Muoi flood area

By dividing the floodplains up into several segments, with each segment its own inundation depth and eventually summing it up together. A rough estimated of the total inundation volume can be made. The total maximum inundation volume based on Figure C-2 for the year 2000 is around 21 billion m^3.

Long Xuyen	Surface		Depth		Volume	
1	300	km2	0,0025	km	0,75	km3
2	1100	km2	0,002	km	2,2	km3
3	1400	km2	0,0015	km	2,1	km3
4	1600	km2	0,001	km	1,6	km3
Totaal	4400	km2			6,65	km3

Dong Thap Muoi	Surface		Depth		Volume	
1	50	km2	0,004	km	0,2	km3
2	550	km2	0,0035	km	1,925	km3
3	1000	km2	0,003	km	3	km3
4	3000	km2	0,0025	km	7,5	km3
5	1000	km2	0,002	km	2	km3
Totaal	5600	km2			14,625	km3

Table C-1 Volume estimation table based on the flood charted of year 2000

To fill this amount of volume within 60 days means that the combined discharge from the main rivers/rain/across border floods towards the flood plains needs to be around 4100 m^3/s. Although the above calculation is highly simplistic, it could be said that the order of magnitude to eliminate inundation should also follow from the Sobek modelling.

Retaining water could also be a possibility. Storing an amount of water and therefore letting a smaller amount of water to be discharged via the diversion channel could result in downsizing of the required dimensions for the diversion channel. As said before, the discharge in year 2000 lasted for 60 days. To store 1000m^3/s for 60 days means that 200.000 to 550.000ha of area is required to be able to retain this amount of flood water.
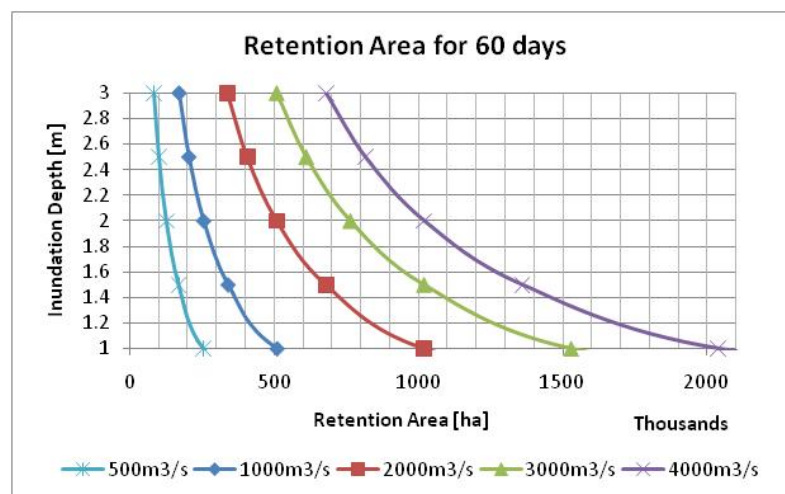
Figure C-3 Retention area against inundation depth for a period of 60 days

The range varies between 200.000 and 550.000ha because it is depending on the possible inundation depth. The larger the inundation depth the smaller the required area is needed to store the water. An overview of the possibilities is shown in Figure C-3 in this figure also the options of storing 500m³/s, 2000m³/s, 3000m³/s and 4000m³/s are shown.

In Mekong delta many households already elevated their houses to cope with the returning flood season, many of them have their houses elevated to a level of approximately 1.5m. Let's for instance say it is possible to store 1.5m of floodwater.

Inundation of 1.5 [m]	
Q [m3/s]	Area [ha]
500	250,000
1000	400,000
2000	700,000
3000	1,000,000
4000	1,500,000

Table C-2 Required retention area

Looking at Table C-2 storing a 1000m³/s means that almost the whole Long Xuyen Quadrangle needs to be inundated for almost 2 months. Looking from this point of view this is not a suitable option. It is better to construct a shallow channel then. As for a shallow channel with a width of 5000m and 70000m long the diversion channel would only take up an area of approximately 35000 ha. That is almost 1/10 of the required storage space of storing 1000m³/s. The reason is the retaining period; if the flood would be less long retaining the water could provide a solution.

C.3. *Optional solutions in draining high water*

A different option to be looked at is the option of using the exciting drainage channels. The motivation to also look at this solution is because in Vietnam, support of having a large diversion channel is very low. The reasons range from cost point of view, to the ability to constructing it. Therefore the idea of working with what is already exciting instead of creating an enormous construction is looked at.

This paragraph is to gain a general idea on what the necessary enlargement should be if the diversion channel is not constructed as one single massive diversion. The idea is to create smaller diversion channels, each transporting 500m³/s, 1000m³/s or 2000m³/s towards the Gulf of Thailand.

The width of the existing drainage channels are between 20m to 50m and some channels are around 75m measured at surface level. The depth of the many drainage channels varies from channel to channel and of course the measuring location. However, it can be said that the range of depth is between the 1m to 3m for the smaller channels and around 4m to 6m for large channels. The common slope of these drainage channels are around 1:2 to 1:2.5.
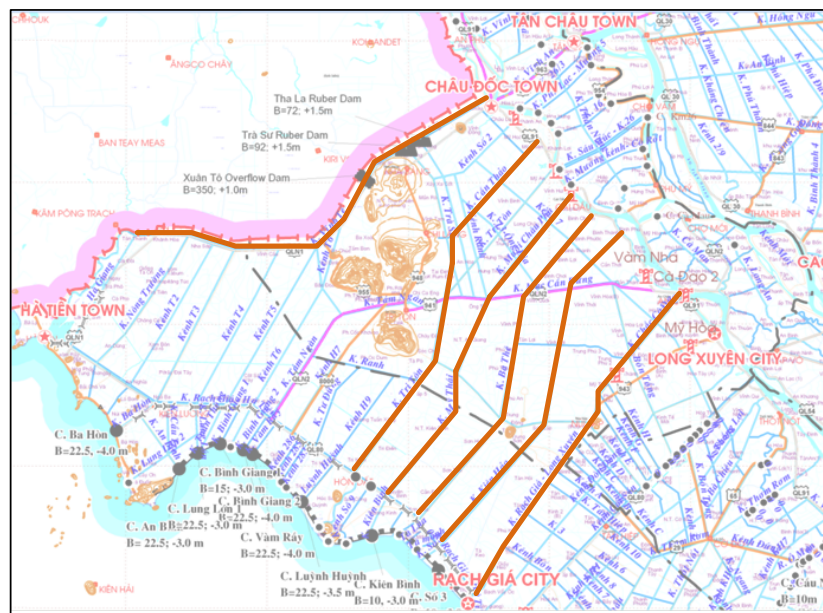
Figure C-4 Perpendicular drainage channels

Within Long Xuyen Quadrangle the network of drainage channels are enormous. However, there are 6 possible perpendicular channels, which are suitable to be enlarged. The channels are shown in Figure C-4. From left to right the channels are: Vinh Te, Tri Ton, My Thai, Ba The, Kien Hao and Rach Gia-Long Xuyen. To get a general idea on the amount of discharge, each perpendicular drainage channel can withdraw from the main river system simplifications are used:

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- The cross-sections are approached as cross-sections with a slope of 1:2.
- The network of parallel drainage channels are neglected meaning that water can only flow from the main river towards the Gulf of Thailand.

In Table C-3 the simplified dimensions of the perpendicular drainage channels are given. Unfortunately the cross-sectional channel of My Thai is not available. Based on these dimensions the possible discharge at the current situation is given in Table C-4 by using equation C-2.

	Width Surface [m]	Slope (1:x)	Width Bottom [m]	Height relative to MSL [m]	Depth relative to MSL [m]	Total water column [m]
Vinh Te	50	2	24.0	2.5	4.0	6.5
Tri Ton	50	2	28.0	2.0	3.5	5.5
Ba The	20	2	8.0	1.5	1.5	3.0
Kien Hao	40	2	12.0	1.0	6.0	7.0
Rach Gia - Long Xuyen	50	2	22.0	1.5	5.5	7.0

Table C-3 Dimensions perpendicular drainage channels

	A [m]	Length slope [m]	P [m]	R [-]	n [-]	Chezy [m1/2/s]	ib [-]	Q [m3/s]
Vinh Te	240.5	14.5	53	16.55	0.03	53	4.29E-05	**289**
Tri Ton	214.5	12.3	52	4.08	0.03	42	4.29E-05	**178**
Ba The	42.0	6.7	21	1.96	0.03	37	4.29E-05	**25**
Kien Hao	182.0	15.7	43	4.20	0.03	42	4.29E-05	**205**
Rach Gia - Long Xuyen	252.0	15.7	53	4.73	0.03	43	4.29E-05	**262**
							Total Q	**903**

Table C-4 Current discharge possibility

Seen from de calculations made in Table C-4 the discharge of the bigger channels are around 250 to 300m³/s. The total possible discharge is somewhat more than 1000m³/s without changing the existing channels dimensions.

However, the necessity of discharging larger amounts of water means these channels have to be enlarged. The Vinh Te channel is the only channel, which does not have housing on both sides of the channel. Meaning enlargement in width and depth is possible for this channel. The other five channels go through the core of the Long Xuyen area therefore widening of the channels means re-location of a lot of households. A list can be made on the required width and depth to discharge a 500m³/s, 1000m³/s or 2000m³/s in Table C-5 the mutual differences are shown.

Q = 500 [m3/s]		Q = 1000 [m3/s]		Q = 2000 [m3/s]	
Width [m]	Total water column [m]	Width [m]	Total water column [m]	Width [m]	Total water column [m]
20	18.05	20	28.2	20	44.2
50	*9.91*	*50*	*15.2*	*50*	*23.5*
100	6.44	100	9.8	100	15.0
150	5.03	150	7.7	150	11.7
200	4.23	200	6.4	200	9.8
250	3.70	250	5.6	250	8.5
300	3.31	300	5.0	300	7.6
350	3.02	350	4.6	350	7.0
400	2.79	400	4.2	400	6.4
450	2.60	450	3.9	450	6.0
500	2.44	500	3.7	500	5.6

Table C-5 Width and depth relationship for a discharging 500m³/s, 1000m³/s & 2000m³/s

If on average the width is 50 meters the total water column must range between the 10m and 25m depending on the amount that is needed to be discharge. Put aside the instability factor of the slopes due to the deep.

Concluding from the above made exercise shows that the system is to small to discharge high water events like that of year 2000. Expending one or more channels in depth and width is necessary to manage these kinds of events.

C.4.   *Rouse Number calculation*

This number determines how sediment is transported in a flowing fluid.

$$Rouse = \frac{w_s}{\kappa \cdot u_*}$$

With:

w_s = *Fall velocity [m/s]*

u_* = *Shear velocity [m/s]*

κ = *von Kármán constant [-] (common used value is 0.41)*

For a spherical grain the fall velocity is given as follow:

$$w_s = \left(\frac{4}{3C_D} \Delta g D \right)^{1/2}$$

A particle fall velocity depends on the size, its density and on the magnitude of the drag coefficient. This drag coefficient C_D depends on the roughness of the particle.

Empirical formulas are given by *Van Rijn* (1993) he formulated formulas based on empirical findings therefore determining the drag coefficient is not necessary any more. The fall velocity of natural sediment for the smallest particles is:

$$w_s = \frac{\Delta g D^2}{18v} \qquad\qquad 1 < D \leq 100\mu m$$

$$w_s = \frac{10v}{D} * \sqrt{1 + \frac{\Delta g D^3}{100v^2}} - 1 \qquad 100 < D \leq 1000\mu m$$

With:

g = *Acceleration due to gravity [m/s²]*

D = *Particle size [m]*

Δ = $(\rho_s - \rho)/\rho$

v = *Viscosity [m²/s] (common used value is 1e-06)*

Relation Sediment size and Rouse number
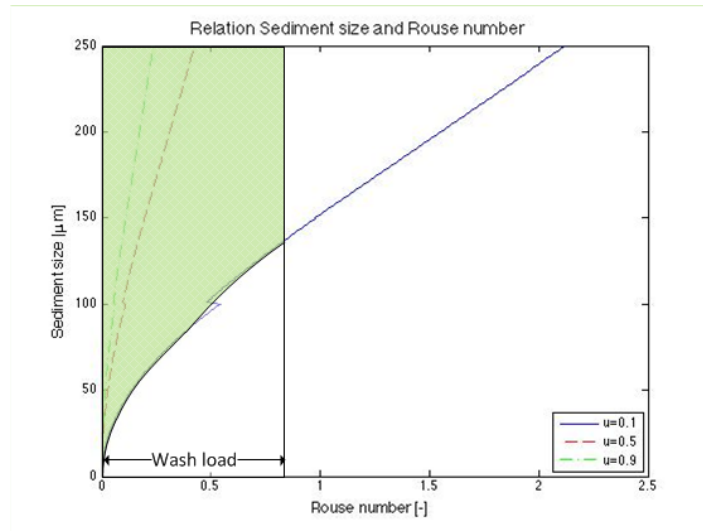
The sediment size in the Mekong River indicated by (Hung, 2011) is varying between the $10 - 15\mu m$. If for instance the bed roughness C is equal to 60 the dimensionless Rouse number is 0.003. This provides a significant small Rouse number meaning that it is must be all wash load transport.

C.5. *Adaptation length approximation of Galappatti*

The adaptation length is the distance that a grain particle can travel during settling.

$$L_a = \frac{\overline{u_f} \cdot h}{w_s}$$

With:

$\overline{u_f}$	= Mean flow velocity [m/s]
κ	= Water depth [m]
w_s	= Fall velocity [m/s]

If hindered settling is not accounted for the fall velocity is described by eq. C-6. The maximum travel length for a grain located at the surface of the water column is dependent on the height of the water column and the flow velocity.

