The influence of hydropower developments on the Mekong delta

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by

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TU Delft Delft University of Technology

Deltares Enabling Delta Life

Preface

This thesis is the result of my final research project for the master Hydraulic Engineering at Delft University of Technology. I have carried out this research at Deltares, an institute for applied research in the field of water. The study focusses on the complicated hydrodynamical processes in the Mekong delta and the influence of hydropower developments on the delta. My project is a part of the Initiative for Sustainable Hydropower (ISH) project of the Mekong River Commission (MRC), which aims to reduce environmental impacts of the hydropower developments by creating a framework for potential mitigation meausures.

First I would like to thank my graduation committee for their supervision and help during my graduation project. Wim Uijttewaal, as chair of the committee, steered me towards a more scientific approach during my project and hereby bringing my research to a higher level. Erik Mosselman was always there for questions about the research approach and especially helped me with my academic writing and report structure. Ymkje Huismans not only helped me getting through the difficult topic of salt intrusion, but was always there for mental support as well. Last but not least, Kees Sloff who with enthusiasm always kept me motivated to get the most out of the project. I would like to thank him for the possibility of doing this versatile and international oriented research, including the opportunity of visiting the MRC.

The Delft3D-FM model of the Mekong delta I used was set up by Thanh Vo for his phd research at the UNESCO-IHE institute. Many thanks to him for letting me use this model and answering all of my questions during our spar sessions.

Besides, I would like to thank some of the Deltares staff for their help. Herman Kernkamp for all his support when I was figuring out Delft3D-FM software. Michelle Jeuken for her support when trying to set up a coupling to DelWAQ and Jurjen de Jong for helping me with all kind of questions regarding to modelling and processing of data. Especially thanks to Ron Passchier, the Deltares project manager of the ISH project, who was a great support always reminding me of my own capabilities.

Finally, I would like to thank my friends and family for their support during the past eight months. Especially the group of fellow Deltares students, who not only helped me with some of the Matlab and LateX issues, but with whom I became good friends and enjoyed many pleasant coffee and lunch breaks. Finally, my family for all their unconditional support even from abroad.

Jenny Pronker
Delft, 3 November 2017

Summary

Rapid hydropower development takes place in the Mekong river and many dams in both tributaries and the mainstream are under construction or planned to be constructed. The present hydrograph has a large difference between the wet season and dry season, but because of the seasonal fluctuations of the water level in the reservoirs of these dams, the hydrograph is expected to change (ICEM, 2010). Not only does the discharge increase in the dry season and decrease in the wet season (a flattening of the hydrograph), but the timing of the wet season will also be delayed. Apart from the change of the hydrograph, also the morphology in the entire river basin will be affected. The hydropower dams block the transport of bed material completely and also the suspended sediment transport will be reduced, because sediment in concentration settles in the reservoirs due to a decrease of flow velocities (Kondolf et al., 2014). The Mekong delta is a densely populated area, where the largest sources of employment, agriculture and fisheries, are depending on the resources of the river (MRC, 2016). However, the population has to deal with potential flood risk and drought risk as well. The Mekong delta is a delicate system, both ecologically and socio-economically speaking, and changes to the river's natural regime are expected to have large consequences. Therefore, the main question to be answered is: How will the hydrodynamics in the Mekong delta be affected by the proposed developments of hydropower in the Lower Mekong Basin and what will be possible measures to reduce negative impacts on the delta from these dams?

In order to assess the effects of the changed hydrograph on the delta, the hydrodynamical processes in the delta and the interaction between them is researched. This enables the assessment of the effects of the hydropower developments on the hydrodynamics and potential risks (and benefits) to ecology and socio-economy can be determined. Finally, a number of local mitigation measures are explored to reduce the negative impacts. In order to obtain a better understanding of the hydrodynamics in the delta, three important processes have been investigated in more detail, namely the in- and outflow of Tonle Sap lake, the discharge distribution over the main branches and the inflow to the Vietnamese canal-floodplain system. This is done by using a numerical (Delft3D-FM) model and by creating a conceptual model, which represents the process using simple analytical formulas. This numerical model is also used for the assessment of hydropower scenarios and effects of mitigation measures.

The in- and outflow of the Tonle Sap lake is governed by the difference in water level between the lake and the Mekong. Especially when the water level in the lake is high, a small water level difference results in a large flow through the Tonle Sap river which connects the Mekong and the lake. Because of the flattened hydrograph, the difference between minimum and maximum water level will decrease. The decrease in seasonally inundated areas has a large influence on both agriculture and the amount of fish. Also the annual flow reversal will be delayed due to the shift of the wet season, which has consequences for the fish migration.

In the Mekong delta the river bifurcates into many branches for which the distribution can be described using the bifurcation laws. At Phnom Penh, the water is distributed unequally over the Mekong (85%) and Bassac (15%). The Vam Nao branch, connecting both branches, redistributes the water to an almost equal distribution. The flattened hydrograph decreases both flood and drought risk and distribution remains the same. However, due to the decreased wet season velocities, the sediment transport capacity will reduce severely. In combination with a reduced supply of sediment to the delta and sediment mining, this might lead to bed level degradation. In case of bed level degradation the potential risks increase even further, for example the water level difference in Tonle Sap lake reduces and the risk for salt intrusion in the dry season increases.

The Vietnamese canal-floodplain system consist of many canals and floodplains surrounded by dikerings. These comparted floodplains are used mostly for cultivation of rice and dependent on inundation for supply of nutrients. In the dry season, water is supplied to the agricultural areas through the canals. In the wet season the floodplains inundate one by one when the water level rises. When the water levels rise above the dikerings overland flows increases the area of inundation. Due to the decrease of the discharge in flood season less floodplains are expected to inundate. More water will be supplied in the dry season, which is favorable for agriculture, except when the bed level in the main branches degrade.

There are a number of mitigation measures that can be applied in the Mekong delta. In order to increase in- and outflow of Tonle Sap lake the cross-sectional area of the Tonle Sap river can be increased by widening or deepening. Besides, a shortcut canal can be considered between the Mekong and Tonle Sap lake. Furthermore, to avoid bed level degradation, it is recommended to reduce the sediment mining and implement sediment management measures at the proposed dams. Also a number of measures to reduce salt intrusion has been proposed. In order to increase the inundation extent of the floodplains, it is recommended to reduce the heights of the dikering which enhances overland flow and floodplain inundation. However, for most of these measures it can be said that a decrease of the potential risk has consequences further downstream in the delta, possibly increasing the potential risks even further.

A future research perspective can be to improve and couple the created analytical models, to make it useful as a rapid assessment tool for the entire delta. Besides, the numerical model can be improved, by including morphodynamics or layers over the depth, to assess the effects (of mitigation measures) in more detail. By including the operational rules of the proposed dams on different hydrological years, the inter-annual effects of the hydropower developments (instead of only average changes) can be better understood. Finally, it is recommended to set up an operational support system including all hydropower dams, to optimize the operations and limit the negative impacts.

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List of symbols and abbreviations

Symbol	Description	Units
a	Bed form factor	m
A_b	Surface of basin	m^2
A_c	Conveying cross section of river branch	m^2
B	Width of river branch or floodplain	m
B_c	Conveying with of river branch	m
C	Chézy coefficient	$m^{1/2}/s$
c	Concentration	kg/m^3
c_a	Near bed concentration	kg/m^3
c_f	Dimensionless friction coefficient	-
$C_{sediment}$	propagation speed of erosion front	m/s
c_{HW}	Propagation speed of flood wave	m/s
D	Grain diameter	m
d	Water depth	m
d_e	Equilibrium water depth	m
g	Gravitational constant	m/s^2
h	Water level compared to reference level	m
h'	Deviation from equilibrium water level due to backwater	m
h_0	Local water level	m
h_b	Water level in basin	m
i_b	Bed slope	-
i_f	Water level slope	-
l	Length of indicated river branch	m
$L_{1/2}$	Half length of backwater according to Bresse	m
m	Sediment transport factor, depending on applied transport formula	$m^{3-n}s^{n-1}$
n	Sediment transport linearity factor	-
N_R	Estuary Richardson number	-
Q	Discharge through river branch	m^3/s
Q_f	Riverine discharge	m^3/s
Q_u	Quasi uniform discharge	m^3/s
q_s	Sediment transport per unit width	m^2/s
q	Discharge per unit width	m^2/s
R	Hydraulic radius of cross section	m
Re_*	Dimensionless Reynolds number	-
S	Sediment transport volume	m^3/s
s	Distance in space	m
t	Time	s
u	flow velocity	m/s
u_f	Riverine flow velocity	m/s
$\bar{u}$	Depth averaged flow velocity	m/s
u_*	Shear velocity	m/s
V_{FP}	Volume water stored in floodplain	m^3
Z	Rouse number	-
z	location in vertical water column	m
z_b	Bed level compared to reference level	m
z_{FP}	Height floodplain compared to reference level	m
$z_{Dikering}$	Height dikering compared to reference level	m

Symbol	Description	Units
Δ	Relative density	-
ΔH_R	Head loss due to friction	m
Δ_t	Time step	s
θ	Shields parameter	-
κ	Diffusion or dispersion coefficient	m^2/s
ν	Kinematic viscosity	m^2/s
ρ_s	Density of sediment	kg/m^3
τ_b	Bed shear stress	$kg/m/s^2$
θ	Shields parameter	-
κ	Diffusion or dispersion coefficient	m^2/s
ν	Kinematic viscosity	m^2/s
ρ_s	Density of sediment	kg/m^3
τ_b	Bed shear stress	$kg/m/s^2$
υ	Tidal velocity amplitude	m/s

Abbreviation	Definition
3S rivers	Se Kong, Se San and Sre Pok
LXQ	Long Xuyen Quadrangle
LMB	Lower Mekong Basin
MRC	Mekong River Commission
PoR	Plain of Reeds
TSR	Tonle Sap River

1

Introduction

1.1. Mekong river and delta

The Mekong river, with a length of over 4000 km and a basin area of almost 800.000 km^2, ranks as one of the largest rivers in the world. The river originates in China as the Lancang river and flows from China and Northern Myanmar to Laos, from where it is called the Mekong river. The Lower Mekong Basin (LMB) spreads out over Laos, Thailand, Cambodia and Vietnam, where it ends in the South China Sea. With a mean annual discharge of 475 km^3, is the Mekong the 8th largest river in the world. This volume is mostly created by the Southwest monsoon rains and the Mekong has therefore a distinguished dry and wet season flow. In the dry season, from December to May, the discharge in the Mekong is below 5,000 m^3/s, while in the wet season discharges (before entering the delta) reach up to 40,000 m^3/s. Many tributary systems in the Lower Mekong Basin contribute to the discharge in the Mekong. Each of these systems increase the total volume downstream, depending on the size and precipitation of the tributary basin, which are shown in Appendix A (MRC, 2005).

This study does not focus on the entire Mekong river basin, but specifically on the delta area in Cambodia and Vietnam. The delta is characterized by low lying floodplains and many bifurcations into a widespread area. The great lake of Tonle Sap (and its tributaries) in Cambodia is also part of the delta of the Mekong, which is connected to the Mekong via the Tonle Sap river (MRC, 2011). During most of the year the lake discharges to the Mekong river, but during the wet season the flow direction reverses and water flows from the Mekong river to the lake. In the Cambodian area of the delta, the river is still in a natural state and irrigation has not fully developed. In the Vietnamese delta, there is a dense canal-floodplain network in order to supply the water resources over a large area (Manh et al., 2014).

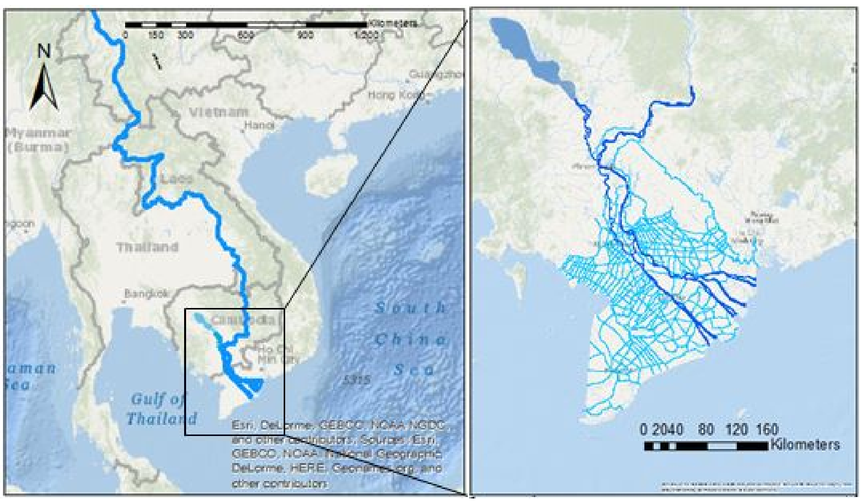


Figure 1.1: Mekong river and study area in the delta

The Mekong river is of importance for the people in the delta area. Because the delta is a very fertile area due to the supply of fresh water and nutrients, the area has become densely populated with over 20 million people relying on the river's natural resources. Agriculture (mostly rice cultivation) and fisheries (both natural and aquaculture) are the largest source of employment in the area (MRC, 2016). The Mekong delta is a complicated system in which water is temporarily stored and distributed over the agricultural areas. Due to the large flood volume in the wet season, large areas in the delta area are annually inundated, hereby storing part of the flood volume and reducing downstream discharges. In the dry periods, the water is released from the inundated storage area and contributes to the discharge further downstream (Manh et al., 2014)(Hung et al., 2012). Especially the Tonle Sap lake has a large influence on the distribution of water in the Mekong Delta (Kummu et al., 2014). The lake area itself is a large source of rice production and fisheries due to the rich ecosystem of the seasonally inundated areas (Arias et al., 2014). The canal- floodplain system in Vietnam depends on the water resources from the river for rice cultivation as well. Besides that, they are an important buffer for water during the wet season and reduce flood risk further downstream (Partners for Water, 2013). Due to the dependence of the delta area on the river water resources, the discharge distribution is of great importance. Risks for flooding in the wet season and droughts during the dry season, and related increase in salt intrusion, are stressing the area and its inhabitants (MRC, 2016).

1.2. Hydropower development

One of the current developments in the Lower Mekong Basin is the exploitation of hydropower. Since all countries in the LMB are rapidly growing economies, a more constant energy supply is required for the industry. Quite some dams were already operational before 2010 in the tributaries of the Mekong river, but plans have been made to construct another 85 tributary dams and 11 mainstream dams. In Figure 1.2 the planned dams for both tributary dams (small triangles) and mainstream dams are indicated. China is exploiting hydropower potential in the Mekong as well and has recently completed the construction of a hydropower dam cascade in the mainstream of the Upper Mekong Basin. Especially the rate of the construction is of concern, because since this map was made construction has started for another 20 dams, including the mainstream dams at Xayaburi and Don Sahong (MRC, 2016).

The effects of the dams on the hydrology are caused by the large active reservoir volumes of which the volume is regulated by the dam operations. The volume stored in the reservoir between the maximum supply level and the minimum supply level for energy, is used to secure a more constant discharge and energy generation during the year and is called the active storage (Lauri et al., 2012). During the wet season, less water flows out through the dams compared to the inflow of the reservoir causing the water level in the reservoir to rise. During the dry season more water is released through the dam than flows into the reservoir, causing the water level to drop. The seasonal fluctuations of water storage in a reservoir cause a shift of discharge from the wet season to the dry season and flattens the hydrograph (Piman et al., 2013)(Lauri et al., 2012). The large reservoir dams in the mainstream of the Upper Mekong in China changed annual hydrograph already (International Rivers, 2014) and this effect will increase significantly by the proposed developments in the LMB. Most of the planned mainstream dams will have rather small active storage volumes (ICEM, 2010), but the dams planned in tributaries do have large reservoir volumes and will enlarge this effect even further (Piman et al., 2016). The flood volume in the wet season is not only decreasing but also shifting in time due to the reservoir dams. Downstream of the dams the flood season will arrive later because the water level in the reservoirs will be raised at the beginning of the wet season first to increase the electricity production. With the planned dams and reservoirs in place, the floodwave of the wet season is expected to be delayed by 2-4 weeks (ICEM, 2010).

Besides the change in the hydrograph, the hydropower dams also have a large impact on the natural morphology of the Mekong river. This is because the sediment transport is expected to be blocked to a large extend by each hydropower reservoir. The sand and gravel, transported over the river bed, are completely blocked by the respective dams. Downstream of a dam the supply of bed load transport will reduce, which will therefore cause river bed erosion. The erosion front propagates downstream very slowly and reaches the delta area only after many years (ICEM, 2010). Besides, sediments in suspension are also partially trapped in the reservoirs. Due to the reduction in flow velocity in a reservoir, sediment in suspension settles and, if the retention time is long enough, it is not able to flow out. Because the construction of many dams is planned, it is expected that the total suspended load will be reduced by 95% in case of a full hydropower development scenario. This effect will reach the Mekong delta on the short term (Kondolf et al., 2014).

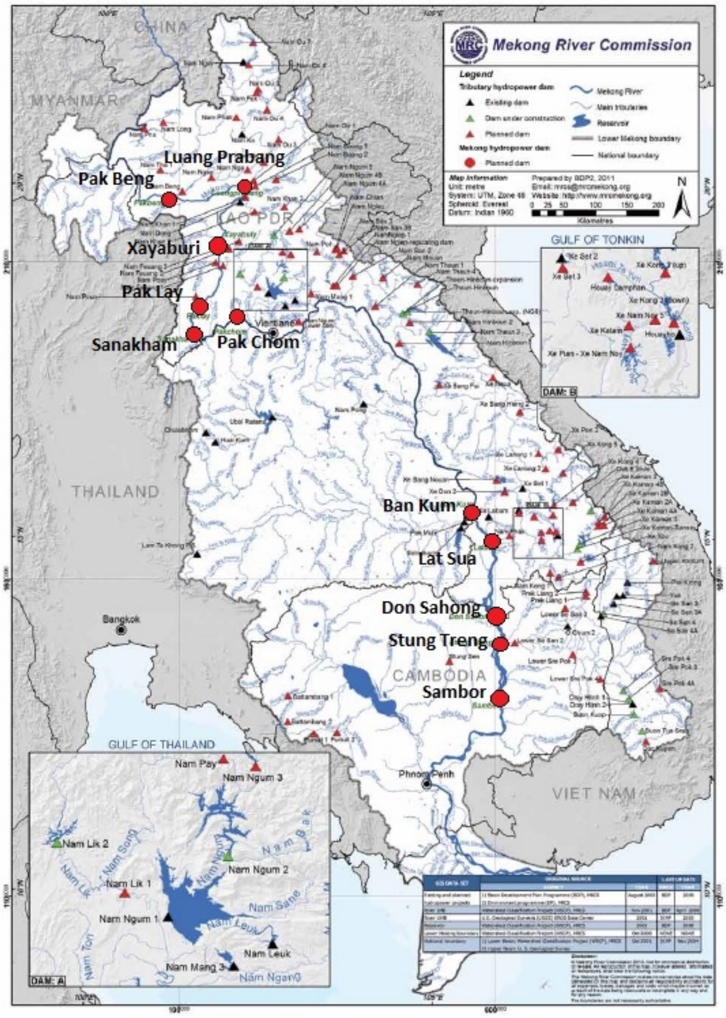


Figure 1.2: Operational hydropower dams (black) and proposed dams (red) in the Lower Mekong Basin (MRC, 2011)

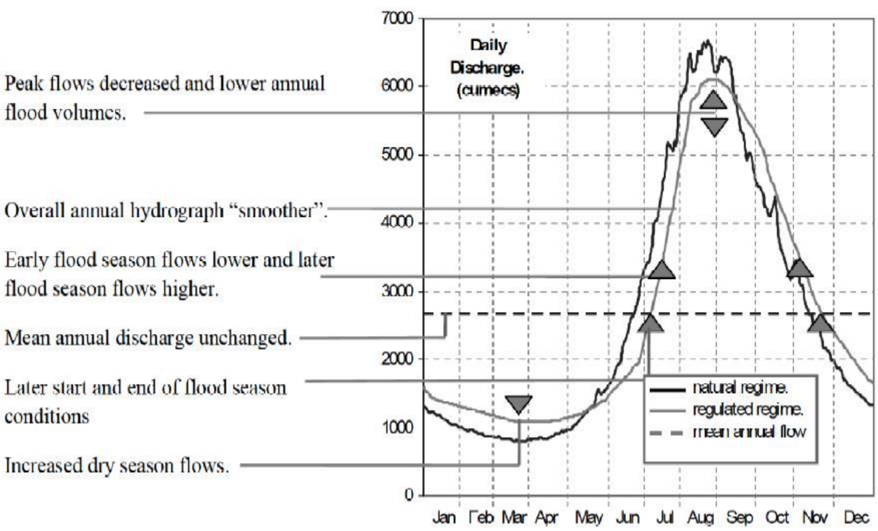


Figure 1.3: Changes in the annual hydrograph due to regulation of storage in reservoirs (ICEM, 2010)

1.3. Problem description

Since the Mekong river has a great potential for hydropower and the member states can benefit economically from the produced energy, the Mekong River Commission (MRC) members are willing to exploit this potential. Laos and Cambodia are planning to construct a large number of tributary dams and both countries are looking at possibilities for mainstream hydropower dams as well. Though the development of hydropower in the Mekong will give an economical boost to the LMB countries, there are potential risks for both ecology and socio economy for the entire Lower Mekong Basin.

Because of the economical and ecological importance of the delta, the changes in the Mekong river are expected to cause a large impact in this region. Due to the decrease of flow in the wet season, filling and flooding of the storage areas (Lake Tonle Sap and Vietnamese floodplains) will decrease. This is considered to put the socio-economy and ecology at large risk, because of the decreased supply of nutrients and habitat areas. Also the effects on the discharge distribution, and herewith the potential for flooding and droughts, are still not fully understood. Therefore, more knowledge is required of the effects of the dams on the different processes within the delta, both with respect to the hydrodynamics and effects of a changed hydrodynamics on other processes such as water quality and morphology.

1.4. Objectives

To start with, it is necessary to obtain a better understanding of the delta system as a whole and the interaction between the hydrodynamical processes. The main objective is to determine the hydrodynamical impacts of the large scale hydropower developments on the Tonle Sap lake and delta, including indirect effects and risks for socio-economy and ecology caused by changed flows. The final objective is to define possible measures to avoid or mitigate the negative impact of the changed flows. In order to limit the extent of this study, changes in morphology due to the hydropower dams are left out of the scope of this research. In order to meet these objectives the following research question is proposed:

How will the hydrodynamics in the Mekong delta be affected by the proposed developments of hydropower in the LMB and what will be possible measures to reduce negative impacts on the delta from these dams?

To answer this question, the following subquestions are relevant:

- How can the hydrodynamical processes be described and modeled to understand how different processes interact and predict the effects of future changes to the system?
- What are the effects on the hydrodynamics of the Tonle Sap lake?
- What are the effects on the discharge distribution over the delta branches?
- What are the effects on the canal-floodplain system in Vietnam?
- Can these effects be mitigated and what type of mitigation measures are suitable?

1.5. Report structure

The first step is to identify all the processes that play a role in the hydrodynamics of the delta system. This has been done by literature review and can be found in chapter 2. The next step is to gain more knowledge into the three main processes, namely the in and outflow of Tonle Sap lake, the discharge distribution over the entire delta and the inflow to and inundation of the Vietnamese canal-floodplain system. This has been done first by creating conceptual models and validating these models, with analytical formulas or with a numerical model. The analyses of these three processes can be found in the system analyses in chapter 3. The next step is to assess the effects of the hydropower development using criteria which relate the hydrodynamics of the process to the socio economical and ecological importance of the area. For the effects a number of hydropower development scenarios is assessed, which is done in chapter 4. The next step is determining which potential risks require mitigation and explore what could be possibilities to reduce the negative impacts. These potential measures are given in chapter 5. Finally, the conclusions and recommendations which follow from the results are explained in chapter 6.

2

Overview of processes in the Mekong delta

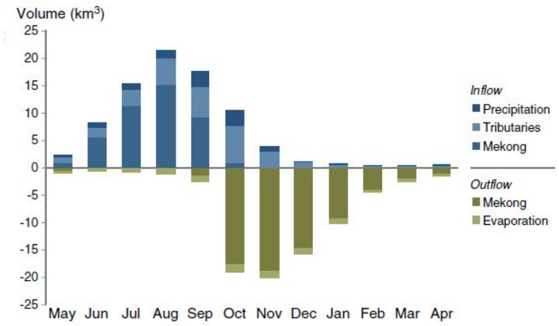
In this chapter, a summary of all hydrological and morphological processes that play a role in the delta area are given. This is to understand how the processes interact with each other, so the effects can be explained better. Furthermore, the largest human interferences on the delta are explained and how they affect the delta.

2.1. Hydrodynamical processes

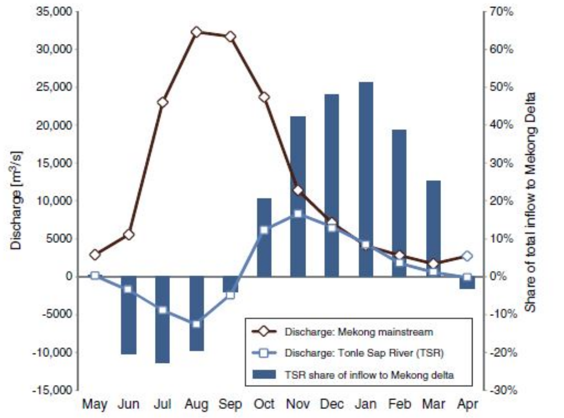
Within the Mekong delta, the incoming flow of water is spread to the different areas. The flows can be described using theory which can be found in Appendix B.1. Because the delta consist of many different areas, the spreading of water to these areas are considered to be different processes. In this chapter each of these processes is described, sequenced from upstream to downstream.

Storage of water in Tonle Sap lake

As mentioned in the introduction, the Tonle Sap lake can be considered as part of the delta. This is because the lake has a large influence on the hydrology within the delta. During most of the year the Tonle Sap lake and tributaries discharge via the Tonle Sap river to the Mekong. The junction of the Mekong and the Tonle Sap river is at Phnom Penh. Every year during the first months of the wet season, the water level in the Mekong rises rapidly compared to the water level in the lake, which causes the flow in the Tonle Sap river to reverse. During this period the surface of the lake increases from 2400 km^2 to an average maximum surfaces of 13,200 km^2. At the end of September, when the highest peak of the flood has passed, the flow in the river reverses again and water flows back to the Mekong. The total inflow volume of the lake consist of about 50% from the Mekong river. The other half consists of both direct precipitation and inflow from the 11 tributaries, covering a drainage basin area of over 85,000 km^2. Direct precipitation and evaporation are in volumes almost similar, but precipitation is largest during the wet season and evaporation largest during the dry season. Due to the shift in raining season between the highlands of Laos and Vietnam and the drainage basin of the lakes tributaries, the maximum inflow in the lake from this tributaries is after the maximum inflow from the Mekong. During the outflow of the Tonle Sap lake, the discharge in the Mekong has already decreased. During the first months, the outflow of the lake is a large contributor to the flow to the downstream branches of the delta. Figure 2.1a depicts the sources and sinks per month and Figure 2.1b gives the contribution of intake and outflow compared to the discharge from upstream of the Mekong (Kummu et al., 2014).



(a) In and outflow balance



(b) Tonle Sap River and Mekong

Figure 2.1: Interaction between Mekong and Tonle Sap lake (Kummu et al., 2014)

Bifurcations and distribution of flow volumes

The main channel of the Mekong bifurcates into a multi-channel system and at every bifurcation the water is distributed over the different branches. A little more downstream of Pnom Phenh, after the junction with the Tonle Sap river, the river splits into two main branches, the Mekong in the North and the Bassac in the South. The ratio of the discharge that flows in each of the branches is determined by the bifurcation laws, which is a balance between several geometry parameters of the downstream branches. In principle, the water flows in the direction of the least resistance to flow to the sea. Because of the larger width and depth of the Mekong, much more water enters the Mekong branch at Phnom Penh. However, this water is redistributed due to canals between the river branches. The Vam Nao branch is the largest natural branch, connecting the Mekong and the Bassac just past the border of Vietnam. Since the discharge and water levels in the Mekong are higher than in the Bassac water flows from the Mekong to the Bassac through this branch. This causes the discharge distribution to become more even to a ratio of around 50%/50% (Manh et al., 2014).
Further downstream the distribution is more difficult to estimate the distribution due to influence of tide on the measurements, especially in the dry season in which measurements are usually overestimate the fresh water discharge (Nguyen, 2008). Also the man-made canals discharge water to the sea, but the amounts are much lower than these of the main branches. On the Bassac side many canals flow into the Gulf of Thailand and at the side of the Plain of Reeds, water is discharged to the Song Vam Co Tay river, that runs beside the Mekong branches to sea. This causes uncertainty of the total volumes discharged to the sea through the main branches.