The estimated flow velocities caused by the tide is between 0.1-0.4m/s if the water depth of 8,7m is taken the adaptation length could be calculated. First the situations with no flocculation of the sediment, the sediment size where between the 10-15μm, see Figure C-5. The adaptation length falls in between the green area if the flow velocity is at maximum 0.4m/s. For the highest flow velocities the adaptation length for the grain size 10-15μm is between the 17 to almost 40 km.
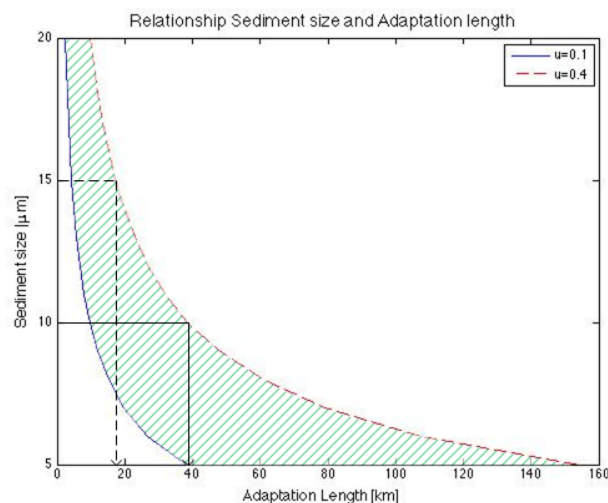
Figure C-5 Adaptation length with a grain size ratio between the 0-20 μm.
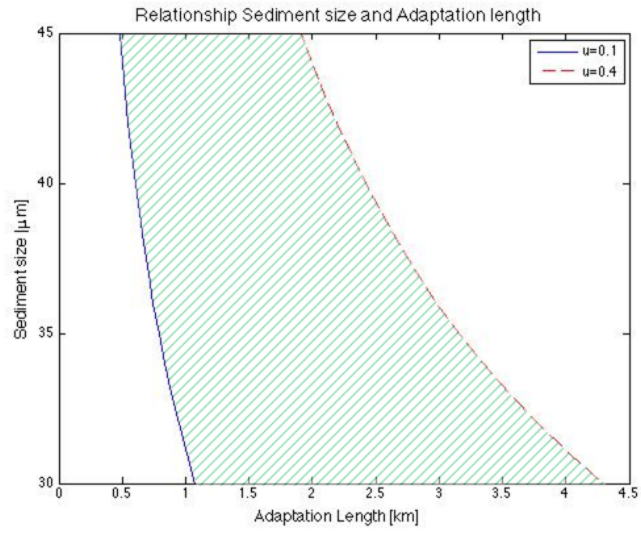
Figure C-6 Adaptation length with a grain size ratio between the 30-45 μm.

Figure C-6 shows that the adaptation lengths are between the 1 to almost 4,5km for grain size that could be that of the flocculation size 30 to 45μm.

D. Fundamental equations for the numerical models

D.1. Sobek & Delft3D

The movement of water is described by a set of equations. These are the shallow water equations described by Navier Stokes for incompressible fluids. First the boundary conditions are needed for the bottom and the surface. By assuming a hydrostatic pressure; saying that the horizontal length and time scale are much larger than the vertical scale and that the vertical accelerations in the z-direction are much small than the gravitational acceleration. This allows for depth integration over the vertical to gain the 2DH equation. In other words to acquire the depth-average continuity and momentum equation used in Delft3D, by further integration also in the 1D model of Sobek.

Continuity also called the conservation of mass implies a situation where the flow gradient is equal to zero in all directions. The momentum equation originated from the second law of Newton (Force = Mass x Acceleration) implies that no momentum can be lost therefore also a balance equation.

The hydrostatic assumption equation follows from the assumption:

$$\frac{\partial p}{\partial z} = -\rho g \qquad\qquad \textit{(Eq. D-1)}$$

With:

p   *= Pressure [N/m²]*
z   *= Vertical direction water column [m]*
ρ   *= Density [kg/m³]*
g   *= Acceleration due to gravity [m/s²]*

Integration over the depth of equation D-1 results in the hydrostatic assumption equation D-2.

$$p = -\rho g z \qquad\qquad \textit{(Eq. D-2)}$$

Using the hydrostatic equation in the shallow water equations result in the boundary condition of the bottom and the surface with z = z_b is bottom and z=ζ is surface.

$$u\frac{\partial z_b}{\partial x} + v\frac{\partial z_b}{\partial y} = 0 \qquad\qquad for\ (z = z_b) \qquad\qquad \textit{(Eq. D-3)}$$

$$\frac{\partial \zeta}{\partial t} + u\frac{\partial \zeta}{\partial x} + v\frac{\partial \zeta}{\partial y} = 0 \qquad\qquad for\ (z = \zeta) \qquad\qquad \textit{(Eq. D-4)}$$

With:

> u, v, w = *Velocity [m/s] in the x,y,z direction*
> z_b = *Bottom Level*
> ζ = *Surface level*

Following from the above made assumptions the depth-average continuity and momentum equation can be formulated. These are already integrated over depth and with substitution of the boundary conditions.

The basic equations used in Delft3D-2DH model are:

Depth average continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \qquad\qquad \textit{(Eq. D-5)}$$

With:

> h = *Water depth ($h = \zeta - z_b$)*

Depth average momentum equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv + g\frac{\partial \zeta}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{bx}}{h} = 0 \qquad\qquad \textit{(Eq. D-6)}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu + g\frac{\partial \zeta}{\partial y} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{by}}{h} = 0 \qquad\qquad \textit{(Eq. D-7)}$$

With:

> f = *Coriolis force*
> τ = *Friction terms*

The first term is the local flow acceleration. The second and third term are the advection terms describing in the x and y direction. The forth term is the Coriolis force multiplied with the corresponding acceleration. The fifth term represents the acceleration due to pressure gradients. The last sixth and seventh term are the turbulent Reynolds stresses. The last term on the left hand side represents the friction term.

By integration over the y-direction result in the 1D equation used in Sobek. The basic formulas solved in Sobek are the one-dimensional (only in x-direction) continuity and momentum balance equations for water motions.

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad\qquad (Eq.\ D\text{-}8)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha_B \frac{Q^2}{A_f}\right) + g A_f \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} = 0 \qquad\qquad (Eq.\ D\text{-}9)$$

With:

Q	= Discharge [m³/s]
t	= Time [s]
x	= Distance [m]
α_B	= Boussinesq coefficient [-]
A_f	= Cross-section with flow [m²]
A_t	= Total cross-section [m²]
g	= Acceleration due to gravity [m/s²]
h	= Water level [m]
C	= Chézy coefficient [m¹/²/s]
R	= Hydraulic radius [m]
B	= Flow width [m]

D.2. CFL condition

The courant number or CFL condition is a number that describes the numerical stability of a numerical model. The purpose of the CFL number is to determine the minimum required amount of time step to achieve stable solutions. A stable solution means that convergence of the numerical solutions. In Delft3D uses an implicit scheme and is unconditionally stable. However, if the CFL number is too large the accuracy of the flow calculation decreases with increasing time steps.

The CFL equation in Delft3D for hydrodynamics is

$$CFL = \frac{\Delta t}{\Delta x, \Delta y}\left(u + \sqrt{gh}\right) \leq 10$$

With:

CFL	= Courant number [-]
Δt	= Time steps [s]
$\Delta x, \Delta y$	= Space steps [m]
u	= Velocity [m/s]
g	= Acceleration due to gravity [m/s²]
h	= Water level [m]

To gain high-resolution computation results the grid size must be small. However, due to the smaller grid size the computational time step must become smaller as well to gain accurate simulation results. The drawback is that more time steps means more computational time. Therefore the CLF condition can help in determining the minimum required time steps needed for the chosen space steps. For the made coastal model for this thesis the space steps are 500m. Therefore a relative large time step is chosen, the time steps are 5 min. Using these $\Delta t \ and \ \Delta x$ the CFL conditions have surpassed the criteria. However, surpassing the criteria is at open sea. Within the area of interest where water depths are relative shallow the CFL condition is small enough that it does not interfere whit the rather straightforward hydrodynamic computations. The manual also indicated that for relative simple hydrodynamic calculations the CFL conditions can also be as large as 25. The area of interest for this model have depths varying between the 0 – 20m. The highest CFL condition is 23.8, which is well below the indication of 25.

Nevertheless, it is recommended that for higher resolution computation. Or for more detailed modelling like the implementation of morphological changes smaller grid and therefore time steps are required. Besides that the requirement to have a small CFL number does play a bigger role then.

E.   Sobek river model

The purpose of making a hydrodynamic model of the lower Mekong is to gain general idea if there is a possibility of discharging, a yet to determine amount of peak discharge, from the main river system towards the Gulf of Thailand. To analyse this a numerical model is needed that can mimic the physical behaviour of the lower Mekong river system. With that model it is possible to analyse if implementing a diversion channel gives a significant effect on the coastline and off shore areas like the touristic island Phu Quoc.

In Vietnam the modelling program Mike (DHI, Denmark) is used to model the lower Mekong delta. At the moment it is impossible to use their model to implement the diversion channel concept because the model they use is not freely available. Therefore it is decided to make a new but simplified model within the model environment of Sobek: Rivers and Estuaries.

As said before the main rivers in the Mekong Delta are the Tien and the Hau River. Connected to those rivers are large amount of smaller diversion flowing drainage channels redistributing the water from the main river system see Figure 2-4. Given the limited amount of available data and the complexity of the dense network channel system in the delta make it impossible to set-up a detailed model starting from scratch. This is also unnecessary given the main purpose of the model. Therefore, it is decided to simplify the Mekong Delta to only model the main river system in a 1D situation. Besides that, the complex and dense network of sub-channels, which are perpendicular towards the main river system, is neglected and there are no floodplains included into the model.

It is important to understand that this Sobek model is not to be used as tool for policy-making decisions or other modelling purposes. This model is set-up to explore the concept of having a diversion channel from the main river towards the Gulf of Thailand.

This chapter is subdivided into five paragraphs. The first paragraph is used to list all the used input data and what kind of assumptions are made if data is unavailable or limited. In paragraph E.2 the 1D hydrodynamic river model is set-up. This paragraph also holds the calibration and validation of the made model.

E.1.   Assumptions input data

Even though the 1D Sobek model is very simplified some key data is needed to set-up the model. Getting data from institutes or companies in Vietnam is difficult. The main reason for this is that data is often their core business. Sharing collected data even for study purposes is not a common thing to do. This paragraph is devoted to explain, which choices or assumptions are made for key values that are needed to set-up the model.

Thus, an overview is given of the needed input data. Assumptions are made if data is not available.

E.1.1. *Manning coefficient*

The Mekong delta was created by deposition of fine sediment of fluvial and marine origin. Within the waterways the top layer consists of very soft clay. This lies on top of stiff clay and sandy silt to silty fine sand. (Mekong Transport Infrastructure Development Project, 2006)

Based on the above information the following three Manning values are chosen see Table E-1, it is based on the gradations made by (Chow, 1959).

Excavated or Dredged Channels	Manning
Earth winding and sluggish	
1. No vegetation	0.025
2. Grass, some weeds	0.030
3. Dense weeds or aquatic plants in deep channels	0.035

Table E-1 Manning coefficients

Manning is a roughness parameter, which determines how rough an area is. The difference between the Chézy is that Manning uses the wet perimeter of the channel to base its total roughness on therefore relating the roughness on the actual water depth. For rivers the Chézy coefficient could range between 25 meaning very rough and 85 very smooth. Manning can be re-written to Chézy with the following equation:

$$C = \frac{1}{n} R^{1/6}$$

(Eq. E-1)

With:

C = *Chézy parameter [m$^{1/2}$/s]*

n = *Manning parameter [-]*

R = *Ratio between cross-sectional area/wetted perimeter [m]*

Within the above mention equation the R is a ratio between the cross-sectional area A [m²] and the wet perimeter P [m]. The manning parameter n is situated at the dominator. Meaning that the larges the manning value gets the smaller the total value will be resulting in a smaller Chézy value, which means a rougher surface.

To set-up the model a starting point of the roughness coefficient is set on 0.030, the reason for this is, because very little is known on the bed surface of the rivers.

Manning for flow overland

Besides the above given manning values for channels Chow also formulated Manning values for floodplains. A distinction is made on cultivated areas with a situation of no crop, mature row crop and mature field crop. The values ranged from 0.030 to 0.040. For

a diversion channel constructed at ground level it is said that farmers do calculated for the possibility of a flood event and therefore the value of 0.030 is used as manning value for this type of diversion channel.

E.1.2. *Slope calculations*

The topography or land variation of the Mekong Delta is not varying very much looking at Figure 2-2. The same cannot be said to the variation in bed surface of the main rivers. In Appendix B.3 a collection of cross-sectional information is given of the Hau and Tien River (The Water Resource University, 2012). The cross-sectional information starts at Phnom Penh somewhat 330km from the South East Sea. At somewhat 120km from Phnom Penh, the large cities Tan Chau and Chau Doc are situated. The Vam Nao passage does already start at Tan Chau but the big split happens at around 170km seen from Phnom Penh.
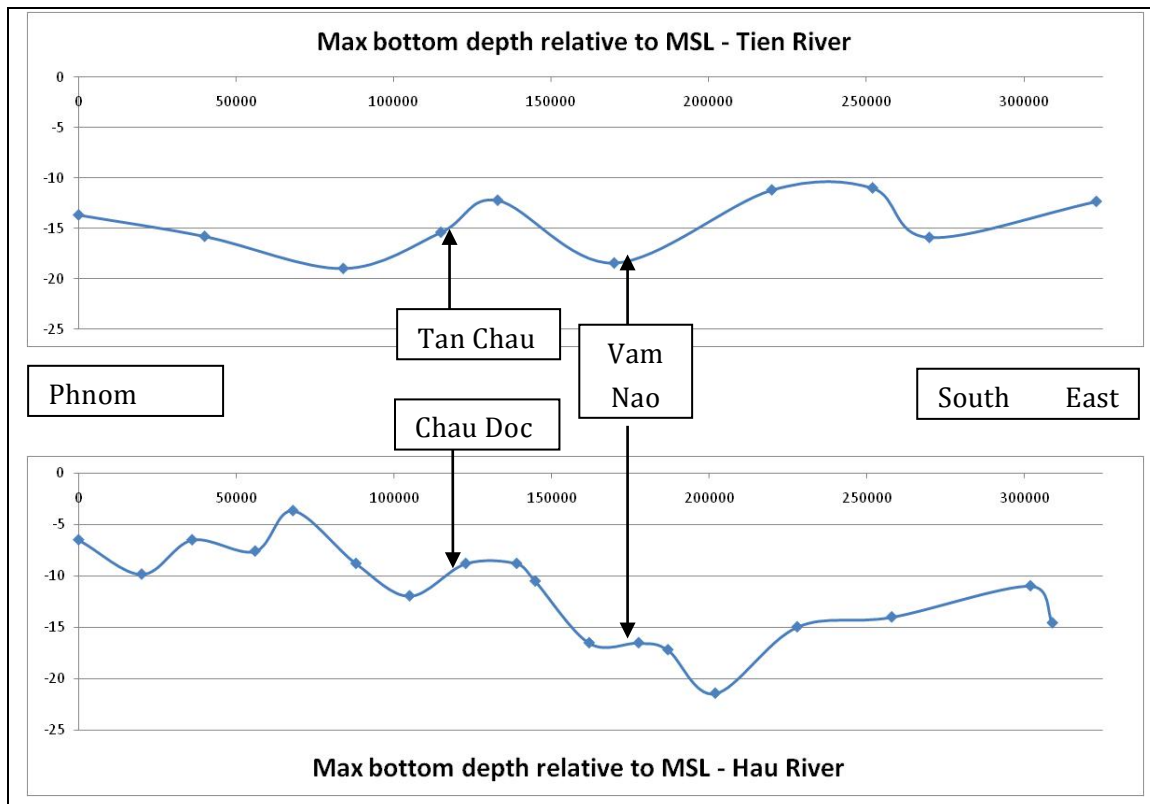
Figure E-1 Maximum bottom depth [m] relative against MSL Between Phnom Penh and South East Sea

Due to the limited cross-sectional information given especially for the Tien River the correctness of the above given maximum depth interpolation lines are doubtful. This becomes clear if a comparison is made on the depths of Tan Chau and Chau Doc with the cross-sections provided by the MRC (Mekong River Commission, 2012) website, the depths of the cross-section from MRC are larger see Appendix B.3.

Although the inconsistency of the provided cross-sections. By considering the cross-sectional information given by (The Water Resource University, 2012) for Phnom Penh and the South East Sea and along with that for Tan Chau and Chau Doc the cross-section

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provided by the MRC. A linear slope calculation can be can be made to calculate the slope of the Mekong River. The results are given in Table E-2.

$$i_b = \frac{\Delta h}{L}$$

With:

i_b = Bed slope [-]

Δh = Height difference between up and downstream [m]

L = Length considered channel [m]

	Δh [m]	L [m]		Slope [-]
Phnom Phen - Chau Doc	7.5	120000		6.25E-04
Phnom Phen - Tan Chau	15	120000		1.25E-04
Chau Doc - South East Sea	4	185000		2.16E-05
Tan Chau - South East Sea	10	195000		5.13E-05
Hau River - Gulf of Thailand	3	70000		4.29E-05

Table E-2 Linear slope calculations Mekong River

Note: That the slope calculations for Chau Doc and Tan Chau towards the South East Sea is backwards tilting.

Uncertainties are within the height difference, due to a limited amount of information of river cross-sections along a stretch of 300km. Therefore it has to be noted the information provide could be incorrect. Within several literature studies the depth within the lower Mekong River varies between 10 to 40 m and becoming shallower in the last 80km near the mouth (5-15m) (Hashimoto, 2001) this information can be supported by the information given in Figure E-1.

In Sobek it is possible to not specify a fixed slope. It is also possible to let the model define an own slope value based on the interpolation between given cross-sections. Although this is a good method unfortunately it is still bound by the limited given cross-sections.

E.1.3. *Tidal influences*

By looking at the main rivers in Figure E-1 and based on the linear slope calculations it can be said that the rivers are more or less a long basin. Therefore it is possible for the tidal influences to be felt during the dry season far upstream as Tan Chau and also Chau Doc. During wet season, water in the main river is rather high relative to MSL. Therefore water flows towards the sea; tidal influences upstream are hardly noticeable during that period.

Because the model is simplified and the tidal influence during high water is rather small the tidal is not taken into account into the Sobek River model. However, to enhance this model for further studies it is recommended to also take into account the tidal factor. Although during wet season tidal influences are small it can still influence the way in which water flows towards the Gulf of Thailand.

E.1.4. *Discharge & water levels*

To get Information on (peak) discharges coupled with (peak) water level measurements is limited. At the moment of setting up the model coupled values were based on the report "Flood and Salinity Management in the Mekong Delta, Vietnam" which is set-up to identify research gaps on floods (Tuan, Hoanh, Miller, & Sinh, 2007). Because the report is written for a broad audience set-up data are based on information taken from a graph see Figure E-2.
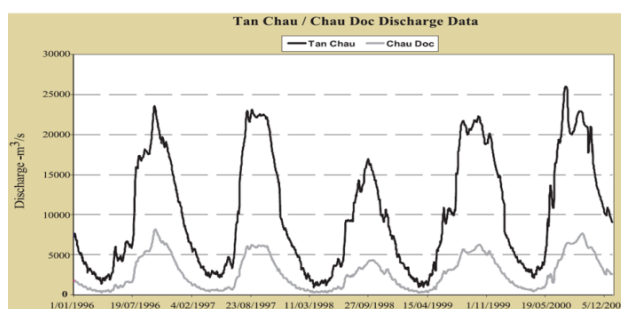

Figure E-2 Coarse discharge graph from (Tuan, Hoanh, Miller, & Sinh, 2007)

This information is coarse but at that moment no other data was available. Fortunately, during the trip towards Ho Chi Minh City the Water Resources University (second base) provided additional coupled discharges and water levels. The provided data is given from 1980 until 2003 with coupled discharges and water levels at Chau Doc and Tan Chau. However, some years between the given periods are not provided or not complete or it is only present at one of the two cities. At the moment the only known extreme discharge event within the available data set is that of year 2000 at that moment the combined peak discharge of Chau Doc and Tan Chau is around 32500m^3/s. The availability of data is limited but for the purpose of this thesis it is sufficient. However, for a follow up study it is wise to gain more coupled discharge and water level measurements. It is also better to gain measured information from more recent years. Due to the limited amount of data it is impossible to define a design criteria other then based on the known extreme event. It is decided that for the calibration two extreme years are used 1998 and 2000. For the validation of the model data of years 1996, 1997, 1999, 2001, 2002 and 2003 are used [*]. Besides these years the model is also validated against a present moment in time based on water level measurements provided by the website of the MRC (2012).

The final decision is to neglect hydrological input due to rainfall and land overflow. The reason for this is because it is unclear what the amounts are for input. It has to be noted that, by neglecting these inputs. Water entering the system is most likely underestimated at the moment.

[*]*Note: Although data is available from 1980 it is decided to start at 1996. The reason for this I sbecause at the moment of calibrating and validating the model the data was not present. The data was provided after the*

model was already set-up. Besides that calibrating the model based on out-dated information does not provide a significant more trust in the made model.

E.1.5. *Sediment transportation*

Written averages approximation of yearly sediment transport through the Mekong River in literature is little and a bit contradicting. In the 80's some rough general information on large river systems in the world are collected. In the manual, Principle of River Engineering by (Jansen, 1979) a table is given on some general information about the Mekong River see Table E-3. The information is a collection of average approximations during the 70's/80's. *It is noted that this information can only be used for indicative purposes and not for policy-making decisions.*

| River | Station | Catchment area 10^6 km^2 | Discharge | | | | Sediment as ppm of discharge |
| | | | Water | | Sediment | | |
			m^3/s	mm/y	10^6 ton/y	10^{-3} mm/y	mg/l
Mekong	mouth	0.80	15000	590	80	70	170

Table E-3 Rough data on Mekong River (Jansen, 1979)

The information given in this table is rough but for the indicative purpose of this thesis detailed enough. The approximation of the average yearly discharge by (MRCS & KOICA) in paragraph 2.1.6 is reasonable in line with the approximation given in this table. Looking at the yearly average sediment transport this table give an approximation of 80 million [ton/y] and density of 170 [mg/l]

A different literature study implies that in general the Mekong delta is discharging on average, 160 million [ton/y] (Sarkkula, Koponen, Lauri, & Virtanen, December, 2010). This is two times as much as dictated in 1979 by Jansen. However, citation of (Jansen, 1979): "Different sources may give variations up to a factor 2 in sediment yield." Further detail information on the type of sediment is not found in literature.

E.2.   *Hydraulic sobek model set-Up*

In the previous paragraph the input data is evaluated. Based on those available data and the purpose of the model the choice is made to make a 1D Sobek model. Only the main river system is taken into account, neglecting all the smaller drainage channels connected to the main rivers. This chapter goes into the set-up of the model itself e.g. cross-sectional design and which boundary conditions are used. But first a small overview on the area of interest is given in paragraph 1.E.1.E.2.1 that also consist of the layout of the total 1D model from upstream to downstream.

E.2.1.   *Area of interest*

The main network of the lower Mekong River consists basically of two river branches the Tien and Hau River. In between the Vam Nao channel connects them together, the connection starts from the Tien River at Tan Chau and ends in the Hau River at Binh Thuy.
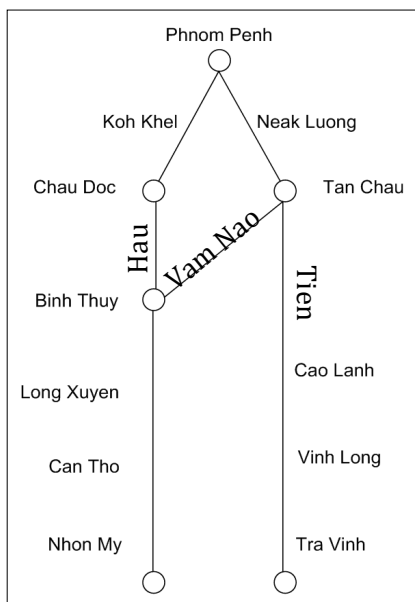

Figure E-3 Scematisation Sobek Model

The hydrodynamic model starts at Phnom Penh but after the Tonle Sap Lake. This lake acts like a high water buffer meaning that high discharges from further upstream first discharge against its natural flow towards the Tonle Sap Lake. The lake falls out of the scope of the area of interest for this thesis. Introducing a buffer lake into the model brings more complexity in an already coarse model, which is unnecessary. Therefore it is decided to start the model at Phnom Penh which is a city situated in Cambodia somewhat 330km upstream seen from the South East Sea mouth.

The downstream schematizations see Figure E-3 is simplified as two branches instead of the bifurcation into nine river branches. The reason for this simplification is that there is no necessity to known the system in full detail after the Vam Nao bifurcation. The second reason that implementing this much detail into a coarse model does not result in a significant better result.

E.2.2.   *Cross sectional design*

In the previews chapter paragraph E.2.1 the decision is made on how the model branches are modelled. In this paragraph the cross-sections of the branches are determined. This is done again based of information gain from the MRC website which is made for a broad audience. This means that the detail of the information is limited. At the moment of setting up the model five cross-sections were available one at Phnom Penh, Koh Khel,

Neak Luong, Chau Doc and Tan Chau. Therefore at that moment in time only depth information was available from Phnom Penh until Chau Doc and Tan Chau. The largest part in the Mekong delta is unknown. Fortunately the chart-room at TU-Delft has some depth measurements of the southeast sea mouth. Based on this information a coarse 1D model is set-up in Sobek. See appendix B.3 for an overview of the cross-sections.

E.2.3. Boundary conditions

The model consist of two boundaries an upper and a lower boundary. The 1D model is further simplified as a stationary-uniform flow, by using a fixed peak discharge at the upper boundary. This simplification will result in that the water depth will approach the normal depth value or equilibrium depth. By eliminating the acceleration and convection terms from the momentum equation (see appendix D.1) and replacing the surface slope $\partial h/\partial x$ with the bed slope i [m/m]. Results in the equilibrium water depth.

$$h_e = \sqrt[3]{\frac{Q^2}{B^2 C^2 i}}$$

(Eq. E-3)

The flow velocity u is also a stationary value and follows from the continuity (see appendix D.1).

$$Q_e = B h_e u$$

(Eq. E-4)

The outcome of the equilibrium water levels and discharges calculated by the model will be used to calibrate the model with measured data. The calibration of the set-up model is further explained in paragraph E.2.5.

One can argue that in nature the Q-h relationship is not always a linear function. It is possible that the Q-h relationship is determined by a hysteresis whereby the Q_{max} is not equal to the H_{max}. Nevertheless, for this study this inconsistency of the Q-h relationship is neglected.

The lower boundary is the South East Sea, which is fixed at the mean sea water level equals 0m. This means that the tidal influences are not taken into account within this model. For further analysis is the recommended to also include the tide into the model. As said before although during high-water tidal influences are small it can still influence the way how much water can flow towards the Gulf of Thailand

E.2.4. Assumptions set-up recap

Because a lot of assumptions are made to simply the 1D Sobek model this paragraph is a small recap on the most important simplifications used to set-up the model.

- The Lower Mekong River is assumed as 1 dimensional (Uniform static flow.)
- Due to the stationary flow the surface slope $\partial h/\partial x$ is equal to the bed slope.
- The main river is schematised as rectangular cross sections.

- It is schematised as two main channels without the lower bifurcations, except the bifurcation due to the Vam Nao passage.
- No Tide influence at the lower boundaries
- The model does not take into account the existence of the complex network of drainage channels.
- Cross-sectional information is taken from Google Earth and MRC.
- The widths of both mouths are set on 1100m to begin with.
  - *Note: The reason of choosing a small mouth instead of combining a mouth width that consists of all the nine branches is because the interpolation method used by Sobek between two given cross-sections. By choosing a mouth width to large results in that water flows as if it is flowing into a large lake. But in reality the cross-section between Chau Doc/Tan Chau and the sea is not varying that much.*
- To set up the model a manning value of 0.030 has been chosen to start with.

E.2.5. *Calibration & validation of the Sobek model*

By altering the cross-sectional dimensions and roughness values, the discharge and water levels are tuned towards the known measured values.

The following information is used to calibrate the model to:

- Based on literature the discharge deviance over the Mekong branches are 20% -80% and after the Vam Nao Passage around 50% - 50% for the Hau resp. Tien River
- In 1998 peak discharge where around 21500m^3/s, Chau Doc had a peak water level measurement of 2.55m and Tan Chau 2.79m.
- In 2000 the peak discharges where around 32500m^3/s, Chau Doc had a peak water level measurement of 4.8m and Tan Chau 5.03m.