Storage of water in floodplain areas

Due to the large difference between the dry season and wet season flow, the river surface expands annually outside its main channel in the delta area. In the floodplains the water is temporarily stored during the rising peak of the flood season. The floodplains can be divided into the Cambodian floodplains and the Vietnamese floodplains. The area that is yearly inundated in Cambodia is around 11,000 km^2 (Manh et al., 2014) and floodplains are still in a natural state. The floodplains in Cambodia are located for the larger part downstream of the bifurcation at Pnom Penh. The Vietnamese delta has, compared to the Cambodian delta, much more human interference on the river system. It has turned into a complex system of canals, dikes and water regulation sluices. The areas with the largest inundation depths in Vietnam are close to the Cambodian border and can be seperated into two main areas (Hung et al., 2012):

- Long Xuyen Quadrangle (LXQ) is the area South of the Bassac (or Hau) river and covers an area of 5000 km^2. The inundation is caused mainly due to overbankflow from the Bassac and overland flow is only of minor influence (Manh et al., 2014)
- The Plain of Reeds (PoR) is the area North of the Mekong river and covers an area of 8000 km^2. Its inundation is caused directly from the Mekong river at first and a second flood peak arrives a couple of weeks later due to the overland flow from the Cambodian floodplains (Manh et al., 2014).

Almost all floodplains in Vietnam are compartmented by dike rings of different heights to increase the agricultural production. They are high enough in order to keep the flood out during the first month of the flood season, until the harvest of the rice in July. But during the highest water levels the compartments fill due to overbank flow and inflowing sediments are deposited into the compartments. The volume stored in the Vietnamese floodplains is around 20% of the total flood volume at Kratie. At the end of the wet season water is pumped out until a level that is suitable for planting new rice crops (Hung et al., 2012).

Overland flow

Overland flow happens mostly in the Cambodian part of the delta, because the irrigation canals are less developed in this area. From the Cambodian delta water flows overland to the Vietnamese delta, mostly to the floodplains in the Plain of Reeds. Therefore this process withdraws water, especially during rapidly rising water levels, from the mainstream. Around 5% of the total flood volume reaches the Vietnamese delta area via overland flow, and is stored in the floodplains from where it enters the branches again (Manh et al., 2014). This overland flow travels much slower compared to the flow through the river and causes a delayed second peak of flooding in the Vietnamese floodplains (Hung et al., 2012).

Tidal influence

The Mekong is mostly influenced by the tidal properties of the South Chinese sea, which has a mixed diurnal and semi-diurnal character. The tide has a period of approximately 12.25 hours and roughly speaking there are two troughs and peaks in a day. The difference between the two tidal periods and the maximum tidal range is changing over a fortnight, due to a spring-neap tidal cycle. Because of the mixed tidal character, the semi diurnal fluctuations are smaller compared to diurnal fluctuations and also vary more over the spring-neap tidal cycle (approximately between 0.1-2.5 m) . The diurnal fluctuations have a much larger range between of 2.2-3.2 m at the mouth of the river (Wolanski et al., 1996).

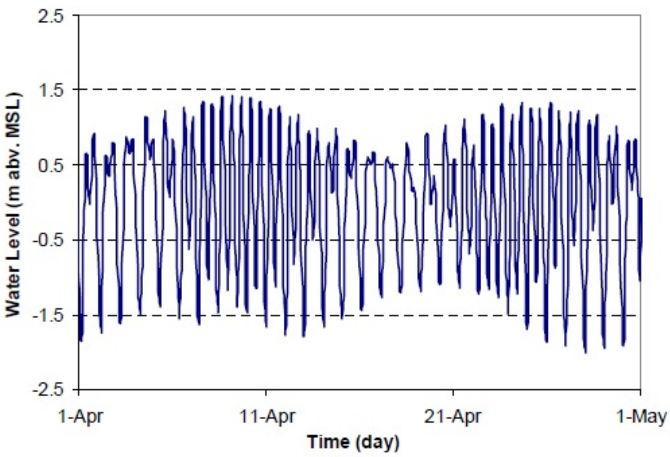


Figure 2.2: Waterlevels at mouth of Bassac river indicating tidal water level fluctuations (april 2005) (Nguyen, 2008)

How far water levels in the river are influenced by the tide is very dependent on the discharge of the river. The tidal wave behaves like a progressive wave and is damped within the delta and therefore causes a phase lag, which is approximately 3 hours between My Thuan and the mouth of the Mekong (Tromp, 2013). Also other properties such as large side channels cause an increase in both damping and phase lag. During the dry season the tide influences the water level and discharge up till the border with Cambodia, especially in the Bassac branch where the effects of damping are smaller. The tidal wave celerity can be calculated using the analytical method of Savenije (Nguyen, 2008).

Salt intrusion

At the mouth of the delta, saline seawater enters the rivers branches and a transition between the fresh river water and saline water is present. Because of the density difference (1025 kg/m^3 for sea water and 1000 kg/m^3 for fresh water), tidal currents and mixing processes, saline water is able to penetrate into the estuary branches. On the other hand, the fresh water flow pushes the saline water back to the sea. This process is described in the 1D salt balance equation:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial s} - \kappa\frac{\partial^2 c}{\partial s^2} = 0$$

c	concentration [kg/m^3]	t	time [s]
u	flow velocity [m/s]	s	distance [m]
κ	Dispersion coefficient [m^2/s]		

This equation contains an advective part (second term) and a dispersive part (third term), which determine the balance of salt concentration (first term). The advection is the transport of concentration with the flow velocity. The dispersive part combines all present mixing processes on both small and large scale. Diffusion take place on a very small scale and can be divided into the molecular diffusion and turbulent diffusion. Besides, the tidal mixing and density driven currents are also part of the dispersion term, which have a much larger spatial scale compared to diffusion. Therefore, these processes are dominant in the dispersion part and diffusion is almost negligible. For 1D modelling, there are a number of predictive equations (for example from Savenije, Thatcher and Harlem, Kuijper and van Rijn), which estimate the dispersion term based on a number of estuary parameters. All of these formulas do include the amount of mixing over the vertical water column, which is called stratification (Daniels, 2016).
In a well mixed estuary, there is a small difference in density over the vertical water column, whereas in a stratified estuary a sharp transition is present between fresh and salt water. The presence of density differences over the vertical (stratification) creates density driven currents. The upper part of the water column is fresh water flowing to sea and the lower part of the water column has a higher salinity and a direction land inward (Savenije, 2007). The stratification can be quantified using the Estuary Richardson number, where $N_R > 0.8$ indicates a highly stratified estuary and $N_R < 0.08$ a well mixed estuary, with very small density differences over the vertical water column:

$$N_R = \frac{\Delta\rho}{\rho}\frac{gQ_f}{Bv^3} = \frac{\Delta\rho}{\rho}\frac{gh_0u_f}{v^3}$$

N_R	Estuary Richardson number [-]	$\Delta\rho$	Density difference [kg/m^3]
ρ	Density fresh water [kg/m^3]	Q_f	Riverine discharge [m^3/s]
v	Tidal velocity amplitude [m/s]	h_0	Water depth in estuary mouth [m]
u_f	Riverine flow velocity		

Because the stratification directly influences density driven currents (which have a large influence on the dispersion coefficient), this estuary Richardson number is included in all the dispersion formulations. However, because dispersion consist of many factors and includes many parameters, no dispersion formulation is able to represent all types of estuaries and processes completely. Therefore, there are calibration parameters included in the formulations, which can be determined by calibration based on measurements (Huismans et al., 2016).
Due to the varying discharge in the Mekong delta, both salt intrusion varies over the year. During the wet season, the river discharge is dominant over the tidal mixing and a salt wedge is present. The fresh water discharge is high and advective transport is constantly directed seawards, pushing the salt wedge back to only a few kilometers inward of the estuary (Wolanski et al., 1996). During the dry season, when fresh water discharge is low, the tide mixes fresh water and saline water, and the branches of the Mekong delta can be considered well mixed (Nguyen, 2008). Because the flow velocity and hereby the advective transport is bidirectional (depending on the tide), the saline water is able to penetrate up to 40 km into the estuary. Because this region is depending on fresh water for agriculture, the salinity of the water is a potential risk for the socio-economy (ICEM, 2010).

2.2. Morphological and sediment processes

2.2.1. Origin and transport mode of sediment

Sediment transport can be described as the movement of grains, sediment particles, due to the flow of a river. It can be separated in two different modes of transport, the first being bed material transport and secondly wash load transport. Bed material transport is transport of particles that are influenced by the river bed, which can be brought in suspension, but can also move over the river bed through rolling or saltation. Wash-load transport are particles that are continuously in suspension and do not interact with the river bed. However, the mechanisms for sediment transport can be better defined between suspended load transport and bed material transport. There is also a clear distinction between the grain size of bed material transport and of washload transport, where bed material transport is generally speaking more coarse (de Vriend et al., 2011).

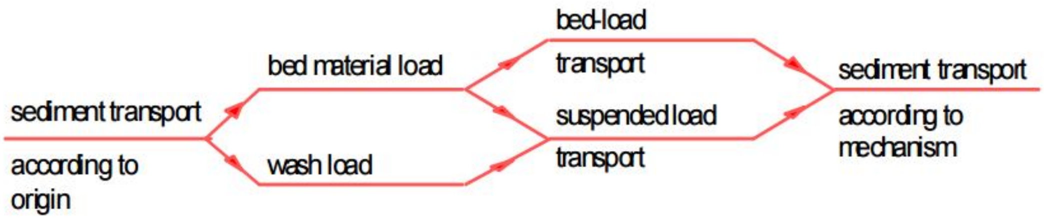


Figure 2.3: Different origines and mechanisms for sediment transport (de Vriend et al., 2011)

The amount of sediment transported by the river is dependent on both the supply as the local hydrodynamics. The latter determines the sediment transport capacity of a river and is mainly depending on the flow velocity. The transport capacity can be derived for both bed material transport as suspended load using empirical sediment transport formulas, which are explained in Appendix B.2. When the transport capacity differs from the supply from upstream either erosion or sedimentation occurs and morphological changes take place.

2.2.2. Morphological processes in the Mekong delta

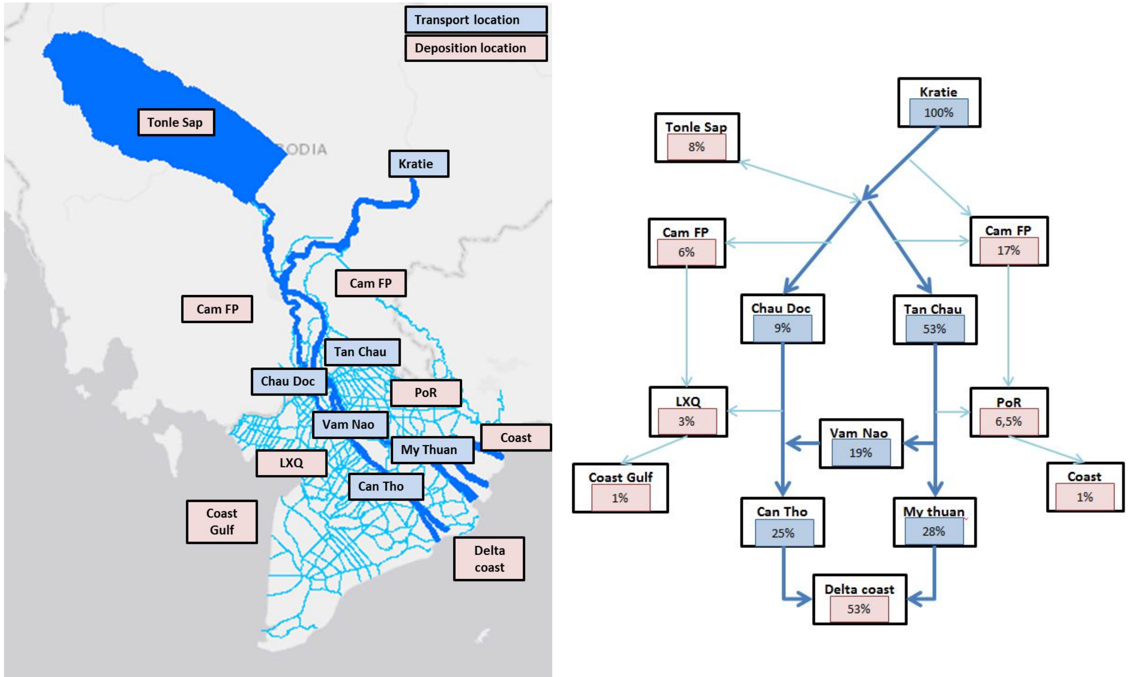
Sediment supply to Mekong delta

The estimation of the total sediment load in the Mekong is difficult to make, since not many data are available. The suspended load at Kratie has been estimated in different researches, based on measurement campaigns between 2009 and 2011. However, the results for the annual load vary between 50 Mt/year (Lu et al., 2014) to 106 Mt/year (Manh et al., 2014) and 160 Mt/y (Koehnken, 2012). The bed load is varying over the entire Mekong, due to steepness and flow velocities in the different stretches (Bravard et al., 2014), but it is assumed that at Kratie most of the transport takes place in suspended mode and bed load is estimated to be around 1.6 - 1.8 Mt/y (Koehnken, 2012). From this total load approximately half of is has its origin in the upper Mekong, where deforestation has led to high erosion rates. Also the 3S rivers, particularly the Se San, have high sediment concentrations that contribute with 25 Mt/yr to the total sediment load at Kratie (ICEM, 2010).
The sediment that reaches the delta is a combination of fine material such as clay and silt, which is transported in suspension. Sand is transported mostly as bed load transport, except in the wet season when flow velocities are high enough to bring sand in suspension. In the research of Bravard et al. (2014) the sediment size from sand bars, which appear during the dry season, has been measured to be between 200 - 400 μm at Kratie. This represents the grain size range for bed load transport over the year. The majority of suspended load has a smaller grain size, because the largest fractions consist of clay and silts (Green, 2016).

Distribution of suspended sediments

Since most of the sediments are transported in suspended mode, the load is distributed over the delta branches and areas almost proportionally to the discharge distribution. In areas where water is temporarily stored, such as Tonle Sap lake and the floodplains, suspended sediment is deposited and these areas act as sinks (Kummu et al., 2008)(Hung et al., 2014). Also due to changes in width and bed slope, the flow velocity changes and hereby the transport capacity. In combination with the distinguished wet and dry season flow, the sediment is deposited and eroded in different stretches in the delta over the year (Bravard et al., 2014). Since up to 90% of the sediment is transported during the wet season, the distribution during this period is the most important for the overall sediment distribution. The volumes of sediment transported to the different areas in the Mekong delta have been calculated by Manh et al. (2014) and are shown in Figure 2.4.

These sediment volumes differ with the annual flood volumes, especially the amounts transported to the lake Tonle Sap (with an average flood around $5 * 10^9$ kg /year (Kummu et al., 2008)) and the floodplains in



(a) Deposition and transport locations

(b) Volumes compared to total inflow

Figure 2.4: Sediment distribution over the Mekong delta

both Cambodia and Vietnam. Also the antropologic influence on the inflow of the Vietnamese floodplains has an influence on the amount of sediments flowing in (Hung et al., 2014)(Hung et al., 2014). In the dikering compartments the suspended sediment is able to settle within a short time, because of the low flow velocities. Subsequently, smaller sediment concentrations are found in canals and floodplains further away from the Mekong (Hung et al., 2014). During the outflow of both Tonle Sap lake and the floodplains the finest particles are still in suspension or are resuspended, causing an outflow of sediments as well (Kummu et al., 2008).