Calibration results

In Figure E-4 and in Table E-4 the differences in measured and modelled value are given after calibration. The modelled lines for both cities are bit more skewed than that of the measured lines. It is important to known that this skewness within the Q-h relationship can result in inaccurate model outcomes. Because the model gives an underestimation if the discharge values are higher than 32500m^3/s and an overestimation of the water levels if the discharge is lower than 21500m^3/s. However the calibrations have been stop, if the skewness is within expectable limits. It is decided that the expectable limits are if the modelled value is within a range of ±0.15m from the measured value. Table E-5 and Table E-6 the final cross-sections and friction parameters after calibration is given of the model.
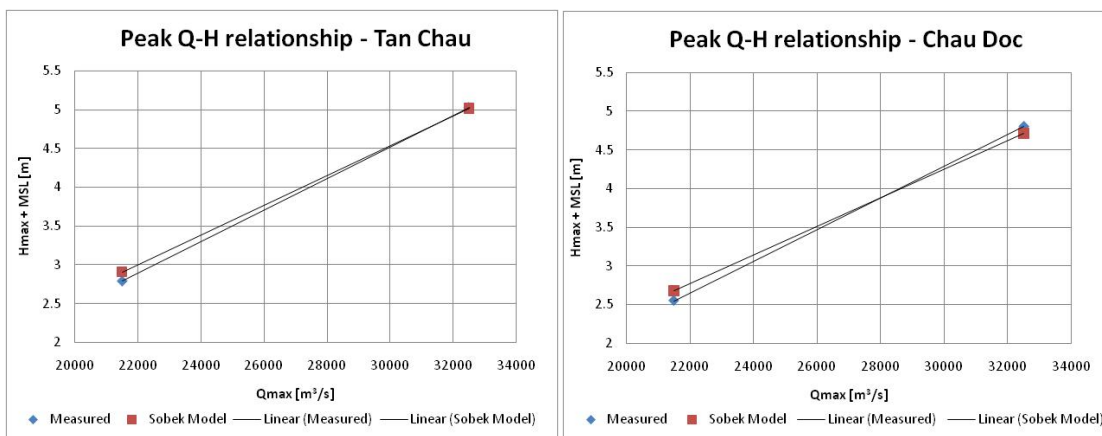
Figure E-4 Q-H relationship Measured and Model Tan Chau and Chau Doc

	Year 1998				**Year 2000**	
	Q=	*21500*		*Q=*	*32500*	
Δh [m]	Measured WL + MSL [m]	Modeled WL + MSL [m]	Measured WL + MSL [m]	Modeled WL + MSL [m]		Δh [m]
Tan Chau	0.12	2.79	2.91	5.03	5.02	-0.01
Chau Doc	0.13	2.55	2.68	4.80	4.71	-0.09

Table E-4 Comparison water levels after calibration

	Width	**Depth against MSL**	**Dike Height against MSL**
Phnom Penh	550	-8	11
Koh Khel	300	-9	8
Chau Doc	500	-18	4
Neak Luong	850	-13	8
Tan Chau	500	-19	5
Mouth	1100	-11	0

Table E-5 Sobek Model Cross Section after calibration

	Manning
Phnom Penh - Chau Doc	0.032
Phnom Penh - Tan Chau	0.033
Chau Doc - Binh Thuy	0.040
Tan Chau - Binh Thuy	0.035
Binh Thuy - South Sea	0.026
Tan Chau - South Sea	0.027

Table E-6 Manning Friction after calibration

Validation Results

First the validation is shown based on the discharge ratios; 20% through Chau Doc and 80% through Tan Chau. For this validation the average monthly discharge is used based

on Figure 2-7, which is given by (MRCS & KOICA). In Figure E-5 on the right side a time-serie of one average discharge year is given. The green line shows the total discharge through Tan Chau and the red line that of Chau Doc. It is quite clear that the ratio between Tan Chau and Chau Doc during peak water levels is quite close to the suggested 80% to 20% ratio based on literature. On the right side of Figure E-5 the situation is given downstream just after the Vam Nao passage the model does represent an almost 50-50 ratio between the Hau and Tien River.
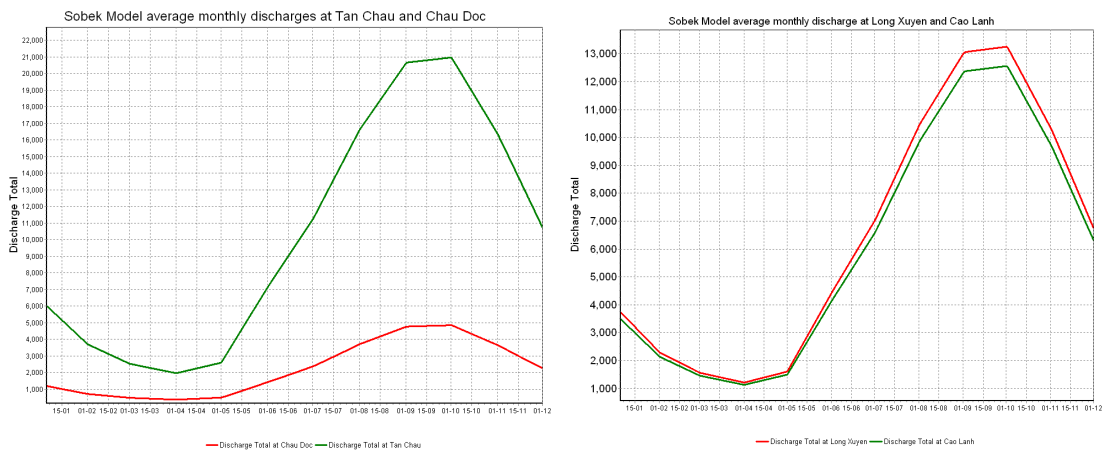

Figure E-5 Modelled discharges within the mekong river (Left: Tan Chau&Chau Doc) (Right: Long Xuyen&Cao Lanh)

The second validations of the model are on measured discharges and water levels. The measured data is gain from year 1996, 1997, 1999, 2001, 2002 and 2003. Beside that also a present situation in 2012 is used to validate the model.

In Table E-7 the measured and modelled water levels are given. The water measurements between years 1996 till 2000 are taken from (Tuan, Hoanh, Miller, & Sinh, 2007). Year 2001 till 2003 the data is provided by the Water Research University (WRU, second base). The values are based on the average value (Q and H) in the month September. The associated discharge level is rounded off upwards and then implemented within Sobek. The last value that is used to validate the model is based on information given at the Mekong River Commission (MRC) website. From the MRC water level data is taken on 08-07-2012 at 7:00AM. Although the exact discharge was not known based on Figure 2-7 the average discharge in June is around 7000m³/s.

Year	1996	1997	1998	1999	2000	2001	2002	2003	2012
Qmax [m³/s]	31500	29000	21500	28000	32500	30000	28500	23500	7000
Than Chau									
Measured [m]	4.80	4.20	2.79	4.10	5.03	4.68	4.53	3.42	0.45
Modelled [m]	4.84	4.36	2.91	4.16	5.02	4.55	4.27	3.33	0.43
|Δh| [m]	0.04	0.16	0.12	0.06	0.01	0.13	0.26	0.09	0.02
Chau Doc									
Measured [m]	*No Data*	*No Data*	2.55	*No Data*	4.80	4.24	4.03	2.98	0.30
Modelled [m]	4.52	4.05	2.68	3.89	4.71	4.25	3.98	3.05	0.39
|Δh| [m]			0.13		0.09	0.01	0.05	0.07	0.09

Table E-7 Measured and Modelled water levels

The result of Table E-7 is also shows within Figure E-6 this figure shows a scatter plot of all the measured and modelled points. What can be noticed is that the error of the modelled values ranges around 0.01m - 0.16m. The only one, which does not fall into that category, is the situation of 2002 for the city Tan Chau. The Sobek model, models a value incorrect with an underestimation of 0.26m.

However, for such static and simplistic model it still managed to model the order of magnitude quite well.
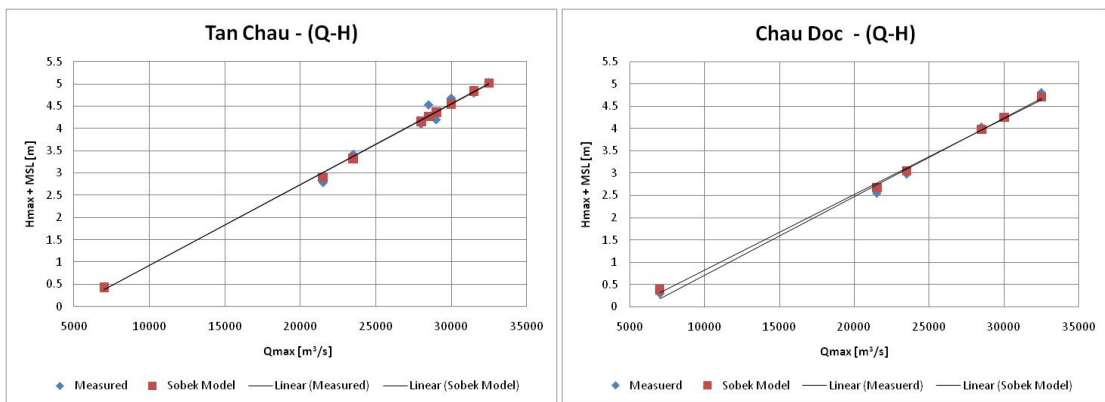

Figure E-6 Q-H relationship Measured and Model Tan Chau and Chau Doc (Validation)

Graphically the modelled water level from Phnom Penh until the South East sea from 1996 till 2000 is show in Figure F-1 and Figure F-2 see Appendix F.1

F. Additional sobek results

F.1. Modelled water levels against flood level limit

Year 1998 was a dry year it was well under the flood level limits given for Chau Doc and Tan Chau. The peak discharges for year 1997 and 1999 where very close to the flood limits. Year 1996 and 2000 water level rose well above the flood limits. The modelled results are shown in Figure F-1 and Figure F-2.
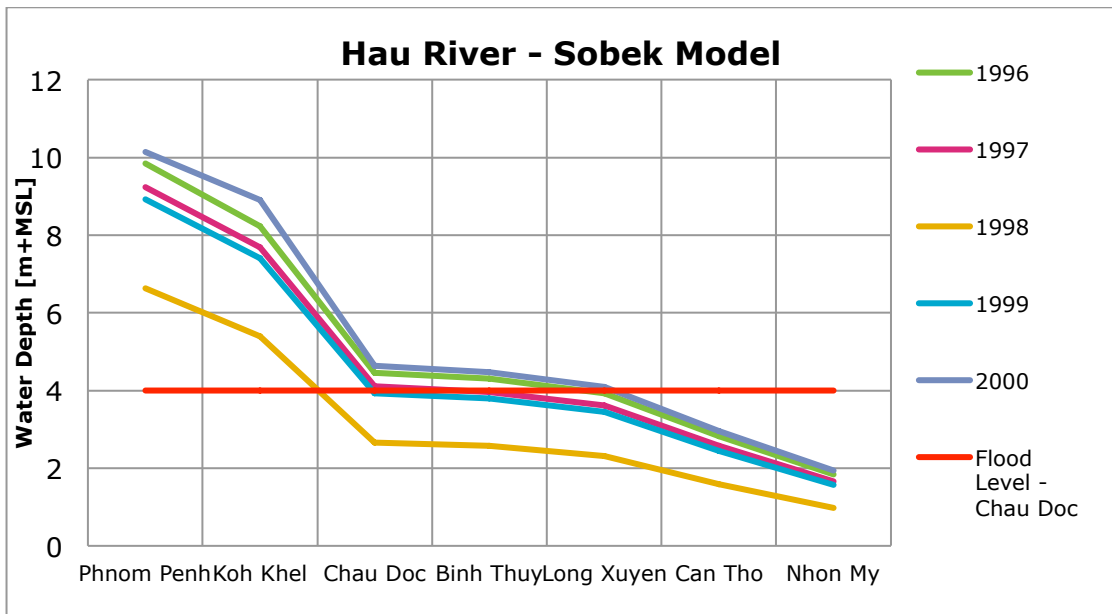

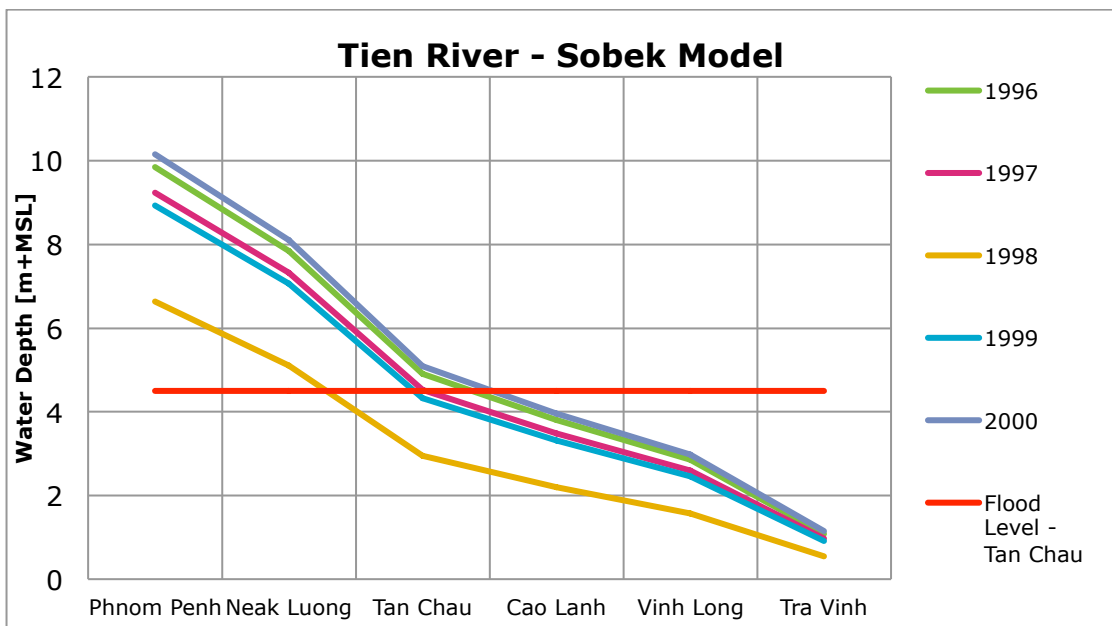*Figure F-1 Sobek Model Hau River (1996 - 2000)*

Figure F-2 Sobek Model Tien River (1996 - 2000)

F.2.   *Sediment transport analysis*

Little is known about the sediment (transport) within the Mekong River and delta to make a reliable morphological analysis. In general various sediment types exist within a river system. With coarse type upstream, finer types in the middle part of the river system and coarser material due to flocculation of cohesive material due to encountering salt water at the mouth. Not to mention the diversity in sediment type within the cross-section of a river channel.

To gain a general idea in what range of sediment type and what could be expected at the Gulf of Thailand. The base model is used as a tool to analyse what the sediment type and eventually the sediment transport could be during a high water event.

There are two goals to reach.

- The first goal is to determine the possible sediment type in the main Mekong River.
- The second goal is to analyse what the impact is of a diversion channel on the sediment transport towards the South East Sea and on the Gulf of Thailand.

There are various sediment transportation formulas base on empirical founding. One of this is the formula made by Engelund-Handson. This equation considers the total sediment transportation.

$$s_b = m * u^n = \frac{0.05}{\sqrt{g} * C^3 * \Delta^2 * D_{50}} * u^5 \qquad \text{(Eq. F-1)}$$

With:

s_b = *Sediment transport capacity [m²/s]*
g = *Acceleration due to gravity [m/s²]*
C = *Chézy coefficient [m$^{1/2}$/s]*
Δ = *Relative density of sediment [-]*
D_{50} = *Median grain size of bed material [m]*
u = *Flow velocity [m/s]*

The equation boils down to a power law of the flow velocity. The higher the denominator the smaller the sediment transport capacity. Within this equation the roughness with a power to three and the flow velocity with a power to five is the most important value. A larger Manning value results in a smaller Chézy value. A smaller Chézy means rougher surface therefore a larger sediment transport capacity.