Interaction saline water and sediments

The salt intrusion into the estuary of the Mekong plays an important role in the location of deposition of sediment. Firstly, this is because the flocculation of fine particles, especially clay contents, increases due to higher salinity of the water. Therefore, the settling velocity increases when the salinity increases. But especially the density driven currents play an important role in the sedimentation of the river mouth. In the wet season when a salt wedge is present, the opposite directed fresh water flow and saline flow meet at the toe, which causes a local deposition of the sediments around 5 km from the mouth of the river. In the dry season when the salinity concentrations are present in the estuary branches and flow velocities are generally lower, (flocculated) sediment settles in the final stretches of the river branch. Due to the more mixed state of the estuary suspended sediments are deposited in a more widely stretched area around 10-30 km from the mouth (Wolanski et al., 1996). For the bed material transport, the flow velocities near the bottom are very important. Due to stratification, the flow near the bed can be directed inland, while the averaged flow is directed to the sea. In order to assess the effect of density driven currents on the morphodynamics, a 3D model is necessary.

Coastal deposition

In the mouth of the estuary and in the coastal waters the suspended sediments settle. This happens mostly because of the decrease in flow velocities, but the salt intrusion also plays a part in this deposition process. From the mouth of the estuary it is spread longshore by waves and it is deposited alongside the shore of the South Chinese Sea. The sand material feed the tidal flats or are deposited close to the mouths of the river branches, where ridges of sand dunes have formed over the years (Nguyen et al., 2000).

Further away from the estuary mouths only mud and clay is transported by wave induced transport along the coast in the direction of Ca Mau point. Over the past 3000 years the delta progressed with a rate up to 26 m/year due to the deposition of sediment from the Mekong. Even beyond the tip at Ca Mau the delta is progressing due to the lower energy wave climate in the Gulf of Thailand. However, in the last decades shore line retreat is taking place over most stretches of the delta shore. This is caused by the combination of sea level rise and a reduced supply to the coast (Xue et al., 2010) (Anthony et al., 2015).

2.3. Interaction between processes

Within the delta the hydrological and morphological characteristics determine the hydrodynamical processes, such as floodplain inundation. These hydrodynamical processes are the most important driver for the ecology and socio-economy in the delta. Besides, the hydrological characteristics determine also the local morphology in the delta, because flow velocities determine the transport capacity. On the other hand affect hydrodynamical processes these drivers and change hydrodynamics within the delta, for example due to temporary storage of water. Therefore, the system can be seen as a feedback loop from the hydrological/morphological characteristics to the processes and back to the characteristics, which is shown in Figure 2.5. At the upstream and downstream boundary an external process influences the characteristics, which is in this case the discharge and sediment supply at Kratie and the water level and tidal influence from the sea. Besides that, local precipitation and evaporation determine water source and sinks within the delta. Finally, human interferences in the delta change hydrodynamical characteristics all over the delta. In Section 2.4, the present anthropological influences in the delta are listed.

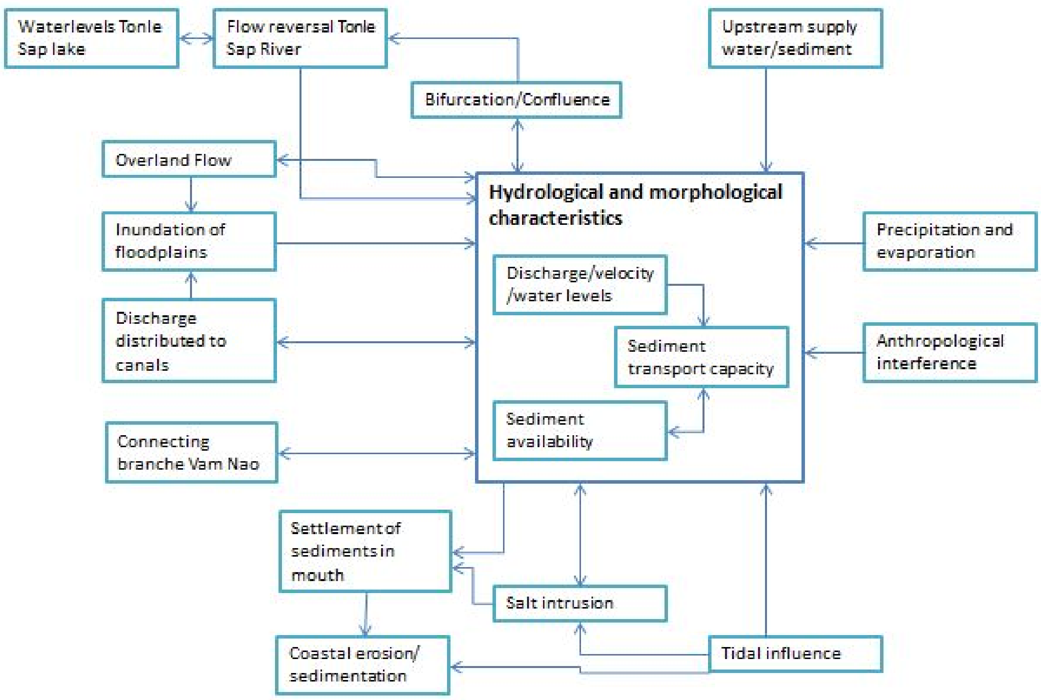


Figure 2.5: Interaction between processes and characteristics within the delta

Whether a process occurs and its quantity is dependent on the upstream hydrological/morphological conditions. For example when the water levels in the river rise and the river burst outside its banks, overland flow from the floodplains of Cambodia to the Plain of Reeds can take place. Due to this overland flow the discharge and sediment availability (the water that flows overland contains sediment concentration as well) in the main branch of the river decreases, including the sediment transport capacity since flow velocities decrease compared to a case without overland flow. This also means that processes, such as the distribution at the bifucation of Pnom Penh and flow reversal to Tonle Sap, influence the entire system downstream, while a process further downstream has less influence.

2.4. Human interferences

Due to the economic developments of the region, the human interference with the river is growing. In this section four different human activities and how they influence the abiotic characteristics within the delta area are elaborated. Since the delta of Vietnam has already been influenced by the irrigation and agriculture for many years, only developments that increased rapidly over the past decade are discussed.

2.4.1. Irrigation and water usage

Large areas in the Mekong delta, especially in Vietnam, are irrigated by a system of human made canals and dikes. This is done to distribute the available water over larger areas to increase agricultural production. In the dry season when precipitation does not meet the demand, water is subtracted from the river for domestic, industrial, agricultural and aquacultural uses. The majority of this amount is used for the rice cultivation and pumped into the rice paddies which are surrounded by dike rings. The water demands per month have been calculated using land use data and hydrological data from 2005 by Deltares (2011). The water quantities subtracted from the canals are largest during January and February, but the percentage of subtracted water compared to river discharge is the highest in april. This causes the water level in the river to drop even further in these month and increases the potential of salt intrusion.

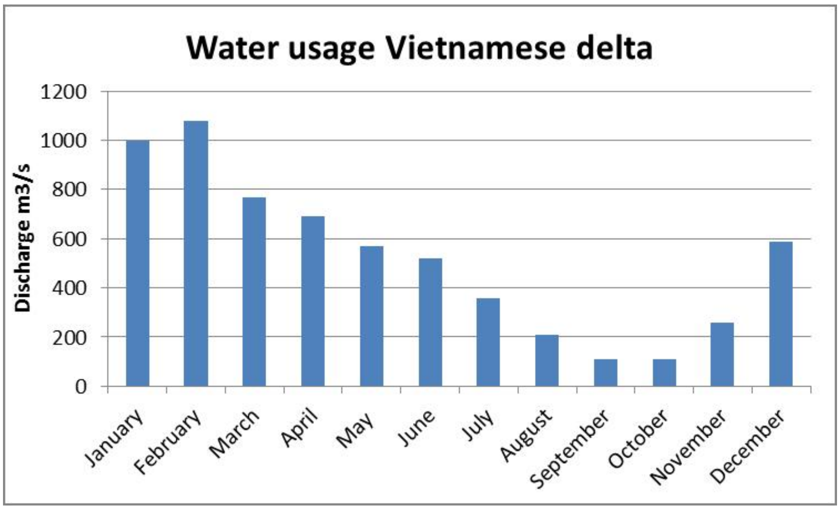


Figure 2.6: Discharge subtracted from river in Vietnamese delta to meet water demands

2.4.2. Damming of the floodplains

A development in the past decade is the heightening of the dikes around the floodplains in Vietnam and an increase in regulation of the in and outflow. The extreme flooding events that occured in the beginning of the century enhanced the need for protection of agricultural lands. Especially the area between the Mekong and the Bassac river is completely protected by high dike systems and the number of high dikes in the PoR is rapidly increasing (currently already above 30 %). In a high dike system it is possible to plant an extra crop during the wet season and therefore economically beneficial. The high dikes reach up to +4.5 m a.s.l. and are able to retain the water during the entire flood season. The water in and outflow is therefore fully regulated by pumps and sluices, leading to a decrease in water storage and deposition of fine sediments. The decrease of nutrients deposited in the field is compensated by the use of chemical fertilizers, which causes stress for the water quality in the entire delta (Hung et al., 2012) (Triet et al., 2017).

Due to the heightening of these dikes around the floodplains, less water is stored within the compartments in the peak of the wet season flow. This causes changes in the hydrologic characteristics within the delta, for example a higher maximum peak in discharge downstream of the floodplains. Also due to the decreased deposition of fines the amount of suspended sediment transported via the main channel will increase. Also the change in hydrology will impact the sediment transport, since the transport capacity is increased in the peak flows (Partners for Water, 2013) (Triet et al., 2017).

2.4.3. Sediment extractions

River bed material, mostly sand and gravel, is being extracted from the Mekong river basin in many areas. Most of the material is used for industrial use such as road construction and land reclamation, both in the LMB and abroad (for example Signapore). Sediment extraction does not only decrease the availability of bed material, but also changes the river dynamics, especially in the case of in-channel extractions. The mining takes place at many different locations spread over the entire Mekong basin, but the majority of the material is extracted in the delta area as can be seen in Figure 2.7.

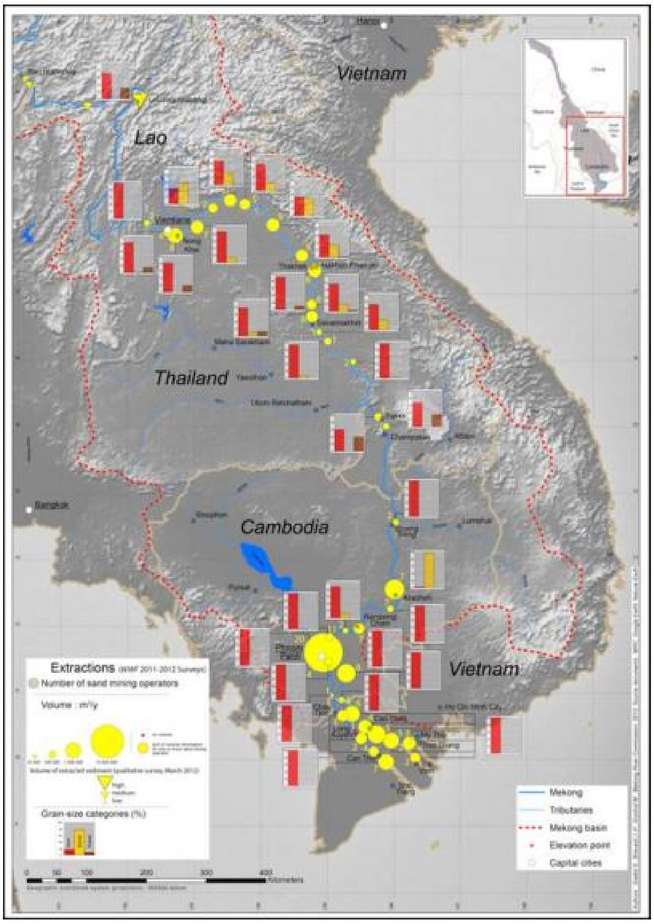


Figure 2.7: Locations and volumes of sediment extractions (Bravard et al., 2013)

The amount of sediment being extracted per year has been estimated based on field research at the extraction locations. This field research was conducted in 2011 and estimated that per year 34,000 m^3/year of sediment is extracted out of the LMB, of which over 25,000 m^3/year south of Kratie. However, the total amount is expected to be underestimated and more than half of the extraction sites were less than three years old indicating that sediment mining activities are increasing. Because of these large extracted volumes, the bed material transport is expected to be reduced in the delta area (Bravard et al., 2013). The extractions lead to less bed load transport in the delta area due to insufficient availability. Brunier et al. (2014) have shown that the bed levels of channels in the Mekong delta were significantly degrading between 1998 and 2008, which could not have been caused by hydropower developments. Also the coast at the South China Sea has been showing erosion patterns between 2003 and 2011, which is partially caused by the reduced supply due to sediment extractions. Finally due to the deepening of the channels at the mouth of the river, the salt intrusion is expected to increase (Anthony et al., 2015).

2.4.4. Groundwater extraction

Due to the urbanization and an increase in wealth in the delta area, the demand for fresh and clean water, for domestic, agricultural and industrial use, has grown over the past decades. To meet this demand more than a million wells have been installed to access the groundwater in the Vietnamese delta area. This has caused the groundwater levels to decrease over large regions within the Mekong delta and causes land subsidence due to compaction of the subsoil. The centers of extraction points are focussed around Ca Mau (the South point of the delta) and between the Mekong and Bassac branches. At the moment the hydraulic head declines with a rate between 10-80 cm/year (average 26 cm/year), causing subsidence rate between 0.28 and 3.1 cm/year (average 1.6 cm/year). Besides a larger flood risk as a consequence of groundwater extraction induced land subsidence, groundwater extraction also increases the subsurface salinity intrusion and hereby endangering agriculture (Erban et al., 2014).

3

System analyses

From the problem description and analyses of processes, three processes have been found which not only have a large influence on ecology and socio-economy, but are also the largest hydrodynamical influences on the delta:

1. The in- and outflow of Lake Tonle Sap
2. The discharge distribution over the main branches
3. The inflow and inundation of the Vietnamese canal-floodplain system

In order to assess the influence of hydropower developments and come up with suitable mitigation measures it is important to understand how these processes work, what the important parameters are in the process and how they interact with other processes in the delta system. Also the effect of other anthropological changes on the processes are assessed. For all three processes that influence the system from upstream to downstream, a conceptual model is made and results are compared to measurement data and a numerical model. Besides the understanding of the processes, this chapter is also meant to identify assessment tools for the delta system, including analytical models as rapid assessment tools.

3.1. Methodology

Development of conceptual models
For each of the processes a conceptual model has been developed. In these models the geometry of the system is simplified and assumptions (for example to neglect certain processes) are made. Then for each process theoretical formulas that apply to the process, for example the shallow water equations, are identified. The formulas should be able to describe the process or combination of processes that take place in the subsystem. From these theoretical formulas hypotheses of how the process works can be made and when validated the conceptual model can be used as a rapid assessment method.

Validation with data
If possible, the conceptual model is validated using available measurement data from the MRC. This is done by applying the formulas from the conceptual model to a hydrological year and see whether the results from the model show similarities with the measured data. However, not all the required data are available and the number of locations is limited. The year 2002 is chosen as the year for comparing the models with data, since for this year data were available for the most locations.

Validation with Delft3D-FM model
Because the conceptual models cannot be validated in all cases using measurements, validation is done using a Delft3D-FM model. This model is used to assess the effects of hydropower developments and mitigation measures as well. The model covers the entire Mekong delta from Kratie to the sea, including the canal-floodplain system in Vietnam. This model allows to obtain discharges and waterlevel data from different locations compared to the available measured data. However, a numerical model always has numerical errors or errors due to assumptions within the model. Therefore, the model has first been calibrated and validated

based on available measurement data for the year 2002. The description and validation results of the model can be found in Appendix C.

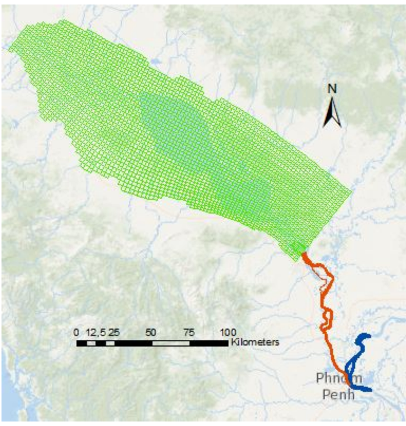
Sensitivity of process parameters
For each process there are uncertain parameters or parameters that are expected to change due to secundary effects of hydropower or antropological changes. Analysing these parameters also helps by understanding the sensitivity of the process to these parameters and to be able to seperate effects of hydropower from other antropologic influences in the future.

Discussion
Finally the applicability of both the numerical model and the analytical models are discussed. Because a numerical model requires computational time and expertise with the program, it can be more advantageous to use a simple analytical model to assess a certain process. However, the analytical model may not always be applicable for all situations or requires extra information.

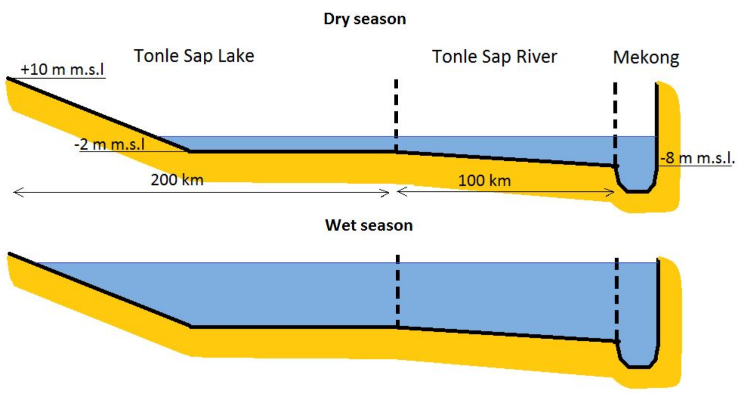
3.2. In- and Outflow of Lake Tonle Sap

3.2.1. Conceptual model

For the conceptual model of the in- and outflow of Tonle Sap lake, the geometry of the lake (green area), the Tonle Sap river (red) and part of the Mekong that is close to the entrance of the Tonle Sap (blue area) are simplified. The Mekong river is around 1.5 km wide at the junction and an average bottom level of -9 m with respect to mean sea level. The Tonle Sap river, connecting the lake to the Mekong, has a length of 100 km. The width and depth of the river varies along the river, where the bottom level increases from the Mekong (-8 m m.s.l.) to the lake (-2 m m.s.l.) and the width increases in the direction of the lake as well. The conveying surface (A_C) and bed level gradient (i_b) are assumed the be constant for the entire river. The conveying surface changes for different water level and the profile of the river is assumed to be rectangular. The lake consist of a permanent inundated area with a bottom level -2 m m.s.l and flooded areas, which stretches around half the length of the 200 km long lake and half the width of 70 km wide. Over the width the gradient of the bed slope is 0.0007 and in the length 0.00012, where the surface area increases from 5,250 km^2 in the dry season (water level 0 m m.s.l.) to 14,000 km^2 in the wet season (water level +10 m m.s.l.) with 875 km^2/m.



(a) Location and subparts system



(b) Cross section of lake river and Mekong at lowest and highest water level

Figure 3.1: Simplified geometry of Tonle Sap system

The in- and outflow of the lake can be described by simplifying the shallow water equations and bifurcation laws. First the short basin assumption can be applied, since the wet season flood wave is much longer than the length of the lake, and the water level in the lake does not vary spatially (Battjes and Labeur, 2014). The in- and outflow in the lake, including the Tonle Sap river, tributaries, precipitation and evaporation, determines the water level and surface area:

$$\Sigma Q = A_{lake}(h_{lake}(t))\frac{\partial h_{lake}}{\partial t}$$

ΣQ	Sum of in- and outflow discharge [m^3/s]	A_{lake}	Surface of lake [m^2]
h_{lake}	Water level in lake [m]		

Furthermore, it is assumed that no water is stored within the Tonle Sap River, since this surface is much smaller compared to the surface of the lake.

When the water level of the lake is higher compared to the water level in the Mekong, a discharge from the lake to the river occurs under free flow conditions. This can be described using the shallow water equations (Battjes and Labeur, 2014):

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial s}(\frac{Q^2}{A_c}) + gA_c\frac{\partial h}{\partial s} + c_f\frac{|Q|Q}{A_cR} = 0$$

Since we assumed a constant flow cross section we can simplify this to:

$$\frac{\partial Q}{\partial t} + \frac{gA_c}{l_{TSR}}(h_{lake}(t) - h_{Mekong}(t) + \Delta H_r) = 0$$

$$\Delta H_r = c_f\frac{|Q|Q}{gA_cR}l_{TSR}$$

Q	Discharge [m^3/s]	A_c	Conveying cross section of branch [m^2]
g	Gravitational constant [m/s^2]	h	Water level with respect to m.s.l. [m]
c_f	Friction coefficient [-]	R	Hydraulic radius [m]
l_{TSR}	length of Tonle Sap river [m]	ΔH_r	Head loss due to friction [m]

During the rising stage, the water is distributed at the junction of Phnom Penh related to the bifurcation equations. In this situation water can flow both to sea and to the lake, depending on the resistance of the way the water has to flow and the geometry downstream of the junction. However, since the bifurcation equations are simplified from Belanger assuming a constant negative bed slope, which is not the case for inflow via the Tonle Sap river, these formulas cannot be analytically solved in this case (de Vriend et al., 2011). For this reason it is assumed that the discharge to the lake is a factor (T) of the head difference between the lake and Mekong in which the factor and friction head (H_{fric}) will be empirically derived from data and model input. This means that the discharge through the Tonle Sap river (Q_{TSR}) can be described as:

$$Q_{TSR}(t) = A_{lake}(t) * \frac{h_{Mekong}(t) - h_{lake(t)} - H_{fric}}{T}$$

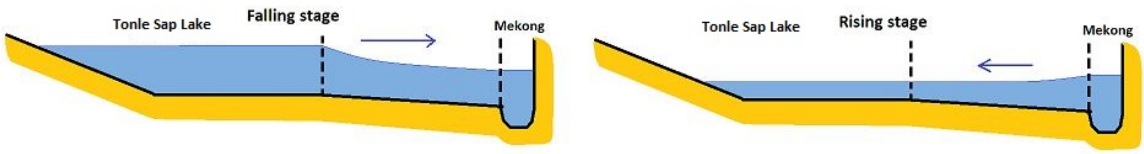


Figure 3.2: Rising and falling stage of lake Tonle Sap

Besides the in- and outflow through the Tonle Sap river there are other sources and sinks that contribute to the water balance of the Tonle Sap lake, such as evaporation, direct precipitation and the discharge from 11 tributaries of the catchment areas around the Tonle Sap lake. Little measured data are available for these sources and sinks, but in the research Kummu et al. (2014) these parameters have been estimated. The monthly estimate per tributary is interpolated in order to obtain a total daily inflow of all tributaries. During the wet season the precipitation and evaporation are of the same order of magnitude, causing a difference of only centimeters water level in the lake per month. In the dry season the evaporation is higher than precipitation, of around 15 cm during the driest months of December to February. The precipitation and evaporation are neglected in the model, because it is not expected that these will have a large effect on the results and the amounts in m^3/day is difficult to estimate due to the short term variability.

3.2.2. Model validation

Data validation

For the validation of the conceptual model with data, the following meaurement data are used from the Mekong River database. The years used for the data validation are 2000-2002, since for these years most data were available. There is no discharge through the Tonle Sap river monitored for these years, so this is calculated by subtracting the discharge in Mekong and Bassac downstream of Phnom Penh from the discharge at Kratie. Figure 3.4 displays the data from the calibration year and two prior years. From these figures the following observations can be made:

Figure 3.3: Locations measurement stations

- Discharge at Kratie
- Disharge at Phnom Penh (Chaktomouk and Chroy Chang Var, both downstream of junction)
- Waterlevel Kompong Luong, lake Tonle Sap
- Waterlevel Phnom Penh Port

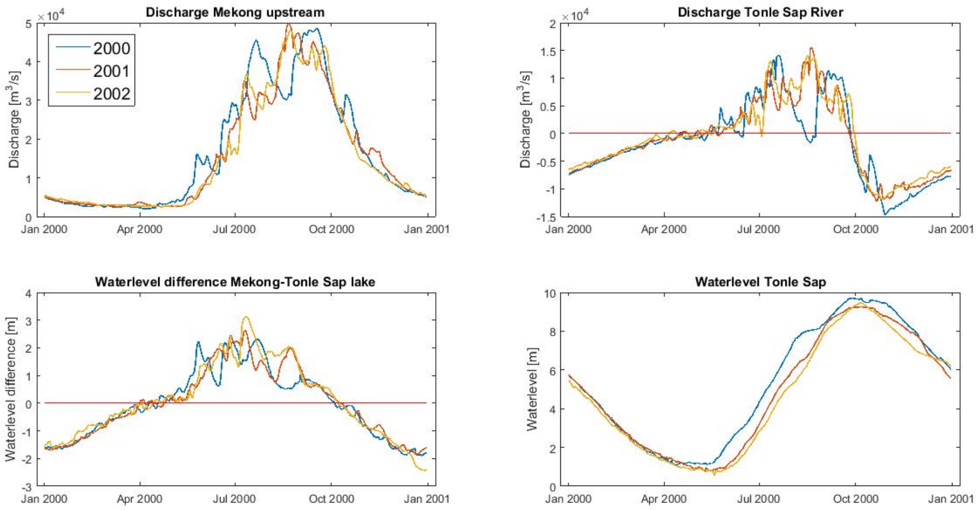
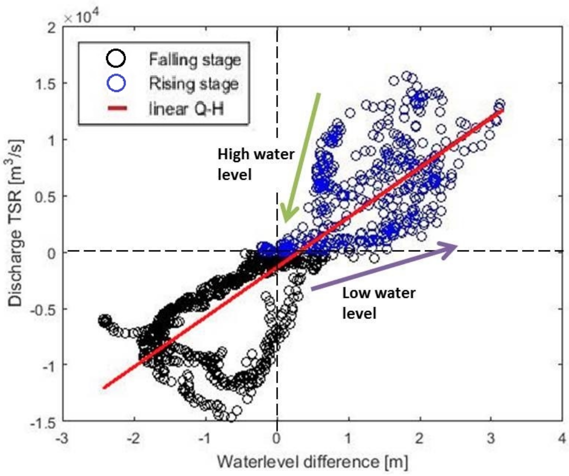


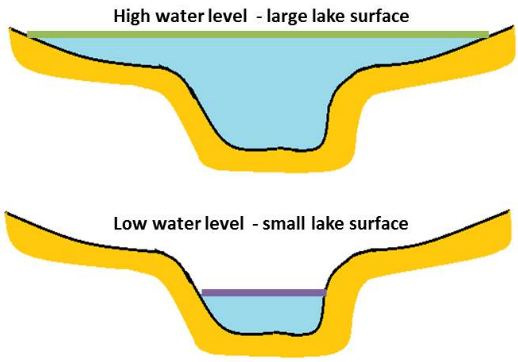
Figure 3.4: Measured parameters of in- and outflow of lake Tonle Sap

- The flow reversal at beginning of wet season occurs with a much lower Mekong discharge compared to the falling stage flow reversal, indicating that the water level difference initiates the flow reversal
- During a positive discharge in the Tonle Sap river the water level in the lake rises and vice versa, which means that the inflow via te lake is the most important contributor to the water level
- The actual flow reversal occurs when the water level in the lake is around 10-40 cm higher compared to the daily average water level in the river. This suggest that there is a minimum head difference between the lake and Mekong that must be overcome, which can be related to friction losses.
- When the flow reverses in the falling stage, the discharge in the Tonle Sap river is relative high compared to the measured water level difference, while when the water level difference becomes higher the flow decreases. This indicates that a certain hysteresis effect is present between water level difference and discharge through the river

The conceptual model indicates that both processes that play a role during the in- and outflow are related with the water level difference between the Mekong and the Tonle Sap lake. This means that these parameters should be correlated. However, during the rising stage the discharge is depending on the discharge distribution at Phnom Penh as well as the water level difference, while in the falling stage the discharge was highest in the month after the flow reversal even with a small waterlevel difference. This leads to deviations in the correlation plot, which can be seen in Figure 3.5a. The black area represents the falling stage, where the water level difference is influenced by the outflow. The blue area shows the rising stage in which the discharge distribution at Phnom Penh influences the discharge in the Tonle Sap River because of downstream conditions of the Mekong, such as the tidal conditions.



(a) Correlation of water level difference between lake and Mekong and discharge through the Tonle Sap River

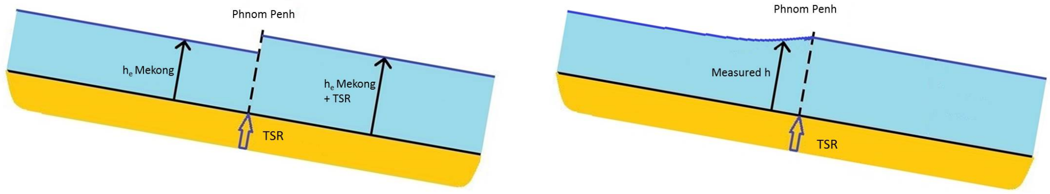


(b) Water level dependent surface of lake

Figure 3.5: Correlation and hysteresis due to variable lake surface

A reason for the deviation in the correlation is the shape of the lake, since the surface of the lake increases with the level of the water as can be seen in Figure 3.5b. Especially for the highest meter of water level, the lake expands over a significant area of floodplains. This causes the higher discharges during the beginning of the falling stage (green arrow) compared to the end of the falling stage (purple arrow), because larger volume of water must flow out of the lake to obtain the same decrease in water level in the lake. The geometry of the lake also affects the rising stage with a lower discharge through the TSR compared to water level difference during the beginning of the rising stage and higher discharges compared to water level difference in the final stage of rising.