As said before this formula is used to calculate the total sediment transport. Via the Rouse number calculation see appendix C.4 it was already determined that wash load is

the dominated sediment transport type. The boundary conditions placed on this formula shows that this formula is not valid for sediment smaller than 0.19mm:

$$w_s / u_* < 1$$
$$0.19 < D_{50} < 0.93 \ [mm]$$
$$0.07 < \theta < 6$$

Therefore this this is not a good method to use to calculate the transport within the Mekong River. Nevertheless, due to the lack of better data and the simplicity of this transport formula the equation is used to see how the system reacts. But it must be kept in mind that this is not a proper way to assess the sediment transport capacity.

The assumptions are:

- Due to the limited information the Engelund-Hanson formula, which is a total transport formula is used.
- The 1D model does not allow morphological changes to occur due to a fixed bed.
- For the yearly average discharge information is based on (MRCS & KOICA). These discharges are an average from 1977 – 1999, see Figure 2-7.
- A possible gradation is based on the classification of the "American Geographical Union" see Table F-1. The following range comes close to what is possible to find in the Mekong River, based on the literature study see paragraph 2.1.4.

Class name	Sizes in micrometres
Coarse Clay	2-4
Very Fine Silt	4-8
Fine Silt	8-16
Medium Silt	16-31
Coarse Silt	31-62
Very Fine sand	62-125
Fine sand	125-250

Table F-1 Sediment gradation list

- The dimensions of the Mekong River model are kept on the situation followed from calibration (Table E-5 & Table E-6). *Note: No diversion channel is placed in the system for the first part.*
- The sediment type is modelled as a constant and the same sediment type is used for the whole Mekong River within the model.

Part 1: Defining the sediment type

What is known based on literature study is that the range of possible yearly average sediment transports of the Mekong River is between 80 till 160 million tonnes. See paragraph E.1.5. By filling in a range of possible sediment types into the base model and running the model for an average yearly discharge. The average yearly sediment transport is calculated. A general idea is found on the type of sediment, which can induce

such an amount of total sediment transport. By looking if the used sediment type can result in the know by literature approximated 80 to 160 million tonnes a year. The sediment type range is taken between 3µm to 188µm respectfully between coarse clay and fine sand.

The model results are shown in Figure F-3, with on the x-axis the sediment type and on the y-axis the associate sediment transport. These transports values are excluding pores.
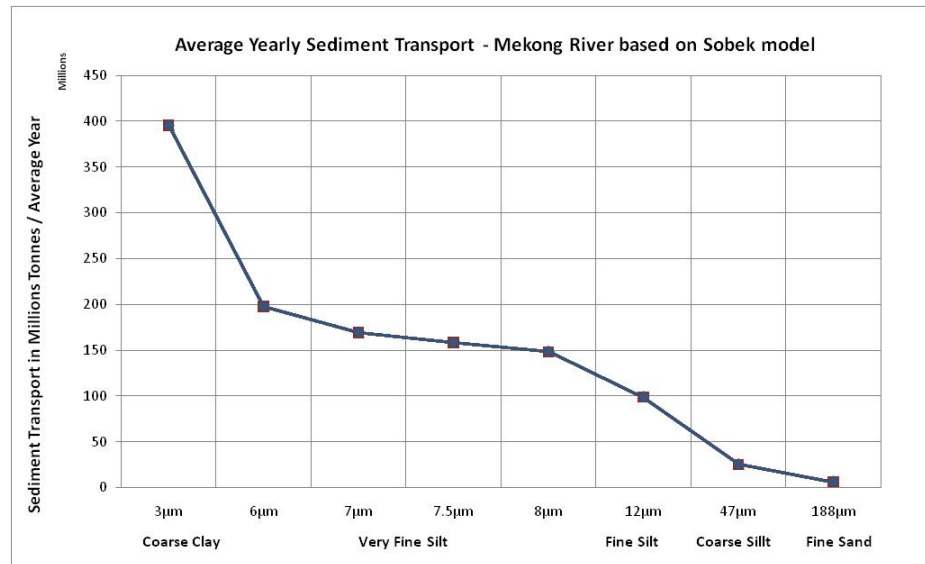

Figure F-3 Yearly average sediment transport, modelled in Sobek

Looking at Figure F-3 shows that 80 million ton/yr. is associate with a sediment type equal to medium silt. The 160 million ton/yr. is associated with very fine silt. Based on the outcome of this coarse estimation the sediment type should range between the 7 – 20μm. It is rather strange that although the Engelund-Hanson formula is used the type of sediment does come close to what is find within the field by (Hung, 2011). He found a sediment type ranging between the 10-15 μm.

Part 2: Sediment transport towards Gulf of Thailand

The second goal to analyse is the impact of implementing a diversion channel on to the main river system. Based on the finding from part 1 the range of sediment size is between the 7-20μm. However, the smaller the particle size is the less force is required to keep it in suspension resulting in the most possible sediment transport and therefore the most conservative situation.

Another assumption is made to analyse the behaviour of a diversion channel on the sediment transport:

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- The sediment type is based on the most conservative situation; this situation is reached if the sediment type is set on 7 μm.

By looking at the used Engelund-Hansen formula, sediment transport capacity within this model can vary due to.

- Chézy coefficient: This value relays on the fact that Manning is used as the roughness parameter, which is dependent on the water height within the channel.
- Flow velocity: This will vary due to the amount of discharge is flowing into the diversion channel.
  - *All the other parameters are set as a constant within the model.*

The model results are shown in

Figure F-4 and

Figure F-5, with on the x-axis the variation of discharge input into the model upstream and on the y-axis the related discharges, average velocity and sediment transport, 10km away from the mouth of the channel to the Gulf of Thailand. Note that discharging 4000m³/s through the diversion channel means an input discharge of 32500m³/s on the x-axis. In both figures the red line is associated with Tien River. The bleu line is associated with the Hau River and the green line is for the deep respectfully shallow channel. Please note that the given transports values are including pores.

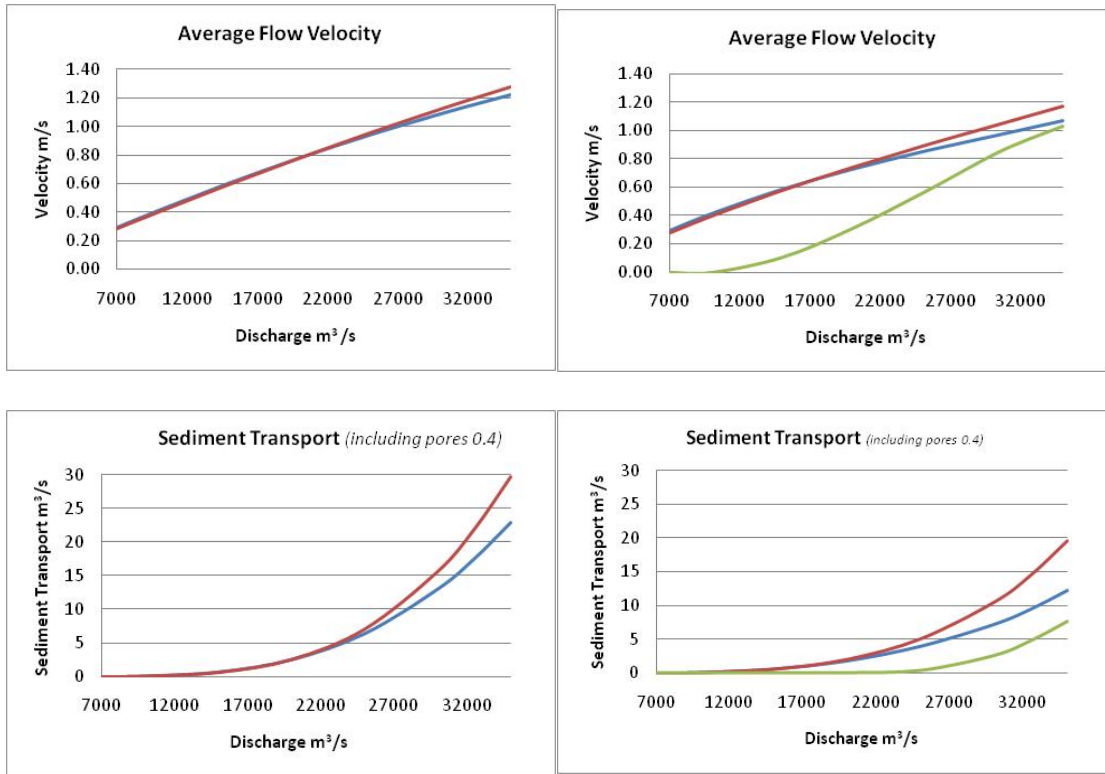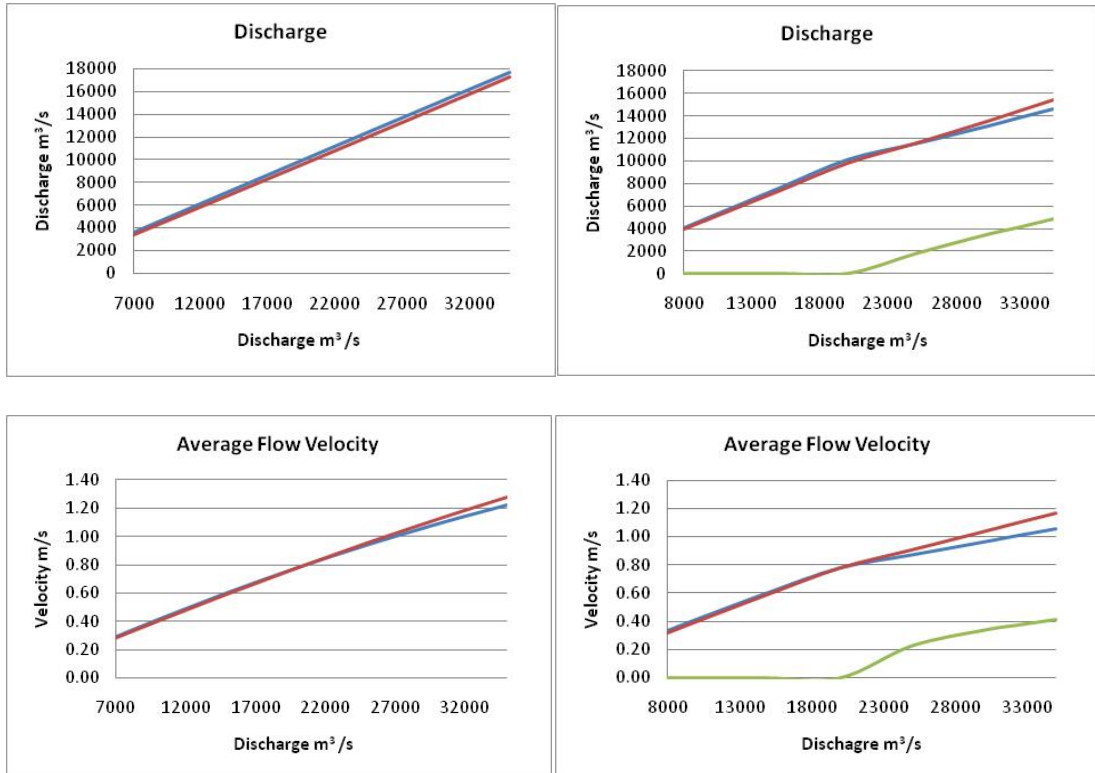Modelled sediment transport **deep** channel:
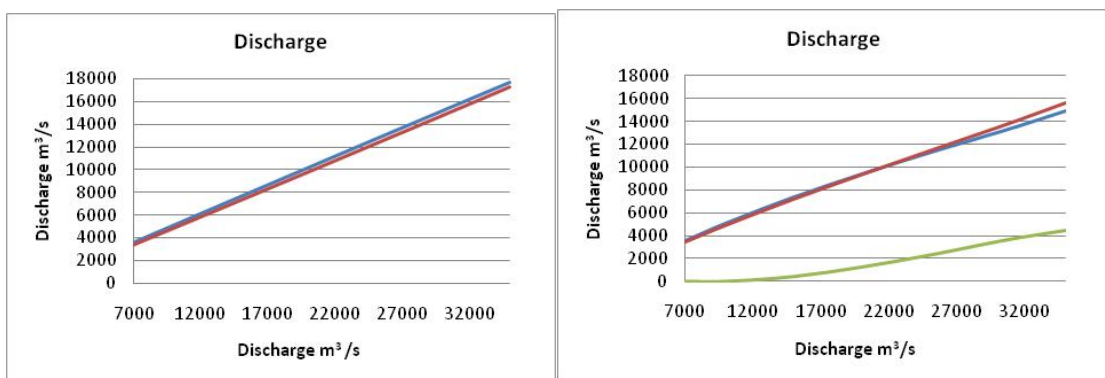
Figure F-4 Left Figure without Diversion channel - Right Figure with Deep Diversion channel

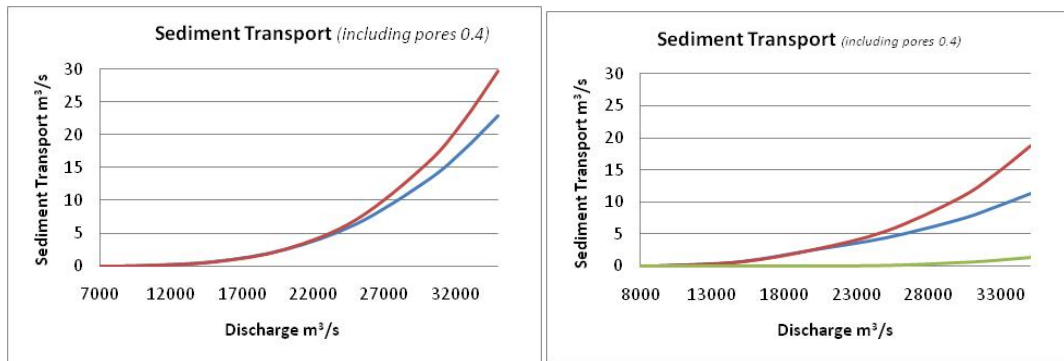Modelled sediment transport **shallow** channel:

Figure F-5 Left Figure without Diversion channel - Right Figure with Shallow Diversion channel

Comparing the discharge graphs with each other it is possible to notice that both diversion channels types are capable to lower the discharges within the main river systems. What is also nice to see, is the way the system reacts because of a weir construction within the shallow channel. Around a discharge of 20000 m³/s the discharge within the diversion channel is suddenly linear increasing. Whereas for the deep channels, where no weir is used the discharge line of the diversion channel is fluently increasing.