Besides the shape of the lake, also the influence of the outflow of the lake on the water level of Phnom Penh could cause a hysteresis effect. In case of outflow of the lake, the extra volume added to the discharge in the Mekong from the Tonle Sap river, causes backwater effects in the approximity to the bifurcation. The equilibrium depth in the Mekong, without extra discharge from the lake, is lower compared to the water level in the lake, causing a flow from lake to the Mekong. In a simplified case with a constant bed slope in the Mekong, the equilibrium depth downstream of Phnom Penh is higher. This would mean a sudden increase in water level, which is in reality not possible. Therefore, a backwater curve exist and since the flow in the Mekong is subcritical, the transition to the new equilibrium depth is located upstream of the junction, as can be seen in Figure 3.6. The measured water level in the Mekong is still in the influence zone of this backwater and therefore the measured water level difference is smaller during a higher outflow. During the inflow this effect is present as well but smaller, because the discharge through the Tonle Sap river is in the inflow stage a smaller percentage of the Mekong discharge.

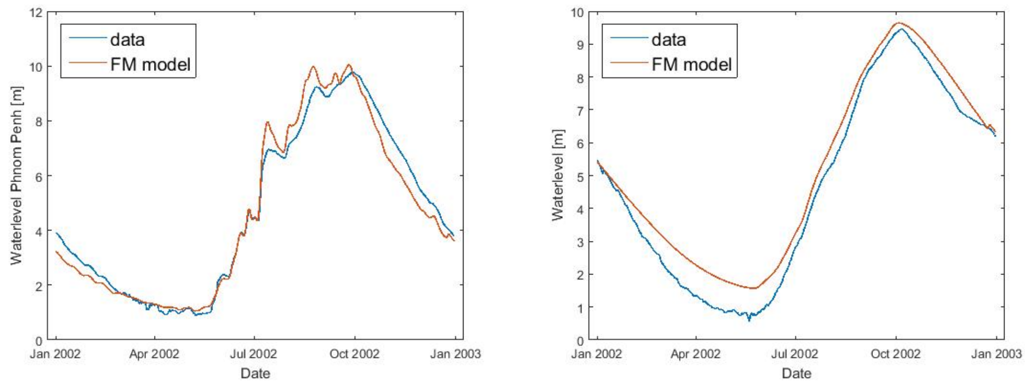


(a) equilibrium water levels around junction (b) Backwater curve and location measured water level

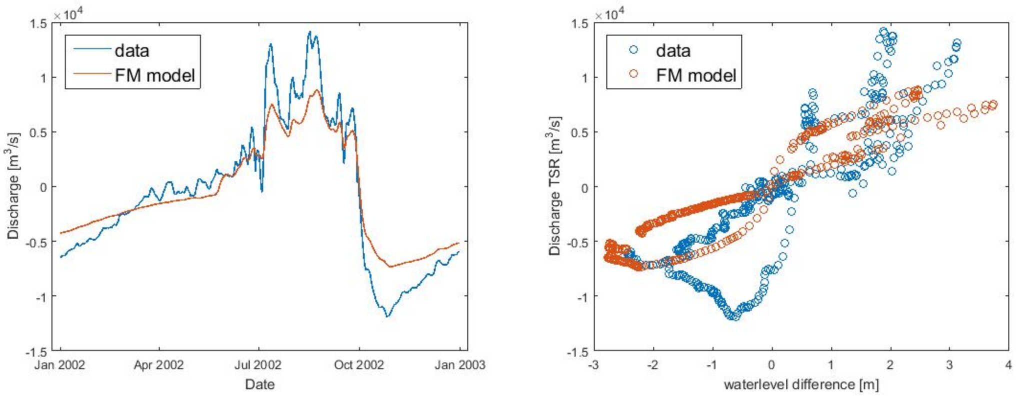
Figure 3.6: Presence of backwater curve in the Mekong river due to large inflow at Phnom Penh influences measured water level in Mekong, especially during outflow of lake

Delft3D-FM validation

The results for the Delft3D-FM model of the inflow parameters around the Tonle Sap lake are shown in Figure 3.7. Here we can see that the model represents the process of the in- and outflow quite well, however there are some deviations as well.



(a) Waterlevel Phnom Penh (b) Waterlevel Tonle Sap lake



(c) Discharge Tonle Sap River (d) Correlation discharge - water level difference

Figure 3.7: Results Delft3D-FM model compared to data

From these figures, the following conclusions are drawn on the performance of the Delft3D-FM model:

- Since the water level at Phnom Penh is calculated by the numerical model, the deviations in the water levels affect the rest of the process. In Figure 3.7a it is seen that during falling stage, both before as after the wet season, the waterlevel in the Mekong is underestimated by the model. During the wet season the water level is over estimated, especially in the smaller flood peaks, since the natural floodplains in Cambodia are not included in the model

- The waterlevel in the lake drops less during the dry season, could be caused by:
  - Bathymetry at Snoc Trau (inflow location of lake) is not represented well in the model causing less in- and outflow. This is because this is a large shallow area with many islands and narrow gullies, and the model does not include the smaller gullies because of the large grid width here, making it more difficult for the water to flow out of the lake with low water levels (Kummu et al., 2008)
  - Evaporation is much larger compared to precipitation from January to April, but not included in the Delft3D-FM model. This effect would cause a drop of around 40-50 cm in these months, which is not discharged via the Tonle Sap river (Kummu et al., 2014)
- The water level rises similar compared to the measured data. However, the discharge through the Tonle Sap River during the rising stage is much lower. This can be caused because of the following reasons:
  - The calculation method of discharge from data overestimates the in- and outflow through the Tonle Sap river, because it is calculated on measured data of points that are stretched over a large river stretch. During the rising stage part of the discharge from Kratie inundates floodplains in Cambodia or is withdrawn for irrigation purposes or flows through the canals directly to the Vietnamese floodplains
  - The height of the floodplains might be overestimated, due to vegetation and therefore excluded from inundation potential. This causes a decrease in storage volume and less discharge through the Tonle Sap river is necessary to reach the same water level. This can also be observed in the hysteresis in correlation, which is much less in the model compared to the measured data.
- The processes are modelled correctly, however due to simplifications in model and possible errors in data, the quantity of the Delft3D-FM model deviates from the data measurements

Analytical model validation
The analytical model is capable to calculate the water levels in the Tonle Sap lake based on water levels in the Mekong in a very short time and is therefore applicable for rapid assessments. The analytical model is as explained divided into the rising stage and falling stage with each different formulas. For the rising stage the friction head and factor of inflow is determined empirically from available data and the Delft3D-FM model. For a friction head ΔH_r varying between 0 and 1.0 m, the factor could be calculated as follows for each timestep:

$$T = \frac{h_{Mekong} - h_{lake} - \Delta H_r}{\frac{\partial z}{\partial t}}$$

This factor varies for each time step and in order to obtain a representative value the average is taken over the rising period. The T-factor was calculated based on both the Delft3D-FM output data as the measured data. However, for a friction head below $H_{fric} < 0.6m$ the analytical model was unstable at the transition from rising to falling stage. On the other hand a larger friction head caused the maximum water level of the lake to be underestimated which is undesirable as well. Therefor the setting with a friction head of 0.7 m and a T-factor of 7.8 (based on the Delft3D-FM output) was chosen and the results are shown in Figure 3.8. It can be seen that the model is not representative in the transition areas between the falling and rising stage, which is caused by numerical instability because of the imposed boundaries between the two processes.

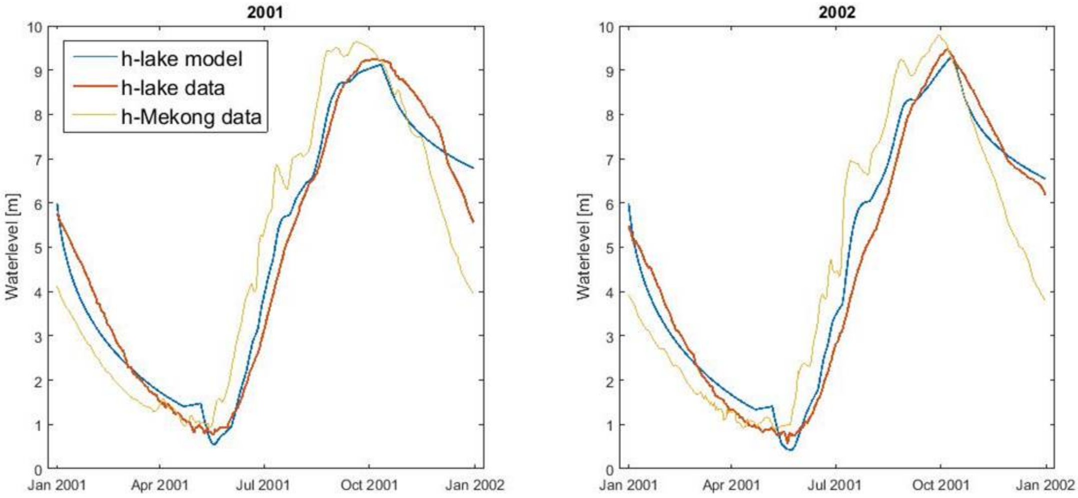
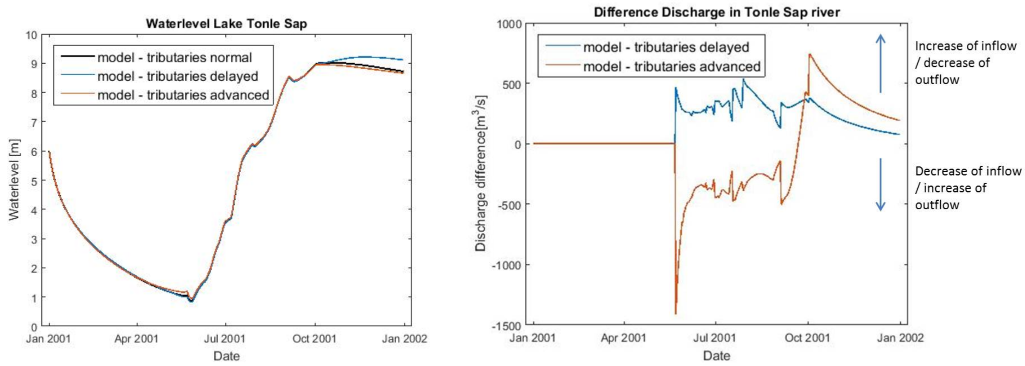


Figure 3.8: Results analytical model for 2001 and 2002

The analytical model calculates the water levels based on the measured water level of the Mekong. However, as explained in Section 3.2.2, these measurements are influenced by the outflow of the lake as well. This means that an extra iteration is required in order to compensate for this influence.

3.2.3. Sensitivity timing flow reversal

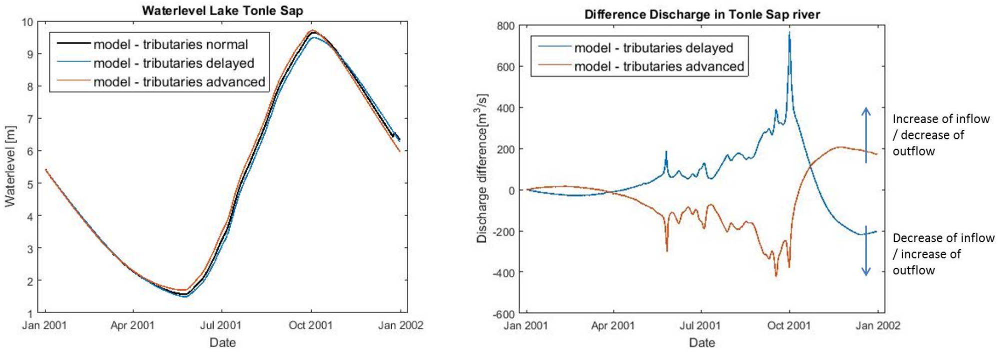
For the ecology and fishery in the lake the timing of the flow reversal is very important. From the conceptual model it follows that the timing of this reversal is depending on the water level difference between the lake and the Mekong. As already explained the shift in rain season between highlands of Laos and Vietnam and the basin of Tonle Sap enhances the water level difference in the beginning of the wet season and is important for the timing of the flow reversal. Due to the expected hydropower developments the arrival of the flood wave in the Mekong might change. This might affect the flow reversal and the sensitivity to a shift in timing between tributaries inflow and floodwave arrival in the Mekong is therefore of interest. For this reason both the analytical model and the Delft3D-FM model are used to assess the sensitivity. In this situation the inflow from the tributaries are delayed and advanced with 3 weeks, which is the estimated delay of the flood season at Pakse (ICEM, 2010).



(a) Waterlevels lake Tonle Sap (b) Discharge difference

Figure 3.9: Results timing tributaries analytical model

As can be seen in Figure 3.9 and 3.10 the water levels only slightly differ if the timing of tributary inflow is changed. However, there is a difference in discharge through the Tonle Sap river and in the case of advancing the tributary inflow (similar to delaying the Mekong floodwave) less water flows into the lake during the wet season. Which also causes a lower outflow after the wet season, which is represented better with the Delft3D-FM model (Figure 3.10b). The decreased in- and outflow does affect the discharge in the downstream delta



(a) Waterlevels lake Tonle Sap

(b) Discharge difference

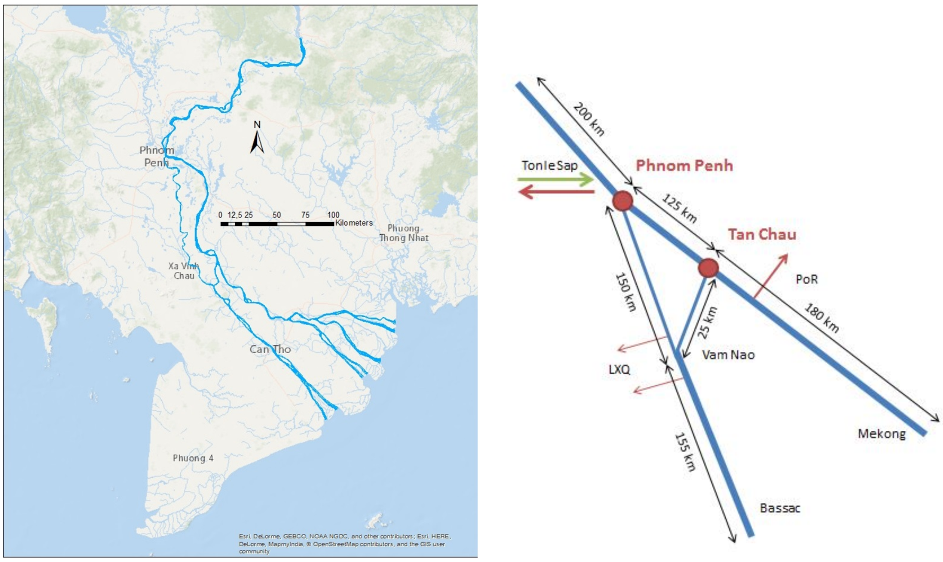
Figure 3.10: Results timing tributaries Delft3D-FM model

branches for which the graphs can be found in Appendix D.1. The discharge in the wet season increases for all the observation points, while (especially in the period after the wet season) the discharges decreases in all points. This increase and decrease is of the same order as the change in discharge through the Tonle Sap river and dampens out further downstream.