Figure F-4 and

Figure F-5 also shows that by implementing a diversion channel result in a significant reduction of the sediment transport capacity towards the South East Sea. The reason for this is because the diversion channel is reducing the flow velocity within the main river system. This reduction in flow velocity caused by the drop in water level also affects the sediment transport capacity. Because sediment cannot disappear the most logical thing must be deposition of sediment after the attachment point of the diversion channel.

Sedimentation must also occur within the diversion channel. Looking at the flow velocity differences between the deep and shallow channel indicates that in both situation the flow velocity in the main river system is lowered by more or less the same amount. However, looking at the discharge in both diversion channeles reveals that although both diversion channeles are discharging the same amount of water, namely 4000m³/s. The deep channel has a higher average flow velocity than the shallow one. This means that deposition of sediment is most likely to occur in the shallow channel option because the average flow velocities are ~0.4m/s. Looking at

Figure F-5 also shows that sediment transport capacity near the mouth is small for the shallow channel situation The difference of sediment transport is also shown in Figure F-6. *Note: that the blue line is for the deep channel and the red line for the sallow channel.*
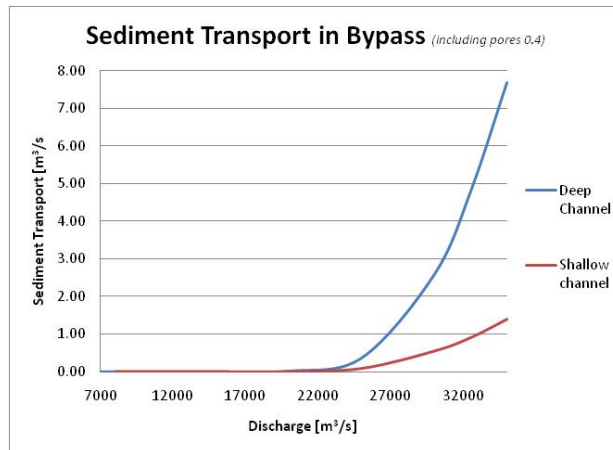
Figure F-6 Sediment Transport Capacity in Deep and Shallow Channel

Discussion

The above made sediment transport results are all based on a situation whereby the whole system is in balance. This means that the 1D Sobek does not take into account morphological changes. This assumption is still valid when modelling only the main river system without the diversion channel. However, once the diversion channel is active the total system is not in equilibrium anymore. The period of the high water event is much smaller than the time needed for the system to move towards its new equilibrium situation. Morphological changes of the channel bed are not taken into account. If morphological changes were implemented in the model it is not unthinkable that heavy erosion of the channel bed occurs, which leads to more sediment transport. This means that sediment transport towards both the Gulf of Thailand and the South East Sea can be different than what is calculated. These morphological changes are important and should therefore be implemented in follow-studies.

G.   Delft3D coastal model

The purpose of this hydrodynamic coast model is to understand what the behaviour is if a peak, point-load discharges enter the Gulf of Thailand. The main reason to do this exercise is to understand where the peak discharge with suspended sediment disperses to once it enters the Gulf of Thailand.

The idea is to approach this behaviour as if the suspended sediment has the same physical spreading behaviour as pollution with a concentration. It has to be kept in mind that this hydrodynamic-pollution model represents the most pessimistic solutions of the spreading patrons. Because in nature cohesive suspended sediment tents to flocculate by encountering salt sea water this behaviour is not taken into account in this preliminary study. It is also decided that for this exploratory research only the hydrodynamics is looked at, in two dimensions. The two dimensional horizontal model (2DH) is a result of integration over the vertical meaning that the flow velocities near the surface and the bed are not computed separately thus ending up with a depth-average velocity (See Appendix D.1 for the fundamental equations).

In Vietnam the modelling program Mike (DHI, Denmark) is often used to Model River and coastal problems. However, usage of such a program in the Netherlands is not so common. In the Netherlands program tools like Deft3D (D3D) is often used to model such complex hydrodynamic areas. The D3D model is used for this thesis because of its capabilities and because it became open source software recently. Besides D3D a pre-processing tool is used to set-up the model, this pre-processing tool is called Delft-Dashboard.

It is important to understand that referring to these results must be taken with caution. Extensive calibration and sensitivity analysis are strongly recommended before the model is suitable for policy makers. Besides that due to the assumptions made, implementation of more physical parameters which influence the spreading like wave forcing and sediment behaviour should be taken into account within further analysis.

G.1.   Assumptions input data

Due to the limited available data, choices are made on which input data is taken into account and moreover what not. This paragraph present these made choices to set-up a coastal 2DH model. Assumptions are necessary but not available at the moment.

G.2.1.   Bathymetry

Provided data does not offer enough information of the whole area of interest to be used as input data for the model. Therefore Delft Dashboard software is used to generate a more detailed offshore bathymetry. This software contains online (free to use) datasets

on bathymetry and tidal data. For the bathymetry dataset the database of GEBCO 0.8 is used, the generated bathymetry charts are based on the assimilation of heterogeneous data types. The depths are given against means sea level. For the purpose of this preliminary research the acquired bathymetry data of GEBCO 0.8 is sufficient. However, for further studies on coastal morphology measure bathymetry data is recommended.

G.2.2. *Waves & wind*

It is unknown if there are any wave buoys transmitting real-time marine conditions. Some data is found via the website BMT Argoss which is based on model records between 1992 and 2010. Unfortunately, the model point is just behind the southern point of the island Phu Quoc. Therefore the question is how reliably this modelled wave climate records are when translated towards the area of interests. Besides that measured wave data near the area of interest are not available. Hence the influence of waves is not included in the hydrodynamic model. However, it has to be kept in mind that these waves energy have a direct effect on the distribution pattern of any discharge from the diversion channel. To incorporate the effects of waves for further studies is recommended.

Likewise as the wave climate wind set-up could result in a different dispersion of the discharge concentration entering the Gulf of Thailand. However, for this pre-study this wind set-up due to fetch is not taken into account. Also this aspect should be further investigated in a follow up study

G.2.3. *Tidal information*

Around the coast of Vietnam with the Gulf of Thailand two tidal stations are situated one is in Ha Tien and the other one in Rach Gia. For the station at Ha Tien only tidal predictions are available for the varying water levels. Fortunately for the station of Rach Gia several measured varying water levels are available. However, this water level variation information is not specifying enough to use them as boundary conditions for the model. The shape of Rach Gia bay and all small islands most likely distort the tidal wave. Once gain the Delft Dashboard software is used to generate the tidal boundary conditions. In order to reach a reliable dataset as tidal boundary conditions the boundaries should be in offshore waters. To limit the amount of boundary conditions sides the grid is chosen such that only tidal information comes from the west and the south. See Figure G-2.

The generation of the astronomical forced boundary conditions (free to use) online TPXO 7.2 is used. This organization like GEBCO assimilates from different sources data to generated there bathymetry or in case of TPXO astronomical forces. To regard the effects of shallow and deep areas at the boundaries, the astronomical forced boundary is separated in 56 parts. 20 of the boundary conditions are set on the west side and 36

conditions on the south side. An example of set astronomical components the amplitude and phases is given in Table G-1.

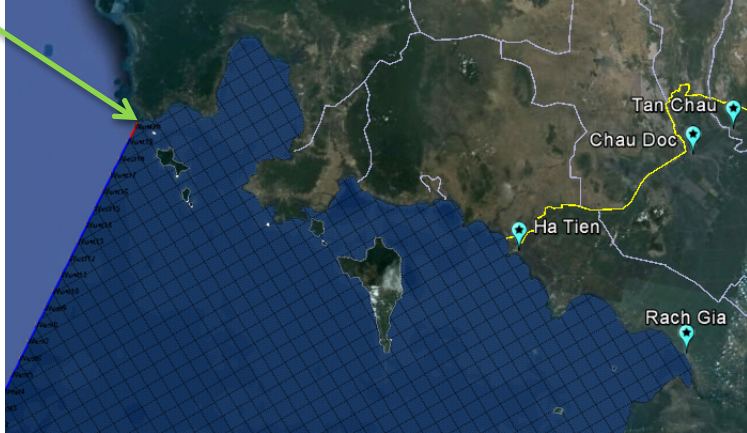| Boundary West 20		
Astronomical Component	Amplitude [cm]	Phase [Degree]
M2	0.079	181.10
S2	0.026	206.14
N2	0.025	159.98
K2	0.009	181.94
K1	0.245	31.87
O1	0.181	358.67
P1	0.077	37.75
Q1	0.038	331.54
MF	0.008	114.83
MM	0.005	46.01
M4	0.002	184.42
MS4	0.001	237.86
MN4	0.001	166.59

Table G-1 Astronomical Component Boundary West 20. Left indication of boundary in overview figure.

G.2.4. *Discharge*

The diversion channel and the coastal model is an uncoupled system, because the tidal influence does not (positive or negatively) influence the discharge of the diversion channel into the Gulf of Thailand. In reality the discharge could be influenced by the backwater curve induced by the tidal range. Looking at the tidal variation the maximum tidal range is approximately 0.9m, with 0.8m HHW and -0.2m LLW both against MSL. For further studies it is wise to also include this effect.

However, again for this pre-study this influence is neglected. The load is based on the results modelled via Sobek in chapter 3. where the diversion channel is dimensioned based on the known extreme event of year 2000, which is $4000m^3/s$.

G.2.5. *Flocculation due to salinity*

As said before if suspended cohesive sediment encounters saline water it tends to flocculated resulting in higher fall velocity due to increase of mass. It is decided that for this preliminary study the suspended sediment is not taken into account. The approach is to imitate the spreading of suspended sediment by means of a concentration.

G.2.6. *Diffusivity coefficient*

Geostrophic eddies can induce mixing in the horizontal. These eddies can have sizes of several hundreds of kilometres. The model uses the advection-diffusion equation for horizontal mixing by eddies for a given concentration c. In (Eq.G-1) the depth-average advection-diffusion equation is given for the x and y direction.

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = \frac{1}{h}\left[\frac{\partial}{\partial x}\left(hK_x\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(hK_y\frac{\partial c}{\partial y}\right)\right] \qquad \text{(Eq. G-1)}$$

With:

c	= Concentration [kg/m³]
h	= Local depth [m]
u, v	= Flow velocity in x- and y-direction [m/s]
$K_{x,y}$	= Diffusivity coefficient in x- and y direction [m²/s]

The first left hand side describes the concentration displacement in time and space (these are the advection terms in x and y directions). The right hand side describes the diffusion of the concentration that is depended on space (the diffusivity term in x and y direction).

Within the 2DH model the K-value is the diffusion coefficient. The diffusion coefficient is actually a calibration parameter and therefore not a known value in this study. The diffusion parameter is selected using a Smagorisky type of approximation that multiplies a constant with the velocity gradient over a horizontal grid and the square of the length of a grid cell. The possible flow velocities are between 0.1 and 0.4 m/s, see paragraph H.1. By setting the constant equal to 0.2 results in a diffusion coefficient between the 10 to 40 m²/s.

A sensitivity analysis shows that the difference between the possible diffusion coefficients are minimal see Figure G-1.
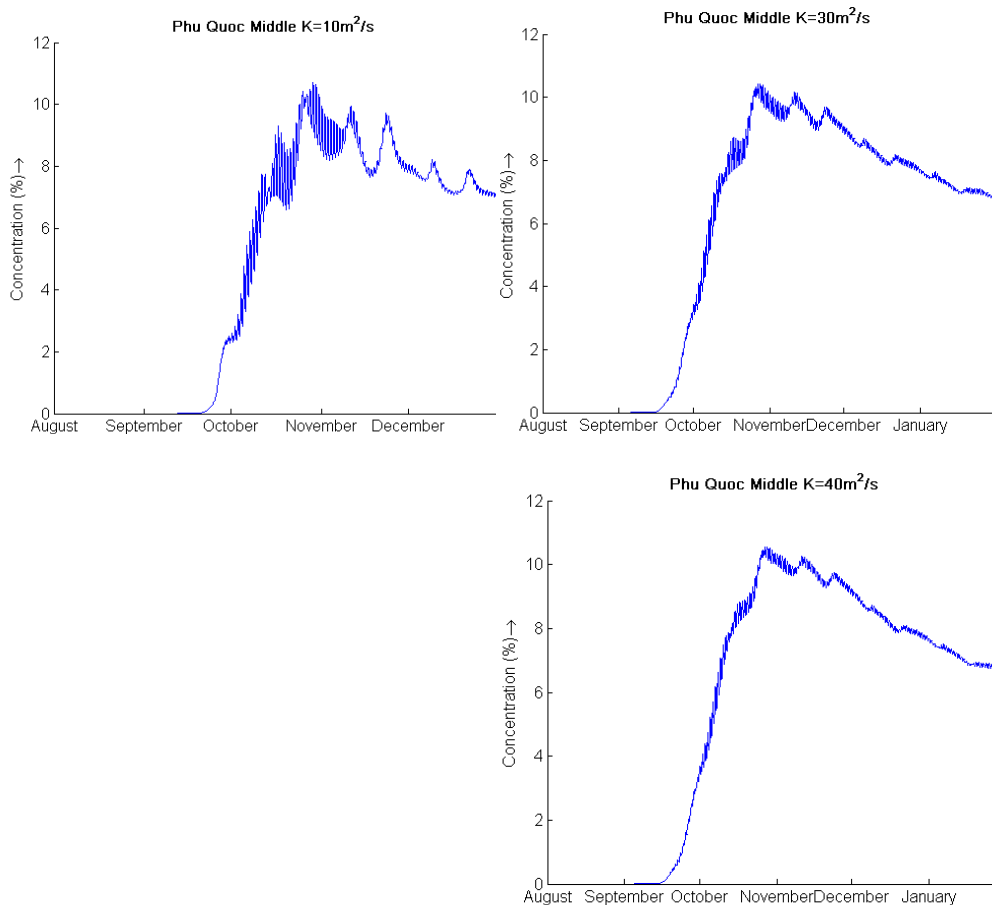

Figure G-1 Sensitivity analysis between the different diffusion coefficient

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The velocity gradient over a grid cell for the used model is assumed to be equal to 0.3m/s. By using the Smagorinsky type of approximation and a constant of 0.2 the diffusion coefficient is calculated to be 30m²/s.