3.3. Hydrological distribution with large scale morphological changes

3.3.1. Conceptual model

For the distribution of discharge over the main branches downstream of Phnom Penh the river is simplified to two branches, the Bassac and Mekong, with a uniform profile and bed slope. Approximately halfway downstream there is a connecting branch, Vam Nao, that redistributes water from the Mekong to the Bassac. The width of the Mekong is around twice as wide compared to the upper part of the Bassac, but downstream of the Vam Nao branch the width of the Bassac is of the same order as the Mekong. The floodplains on both sides of the branches drain part of the discharge from the main branches. On the side of the Bassac this occurs mostly upstream of the Vam Nao branch and on the side of the Mekong both upstream and downstream. The schematization of the conceptual model can be found in Figure 3.11.



(a) Location main branches

(b) Simplified geometry

Figure 3.11: Conceptual model main branches

The distribution of discharge over the main branches can be described via bifurcation laws, which follow from the continuity and momentum equations. To do this a number of assumption must be made, such as a constant bed slope and uniform flow conditions (water depth is equal to the equilibrium water depth and no back water curves are present). The following formulas must uphold at a bifurcation:

$$Q_0 = Q_1 + Q_2$$

$$Q_1 = B_1 * C * d_1^{3/2} * i_{b,1}^{1/2}$$

$$Q_2 = B_2 * C * d_2^{3/2} * i_{b,2}^{1/2}$$

$$h_0 = h_1 = h_2$$

$$d_1 = h_1 - z_{b,1}, d_2 = h_2 - z_{b,2}$$

B	Width of river branch	C	Chézy coefficient [$m^{1/2}/s$]
d	Water depth [m]	i_b	Bed slope [-]
h	Water level with respect to m.s.l. [m]	z_b	Bottom level with respect to m.s.l. [m]

For this area there are two locations, that are assumed to follows these laws: The junction at Phnom Penh and at Tan Chau, indicated with the red dots in Figure 3.11b. The inflow discharge at Phnom Penh can be determined by coupling the analytical model from the Tonle Sap to the upstream boundary of the analytical model of the main branches. However, this would require iterations, because the water level at the junction is depending on both downstream conditions (calculated with the analytical model of the main branches) and the in- or outflow of the Tonle Sap river (calculated with the analytical model of the Tonle Sap lake). To verify whether the discharge distribution can be calculated using the bifurcation laws, the total inflow discharge from Phnom Penh is calculated by adding measured discharges from the downstream branches:

$$Q_{PhnomPenh} = Q_{Chaktomouk} + Q_{ChroyChangVar}$$

The floodplain areas LXQ and PoR are threated as sinks and from the upper Mekong to the Bassac there are several small canals that discharge water from Mekong to the Bassac. Because the measurement station at Tan Chau only monitors water levels, the upstream discharge at Tan Chau is calculated as follows:

$$Q_{TanChau} = (Q_{Mekong,upstream} - Q_{diff})^{0.98}$$

$$Q_{diff} = Q_{ChauDoc} - Q_{Chaktomouk}$$

Figure 3.12: Locations measurement stations used for validation of conceptual model

In which the Q_{diff} the increase of discharge in the Bassac from the junction at Phnom Penh (location Chaktomouk) to upstream of the floodplains is (location Chau Doc). These locations can be found in Figure 3.22. The discharge in the Mekong and Bassac downstream of the Vam Nao branch is calculated by:

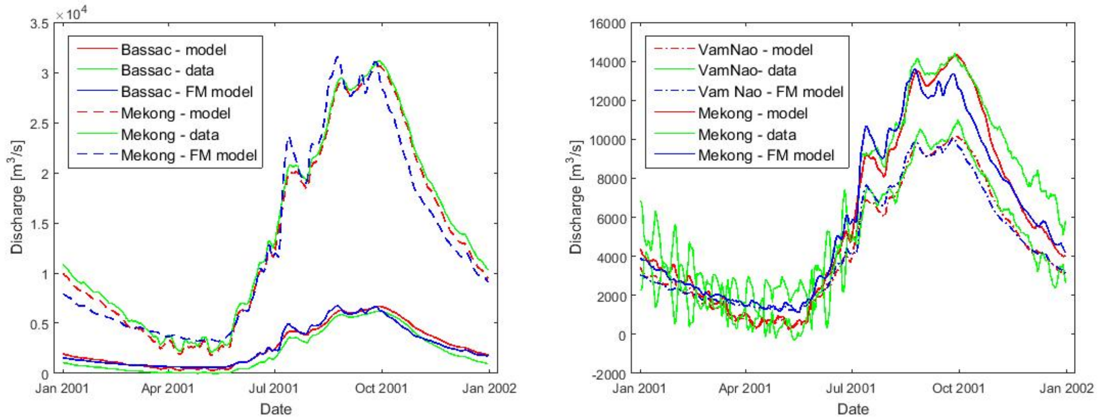
$$Q_{Mekong,downstream} = Q_{TanChau} - Q_{VamNao}$$

$$Q_{Bassac,downstream} = Q_{ChauDoc} + Q_{VamNao}$$

For these discharge it should be noted that they ignore the outflow via the canals and floodplains, which causes overestimation, especially in the wet season, of the downstream discharge.

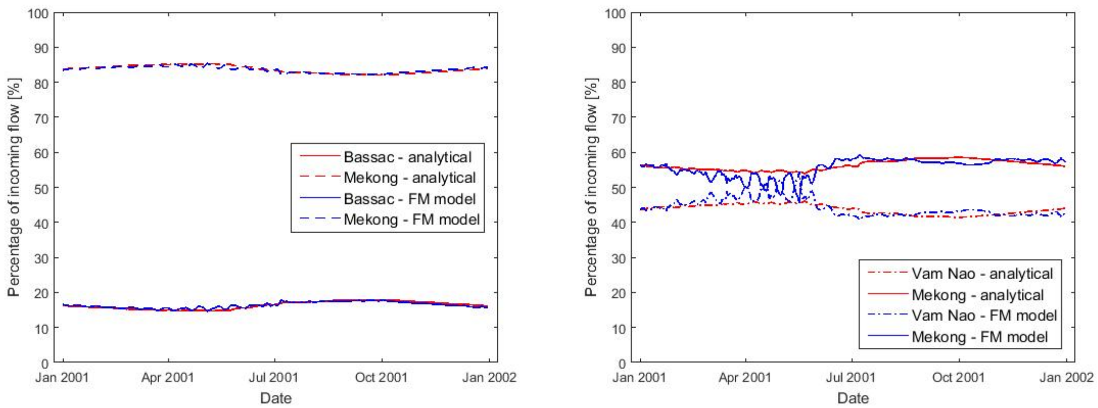
3.3.2. Model validation

For the validation, the conceptual model and Delft3D-FM model are both compared to the measured data from the following locations, shown in Figure 3.22. The discharges after the junction at Phnom Penh are represented by Chaktomouk for the Bassac and Chroy Chang Var for the Mekong. The results of the analytical and Delft3D-FM model compared to the measurements are shown in Figure 3.13 for daily averages.



(a) Phnom Penh (b) Tan Chau

Figure 3.13: Results of analytical and Delft3D-FM model for discharge distribution for both bifurcations



(a) Phnom Penh (b) Tan Chau

Figure 3.14: Results of analytical and Delft3D-FM model of percentage of incoming flow for both bifurcations

The distribution at both bifurcations is calculated quite well for both the analytical as the Delft3D-FM model. The Delft3D-FM model does deviates from the measurements more than the analytical model, because the inflow discharge is already different at a bifurcation (calculated by the numerical model), while the analytical model uses measured data for the inflow. At Phnom Penh both models overestimate the inflow of the Bassac, especially in the dry season, which could indicate that the bathymetry or width is not estimated accurately. At Tan Chau the measurements are influenced by tidal variations in the dry season. This causes fluctuations with a period of the spring-neap tidal cycle, because measurements are made at a set time on the day.
In Figure 3.14, the percentage of incoming flow going through the downstream branches is shown for both bifurcations. For both locations the exact distribution varies between the wet and dry season. The bifurcation at Phnom Penh has a very unequal discharge distribution of 85% to the Mekong and 15% to the Bassac. This inequality exist mostly due to the narrow and shallow entrance of the Bassac. At Tan Chau the distribution is more equal with approximately 55 % to the Mekong and 45% to the Bassac. The difference becomes smaller because of a shorter length via de Vam Nao and Bassac, a wider entrance of the Vam Nao and a shallow part in the Mekong near the junction. The difference in wet and dry season is caused because of the varying equi-

librium water levels which changes the distribution over the branches.

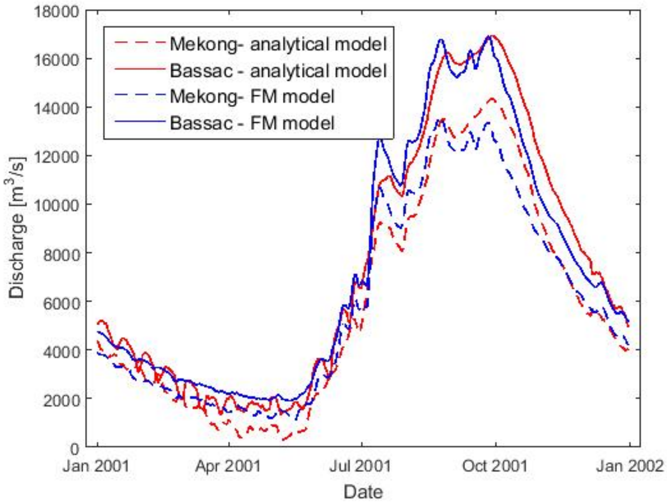


Figure 3.15: Discharge through Mekong and Bassac downstream of Vam Nao for analytical and Delft3D-FM model

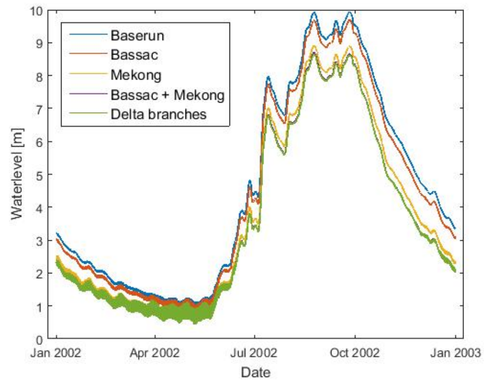
Even though both junctions distribute a higher percentage to the Mekong, the amount flowing through the Mekong downstream of Vam Nao is smaller compared to the Bassac. In Figure 3.15 the discharge through the Bassac and Mekong are shown for the analytical and Delft3D-FM model. The amount of flow in the Bassac by the Delft3D-FM model is calculated by adding the discharge at Chau Doc with Vam Nao in order to neglect the outflow to the LXQ floodplains upstream of the Vam Nao (which is neglected in the analytical model as well). The discharge downstream of the Vam Nao branch and floodplains is of importance for salt intrusion. The higher discharge in the Bassac (and less bifucations further downstream) suggest that the salt intrusion would be less in this branch compared to the downstream branches of the Mekong.

3.3.3. Sensitivity main branches

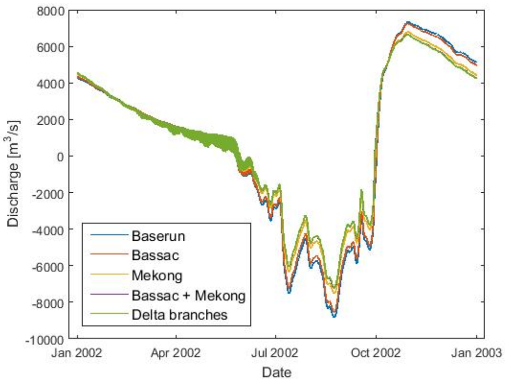
Due to both hydropower developments and sediment mining the sediment transport regime in the Mekong is expected to change. The decrease in sediment supply could lead to large scale morphological changes in the delta branches, which in return influences the hydrodynamics in the system as well. In order to understand the influence of these large scale changes on the discharge distribution the following changes are investigated using the Delft3D-FM model. In these scenarios only the main branches indicated in the conceptual model in Figure 3.11b are lowered:

- Decrease bottom level of Bassac with 2m
- Decrease bottom level of Mekong with 2m
- Decrease bottom level of Mekong and Bassac with 2m
- Decrease bottom level of all main branches in the delta with 2m

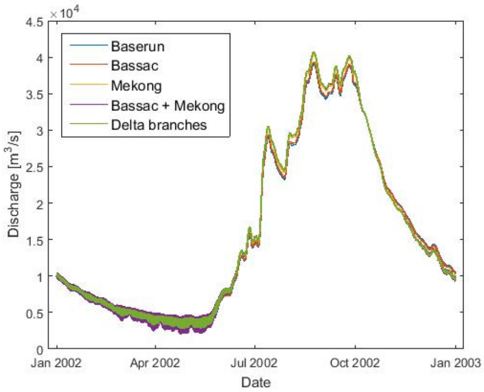
For the sensitivity of the bathymetry of the main branches only the numerical model can be used. In order to use the analytical model, the total amount of water which is distributed over the Bassac and the Mekong must be known. Due to a decrease in bed level, both upstream and downstream of the bifurcation at Phnom Penh, the water level will drop. This causes the in- and outflow of the lake Tonle Sap to change and therefore the discharge to the bifurcation between the Mekong and Bassac as well, which is shown in Figure 3.16.