G.2. *Hydraulic D3D model set-up*

In the previous chapter the input data of the model is elaborated. Based on the availability of input data, choices are made on how to execute the model. This chapter goes into the setting-up of the model. Choices made on the grid sizes, positioning of the grid and boundary conditions. After the preliminary chosen set-up a calibration is done using the sensitivity analysis method to a sure the best possible computational time, grid size and set-up.

G.2.1. *Area of interest*

The diversion channel has its discharge point somewhere between Ha Tien and Rach Gia. Therefor the main area of interest lies within the Gulf of Thailand towards the west of the Mekong Delta. It is between island Phu Quoc and the northwest coast of Vietnam. This coastal area is roughly saying 6000m² and indicated with the red square in Figure G-2. The effect of this discharge is looked at with the help of the delft3d model.
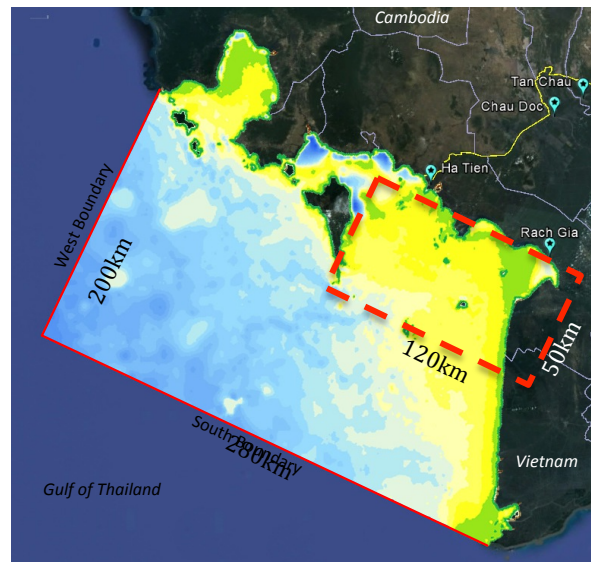

Figure G-2 Delft3D model area, with bathymetry contour lines

G.2.2. *Bathymetry*

As already indicated the bathymetry is taken from GEBCO 0.8 although it is quite detailed for the purpose of this research. It does have some flaws when implementing it. Because it also takes water bodies into account which are situated land inwards. These water bodies create unwillingly open boundary condition. Due to this implication all landwards water systems are excluded from this model. This means that small estuaries like that at Ha Tien are not taken into account.

In Figure G-2 the bathymetry is given of the whole model area. The colour indications shows that the near coastal area depths area >MSL-15m. The green colour indicated depth ~2 to 3m -MSL. The deepest points are near the boundaries with the dark blue colour depths of almost MSL-90m. It has to be noted that small areas above the large island Phu Quoc just next to the area of interest deeper spots are found.

G.2.3. *Grid design*

To keep the model as simple as possible a structured grid network is chosen to be the bases of the 2DH model. A drawback of not using curvilinear grid cells is that cells at the coastline could vary largely from one corner being on land to the other corner, which lies in sea. To prevent too much depth difference in one cell and limit the inaccuracy close by the area of interest the whole network is rotated.

The total grid network is 280x200km the area of interest is around 120x50km these two areas are shown in the Figure G-2 the main information of the grid design is presented within the following table.

Grid points M	555
Grid points N	400
Step size (dx)	500 [m]
Rotation angle	-25,5483 [º]

Table G-2 Main aspacts grid cells

There are a few reasons why the total grid size is set on 280 by 200km. The first one is because of the rotation. If a smaller length was chosen, the results are an extra open boundary at the east of the grid cells, the east side location would results in high velocities because the depth at the tip of Ca Mau is relatively seen shallow. Large amount of water does enter and leave via this boundary. The second reason why it is set on 280 by 200km is because the boundary conditions need to be placed at sufficiently enough depth to get reliable enough tidal boundary conditions. Thus the boundary is placed at such a depth whereby the effects of the boundaries have no significant influence on the area of interest.

G.2.4. *Calibration & validation D3D model*

At the moment of calibration only predicted tidal data were available of two stations. One is at the coastline of Cambodia at the city Kampong Som and the second one is in Vietnam at Ha Tien. The main purpose of this calibration is to fine tune the model results to mimic the magnitude of the hydraulic processes in this case the water levels based on the tidal predictions. The main parameters which can be used to fine tune the model is by altering the bottom roughness or enlarge constriction points. These constriction points are the result of choosing the grid sizes too large, whereby the interpolation could be off balance between two depth points.

The first step is to validate if the model is valid to use. This is more a sensitivity step to see if the chosen set-up grid size Δx and time step Δt have a negative influence on the model outcome. So the question is if the numerical stability (CFL condition) of the model could be the reason why the comparison of the tidal prediction and the model outcome is

not perfect. Appendix D.2 gives the explanation of the CFL equation. The result of this sensitivity analysis is that choosing a grid size of $\Delta x = 500m$ and the time step of $\Delta t = 5min$ does not have a significant negative effect above choosing a model with smaller grid cells and a lot smaller time scale. The reason is that the CFL condition is dependent on the water depth. Fortunately the water depth at the area of interest is rather shallow. Therefore even though the CFL value rangers from <1 near the coast to almost 50 at the boundary conditions. Within the area of interest the range of CFL value is between the 1 - <25 which is a reasonable CLF value for this purpose of modelling.

Calibration results

A calibration is done on altering the total water depth using again a sensitivity analysis. Altering the local water depth does not give significant changes; the reason is that tidal waves are long waves, which does not get altered by small local variations of the bottom. Altering the total depth does shift the modelled tide up or down. However, the spring tides are already modelled rather well without changing the depths. What does help a little is by increasing locally the constrictions above the island Phu Quoc.

The last calibration is based on a sensitivity analysis altering the total roughness parameter. As it turns out is that the default roughness of a manning coefficient of 0.02 is the best one.

The results are given in Figure G-3, the red line indicated the tidal prediction and the blue line the modelled tide. All calculations are based on 1 month of modelling time; this is from 26 July until 28 August.
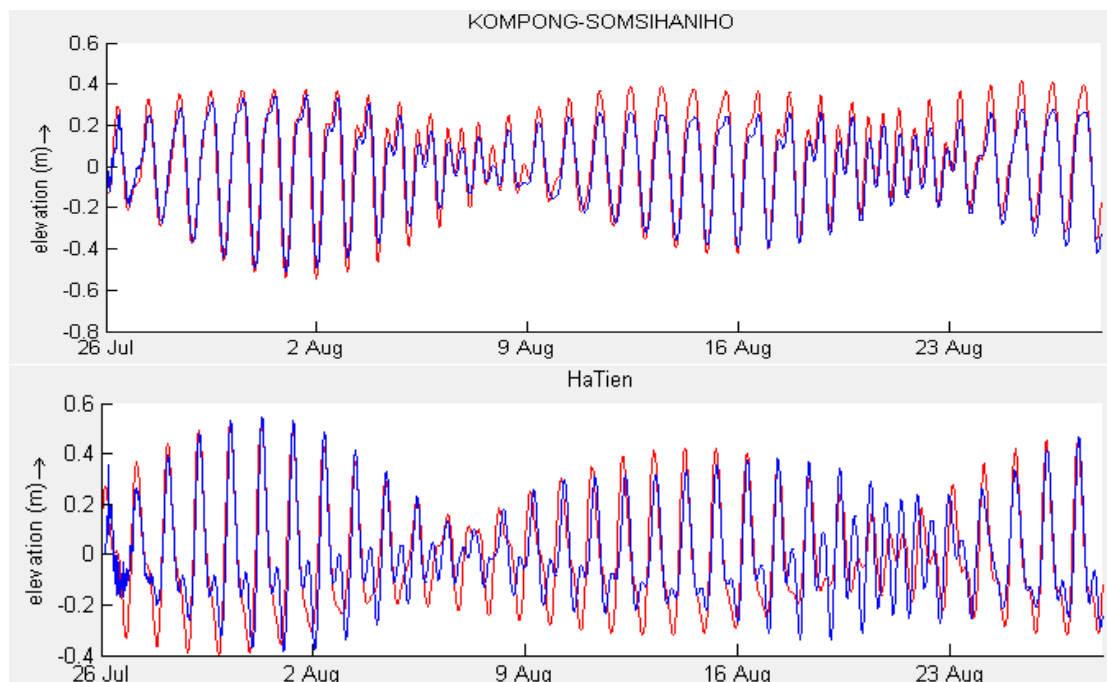

Figure G-3 Tidal prediction (red), Tidal modelled (blue), [top panel station Cambodia, lower panel station Vietnam]

Although the modelled tidal signal is not perfect, overall the modelled period and amplitude of the model tide does represent the tidal prediction well. There are differences but the model is capable of predicting the moments of high and low water and in a sense the tidal range. To analyse if the calibrated model can be used validation is necessary with a different measured data set.

Validation results

During the trip to Vietnam, a data set was provided with measured water levels of Rach Gia. This is used as validation data, to validate the outcome of the model against real measured data. The data was again provided by (The Water Resource University, 2012). However, it is not clear how accurate the measured data are.

The validation result for the duration from 26 July until 28 august is seen in Figure G-4 and a close-up in Figure G-5. In these figures the red line is the measured water levels and the blue line the modelled tidal water level.
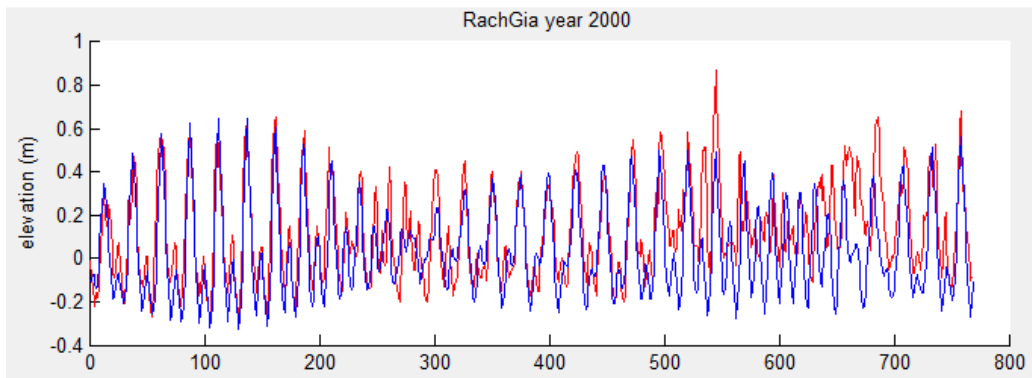
Figure G-4 Validation results of modelled tidal elevation against measured tidal elevation (relative to MSL)
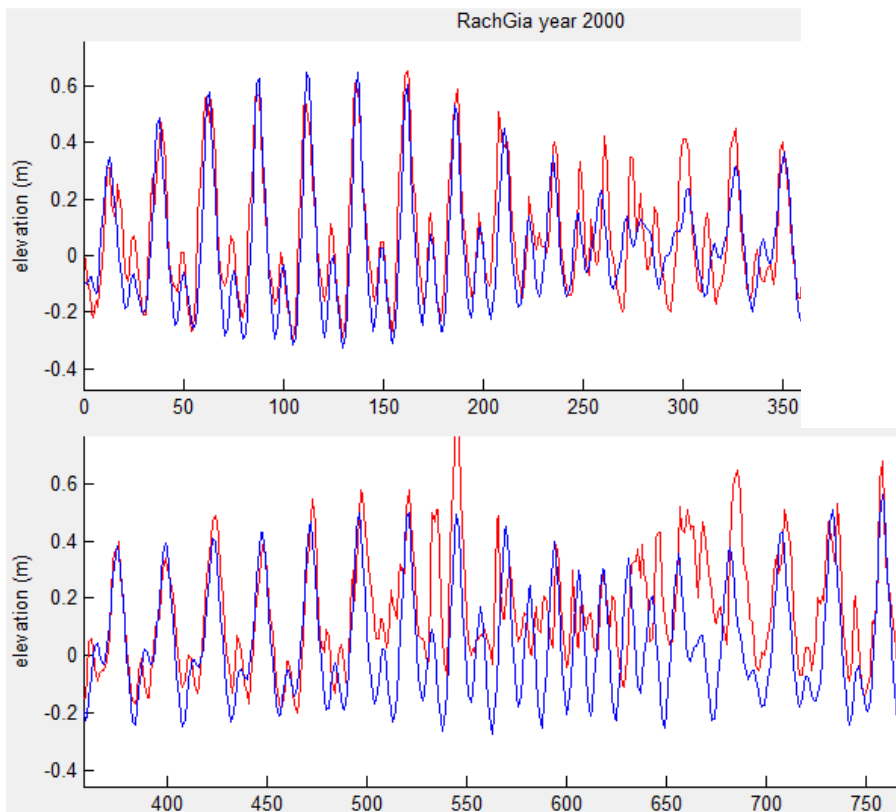

Figure G-5 Validation results close-up

By looking close-up in corrections are noticed, especially during neap tide. Differences within the measured tide and the model tide are seen after the first neap tide. Here the low tide measured higher than what is predicted. The reason for this could be due to wind set-up, which is not within the model. On the other hand spring tide is represented rather well by the model. Also the tidal cycle (high and low tide) and amplitudes are modelled quite well.

Although these differences are noticeable, the model is capable to model the tides magnitude. Therefore it can be said, given that the measured data is valid to compare to, that the coastal model is capable of representing the tidal forcing.

H.   Additional delft3D results

H.1.   Mean Velocities in the area of interest

The highest flow velocities occur when the water gradient is the largest. So during water level rising or falling. The lowest flow velocities are during high and low water slack. To analyse this, a tidal signal of one natural day is enlarged. The chosen signal is during spring tide at Ha Tien see Figure H-1. It shows that on this day the system is flood dominance. It takes around 8 hours for the tide to rise and 16 hours for the tide to fall. It also shows that the tide is of a mix tidal signal but pre-dominantly diurnal.
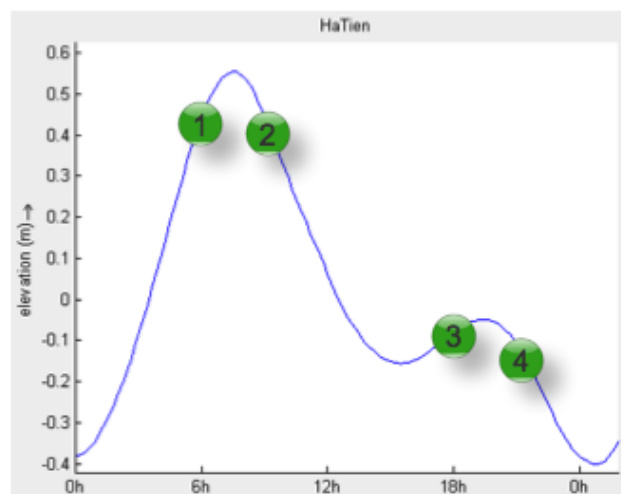

Figure H-1 One natural day tidal signal in Ha Tien (31 Oct – 1 Aug)

Four stages are shown in Figure H-2, of the area of interest in plane view of the depth average velocity. The upper two panels show the situation during flood period and the lower two shows the depth average velocity during ebb period.
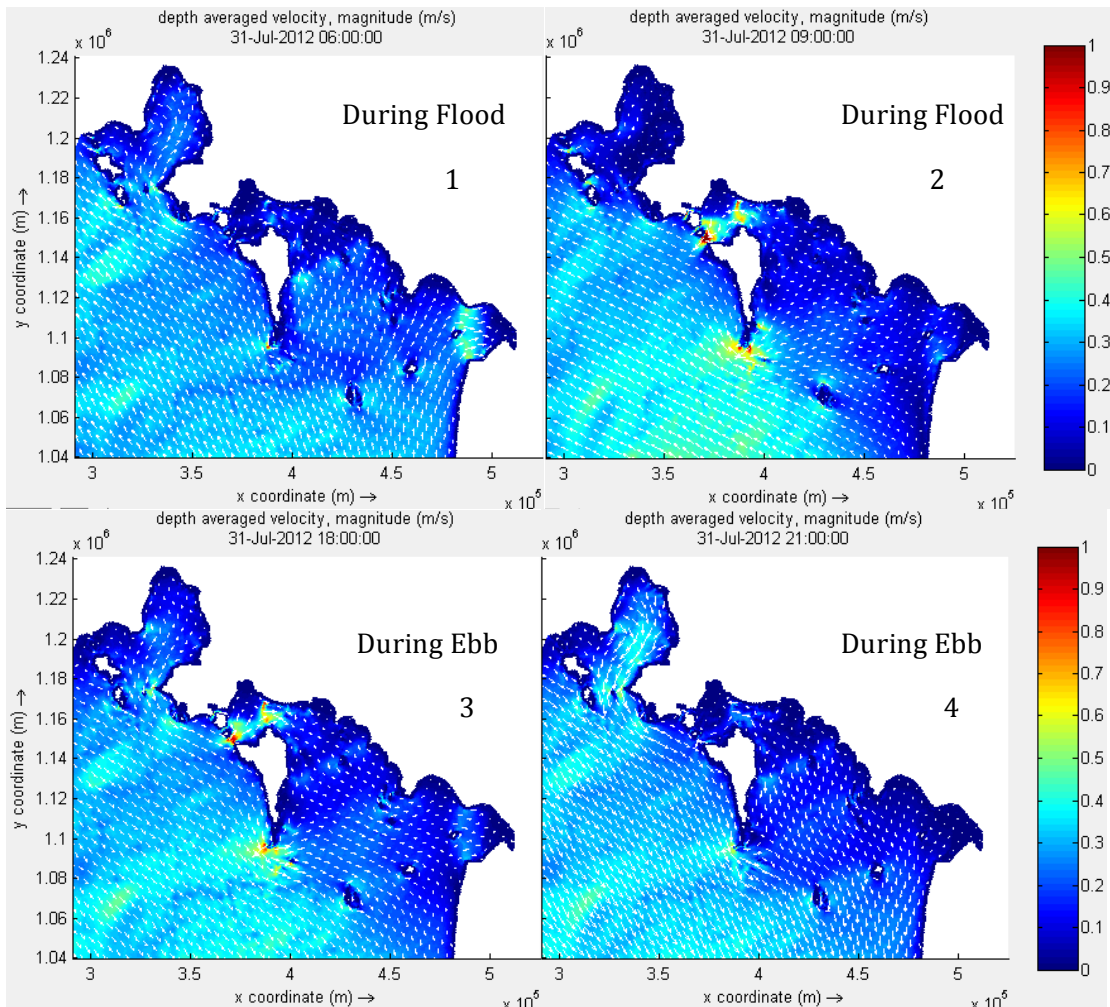
Figure H-2 Depth average velocity during one natural tidal signal (6h, 9h, 18h and 21h)

Based on the results given by the model the depth average flow velocity within the area of interest, the particular current velocities varies between 0.1 – 0.4m/s. Locally the velocity can increase >1.0m/s near the constrictions at the north of the Island Phu Quoc and around the southern tip of that island.

Intermezzo: Hypotheses dominant alongshore current

Looking closely to the bathymetry between Ha Tien and Rach Gia reveals how the main direction of the alongshore current along the coastline should be. Based on a simple elementary straight coastline profile and a perpendicular groyne principle. Between Ha Tien and Xom Ba Tra, the bathymetry is rather shallow; also no significant erosion of the coastline is noticeable between these two cities. After the outwards sticking city Xom Ba Tra the coastline up until Rach Gia does show erosional signs. Sea dikes

and mangroves protect this part of the coastline. Due to a fixed coastline, erosion occurs only of the bed level as an answer to fixing the coastline. So the hypothesis is that the main alongshore current is
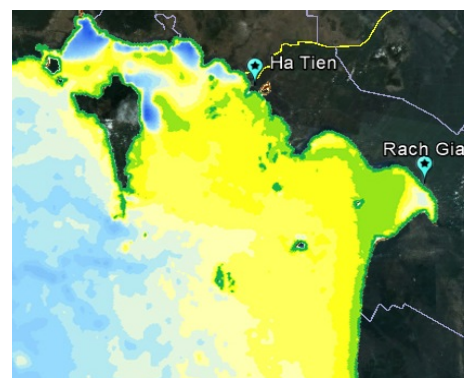
most likely clockwise directed from Ha Tien towards Rach Gia. Due to the lack of measure current field this can only be a hypotheses.

From Figure H-2 it is possible to say that during flood period the current is anti-clockwise. Beside that during this period there is also a strong current directed into Rach Gia Bay. During the ebb period the current is clockwise directed and water flows out of Rach Gia bay. What is also likely to say is that the "netto" tidal current is clockwise directed based on the previous saying that it is flood dominance see Figure H-1. The correctness of this saying is unclear. However, the reason to say this is because during flood and ebb period both depth average flow velocities are quite the same. However, the ebb period is longer than the flood period. Thus it is possible to say that the "netto" current -because the time span is longer- is clockwise directed. This also explains the hypotheses made in the intermezzo *Hypotheses dominant alongshore current.* Better measurements are necessary to validate this made assumption.

H.2. Simulation runs using Method A

The coastal runs for the Middle location are not significantly different than that of discharging at Ha Tien. Top panel discharge 4000m³/s the lower panel 8000m³/s both results used Method A for the other boundary conditions.
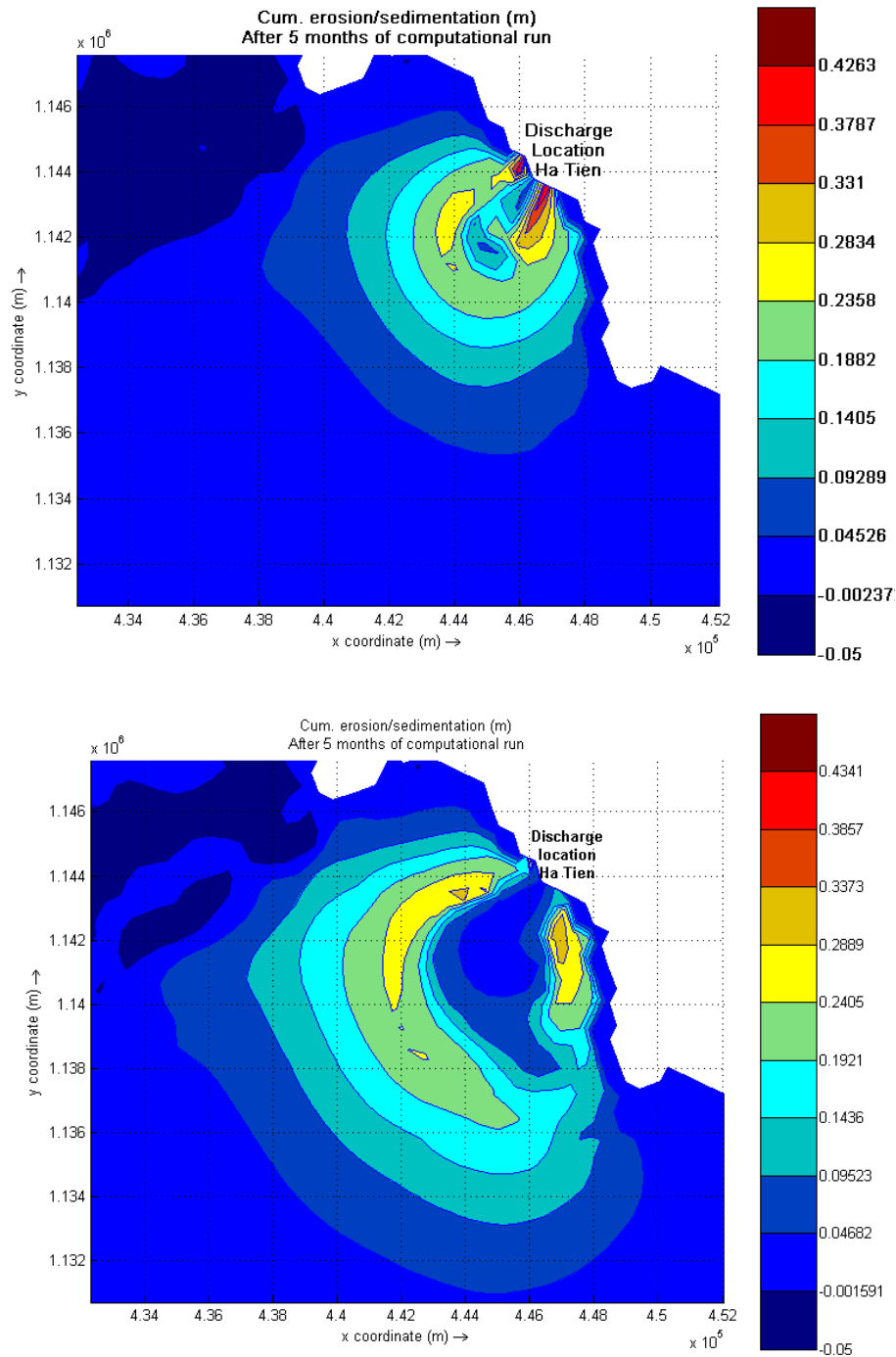

Figure H-3 Simulation run with boundary conditions (A) and the discharge location is at Ha Tien. The figure shows the cumulative erosion or sedimentation against the initial bed level in m. The top panel has a discharge of 4000m³/s and the lower panel a discharge of 8000m³/s.

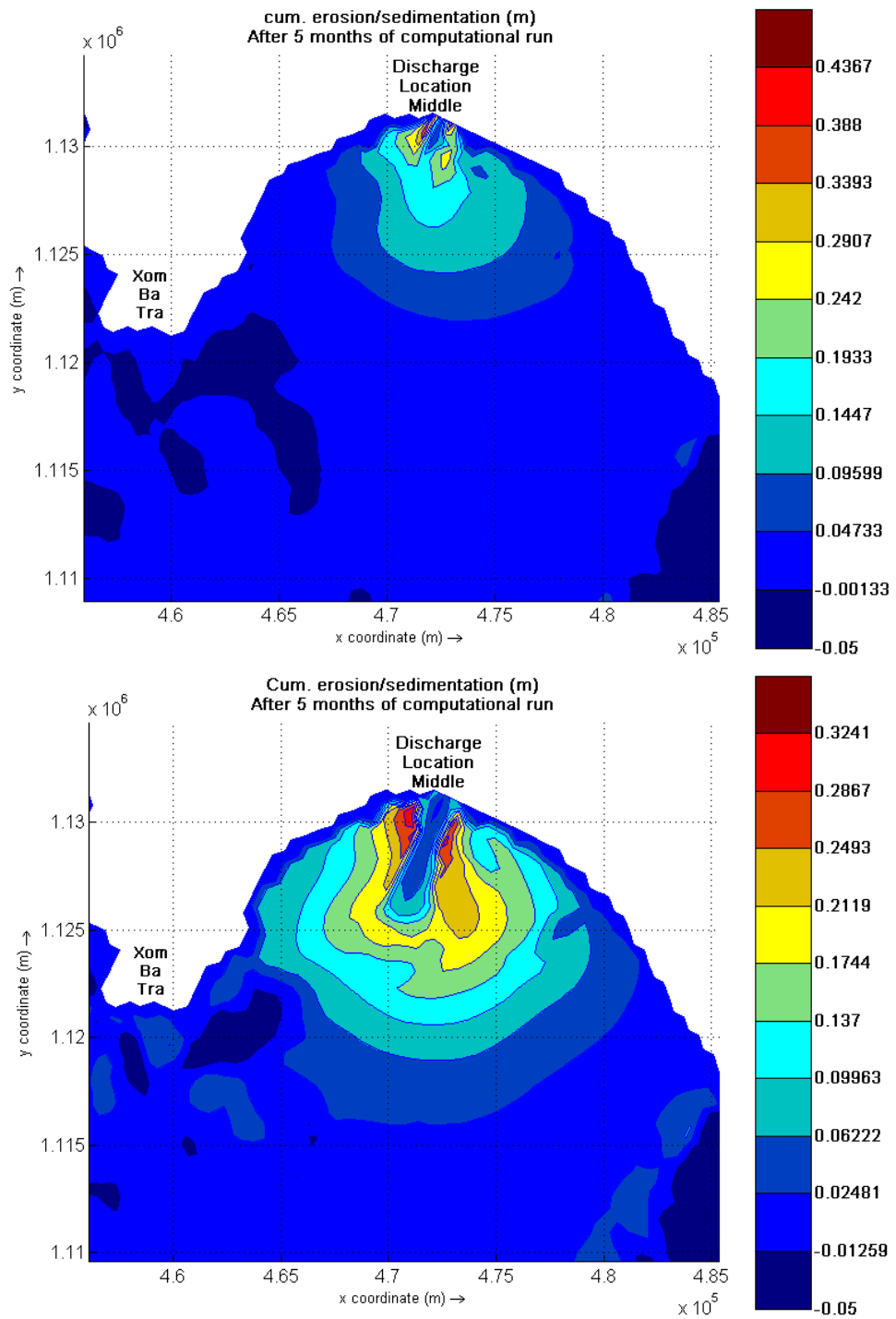Discharge location is at the Middle location.

Figure H-4 Simulation run with boundary conditions (A) and the discharge location is at Ha Tien. The figure shows the cumulative erosion or sedimentation against the initial bed level in m. The top panel has a discharge of 4000m³/s and the lower panel a discharge of 8000m³/s.

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