(a) Waterlevel Mekong Phnom Penh

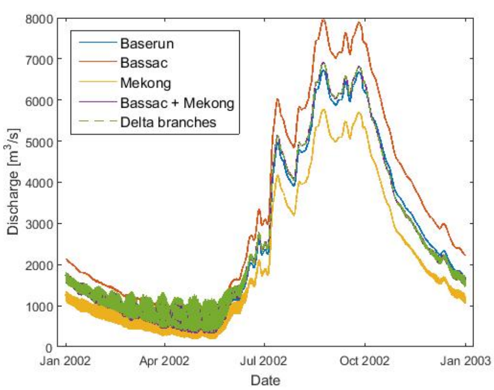


(b) Discharge Tonle Sap River

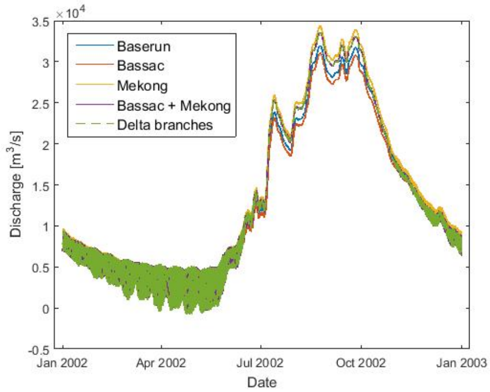


(c) Discharge to bifurcation Phnom Penh

Figure 3.16: Bathymetry changes in water level at Phnom Penh causing a different distribution to lake Tonle Sap and the bifurcation at Phnom Penh



(a) Bassac



(b) Mekong

Figure 3.17: Discharge distribution over the branches at Phnom Penh for different scenarios

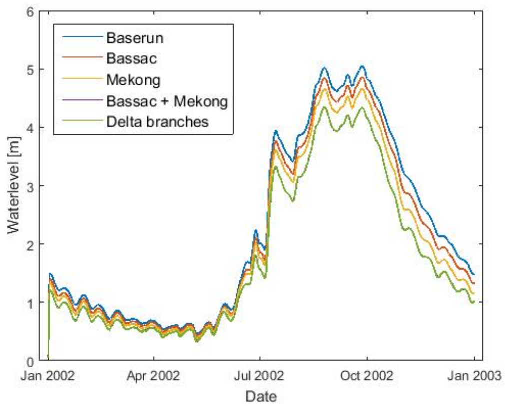
In Figure 3.17 the discharge through the Bassac and Mekong after the bifurcation at Phnom Penh is shown. The discharge distribution at Phnom Penh changes mostly in case of a decrease in bed level in one of the two branches. Bed level degradation that is spread equally over the branches has only minor influence on discharge distribution at this location, because of the nonlinearity of water level in the bifurcation laws. Besides the change in discharge distribution it can be seen that the tidal influence reaches the bifurcation, causing a fluctuating discharge. The tidal wave is dampened less in the case of a deeper estuary branch, especially in the case of a lower discharge during the dry season. The tidal influence is the largest if both branches are degraded. The maximum tidal fluctuations at Phnom Penh in the dry season are shown in Table 3.1.

Scenario	Waterlevel fluctuations [cm]	Discharge fluctuations [m^3/s]
Baserun	10	350
Bassac -2 m	15	700
Mekong -2 m	30	900
Bassac and Mekong -2 m	40	1600
All delta branches -2 m	45	2500

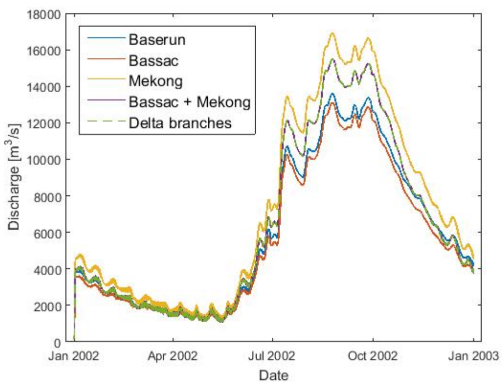
Table 3.1: Tidal water level and discharge fluctuations upstream of bifurcation Phnom Penh for the different bathymetry scenarios

At the bifurcation of Tan Chau the tidal influence is even larger, so in order to obtain a better view of the distribution, the output of the Delft3D-FM model is daily averaged. Because of the lowered bed in the Mekong or decreased discharge (in case of lowered Bassac bed level) the water level at Tan Chau drops. Except for the case with a lowered Bassac, the discharge in the Mekong will be higher with a degraded level. The changes at the bifurcation at Tan Chau are shown in Figure 3.18.

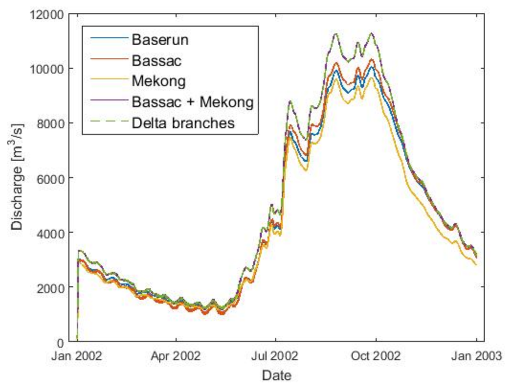
If only one of two branches is degraded, the distribution becomes more unequal with an increase to the degraded branch. In the case of a degraded bedlevel in the Mekong the increase of discharge in the Mekong is not proportional to the decrease of discharge through Vam Nao and also the percentage of inflow increases for both branches in case of two degraded branches. This indicates that due to a lowered water level (caused by lowering of the bed level) less water is flowing out of the main branches into the canal floodplain system.



(a) Waterlevel Tan Chau



(b) Discharge Mekong downstream



(c) Discharge Vam Nao

Figure 3.18: Waterlevel and outflowing discharges of bifurcation at Tan Chau

3.4. Inflow of Vietnamese canal-floodplain system

3.4.1. Inflow to canal-floodplain system

In order to understand the inflow to the canal-floodplain systems, the area north of the Mekong branch, the Plain of Reeds (PoR), is chosen as study area. The complicated canal-floodplain system is simplified by 4 main canals supplying water to the area with surrounding floodplains on both sides, as can be seen in Figure 3.19. The floodplain areas around the canals differ in width, as is the case in the PoR as well, and a grid of 10 km is used in the longitudinal direction of the canal.

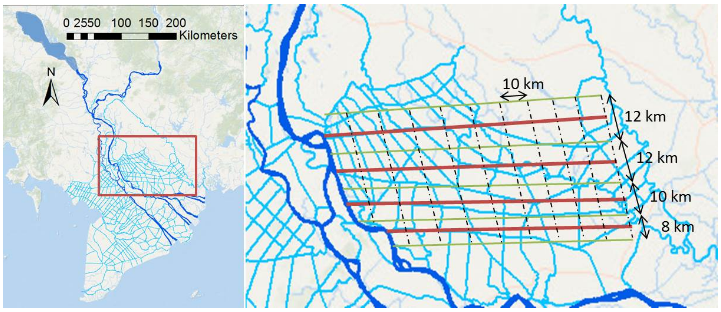


Figure 3.19: Simplified canal-floodplain system in PoR

In case of steady and uniform flow conditions, the discharge into a canal can be described with (de Vriend et al., 2011):

$$Q_{canal} = B_{canal} * d_{canal} * u = B_{canal} * d_{canal} * C * \sqrt{d_{canal} * i_f}$$

The depth can be calculated by: $d_{canal} = h_{canal} - z_{b,canal}$ and i_f represents the slope in water level. The water level at the inflow point is equal to the water level in the Mekong at the connection. In this case the storage of water in the floodplains is not taken into account. The discharge to the floodplains depends on the water level in the canal reaching above the dike ring. The water level in the canal decreases with the distance from the river with the water slope, and inflow of a floodplain occurs when the following statement is valid:

$$h_{Mekong} - i_f * l > z_{DikeRing}$$

$$V_{FP,j} = B_{FP} * (h_{canal,l} - z_{FP}) * l$$

The water level in the canal and hereby volume of inflow to the floodplain is determined for steps in distance from the river (l) of 10 km. The discharge to the floodplains can be calculated by the increase of stored volume per time step (j). In this case only the inflow of the floodplains is taken into account:

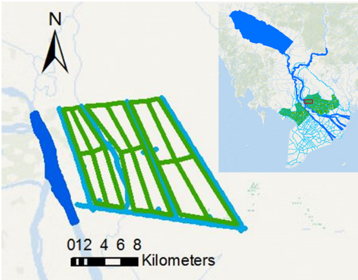
$$Q_{FP} = \frac{V_{FP,j} - V_{FP,j-1}}{\Delta t_j} \qquad \text{if} \quad V_{FP,j} - V_{FP,j-1} > 0$$

i_f	Water level slope [-]	l	Distance in canal from Mekong [m]
$z_{Dikering}$	Height dikerings with respect to m.s.l. [m]	V_{FP}	Volume water stored in floodplain [m^3]
B_{FP}	Height dikerings with respect to m.s.l. [m]	z_{FP}	Height of floodplain with respect to m.s.l. [m]

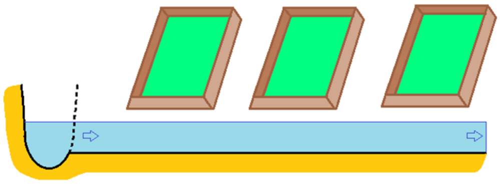
The total inflow to the Plain of Reeds can now be calculated, assuming that the normal uniform flow through the canals is not influenced by the inflow to the floodplains. Because the only unknown factor for this model is the water level slope (i_f) in the canal, it is assumed that this is only dependent on the water level in the Mekong (Tan Chau) via a correlation. Not only in the canal, but also in the Mekong, a water level slope is present. In the dry season, this slope is very small, because small amounts are discharged to the canal system and the difference in water level height with respect to the sea is also small. However, in the wet season the water slope in the Mekong cannot be neglected for the inflow of the floodplains. Therefore, the water level at the entrance of the 2nd, 3rd and 4th canal (from upstream) is lowered with 0.5 m, 1.5 m and 2.0 m, respectively, due to the large inflow to the floodplains in the first two canals.

3.4.2. Inflow of individual floodplains

Because the floodplains in this area are all surrounded by dikerings, the inflow of the floodplains is more complicated than the analytical model suggest. Besides that, the inflow of the floodplains is expected to influence the hydrodynamics in the canal as well, which is not included in the analytical model. Therefore a conceptual model of the inflow of comparted floodplains is created to obtain a better understanding of this process. For the inflow principle of the Vietnamese floodplain areas the conceptual model is based on a small part of the area, consisting of the adjacent part of the Mekong river connected to a single channel in the Plain of Reeds (PoR). Next to the channel three separate floodplains are present, which can be represented as rectangularly shaped buckets. The borders of these buckets (representing the dike rings) are at a height of +2.5 m m.s.l. and the bottom of the buckets (representing the floodplain) is at a height of +1.0 m m.s.l.. It is assumed that the water level in the river is influenced only by the supply from upstream and the canal is supplied by the river depending on the water level in the river and the canal. The process of the inflow can be described as follows and is visualized in Figure 3.21:



(a) Location and subparts system



(b) Simplified geometry

Figure 3.20: Simplified model of Vietnamese floodplains

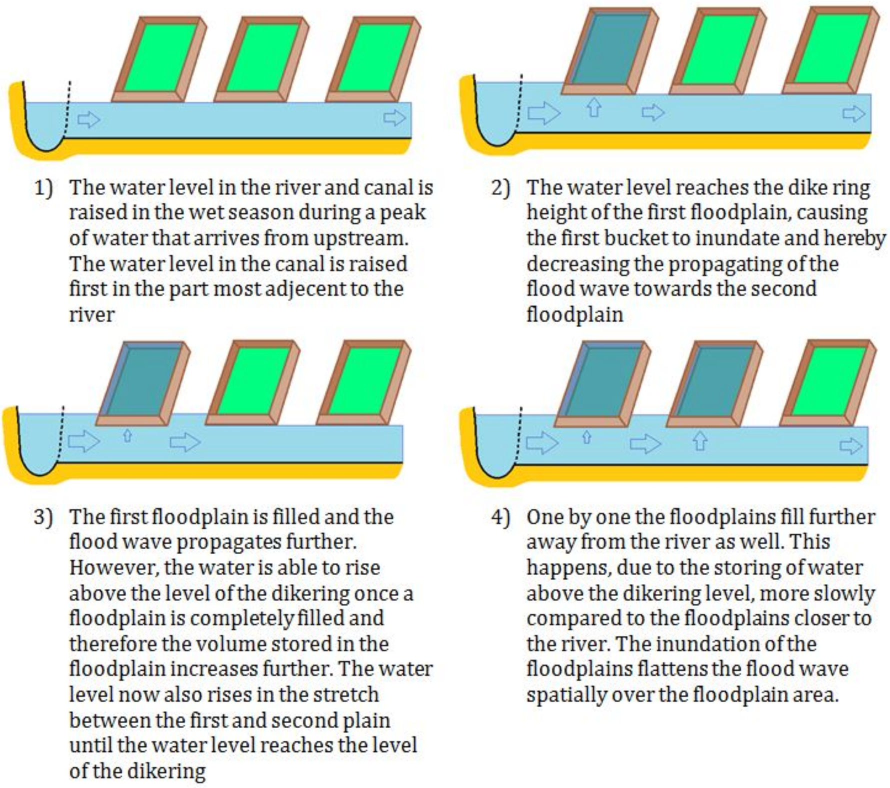


Figure 3.21: Schematization and description of the inundation process

3.4.3. Model validation

The two conceptual models, inflow to the canal-floodplain system and the inundation process of individual floodplains, are validated done based on the results of the Delft3D-FM model. This is because no data (both topographic and hydrodynamic) were available for this part of the floodplain area. A simplified topography of the floodplain is therefore implemented in the Delft3D-FM model. In the Plain of Reeds a number of observation points is placed in the floodplains and the (main) canal south of these floodplains on both sides of the canal-floodplain connection. In order to compare the results of the analytical model, the measurement stations in the Mekong branches (Tan Chau, Vam Nao and My Thuan) are used as well.

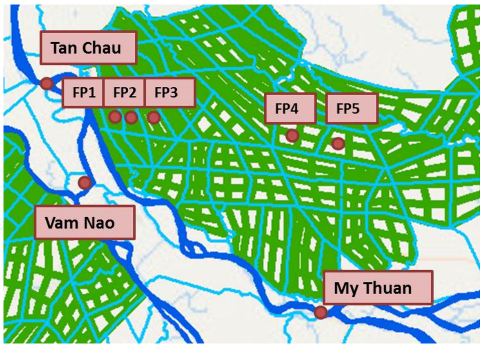


Figure 3.22: Location of measurement stations used for validation of conceptual model

Analytical model for the inflow to the Plain of Reeds

First the water slope must be related to the water level in the Mekong in order to calculate the discharge to the canal. The water level slope is retrieved from the model, from the difference in water level between the observation points in one of the main canals through the PoR. In Figure 3.23, the correlation between the water level slopes and the water level in the Mekong is shown. From these model observations, a power fitted curve is obtained (the fitted curve from the slope between observation points 1-3 showed best overall results). When the water levels in the Mekong rise above +2.5 m m.s.l., the water slope is at some points much larger compared to the fitted curve. These deviations coincide with the inflow of floodplains, which indicates that during the inflow of the floodplains, the slope and flow velocity in the canal are temporarily much higher. During the outflow of the floodplains the slope is smaller compared to the fitted curve.

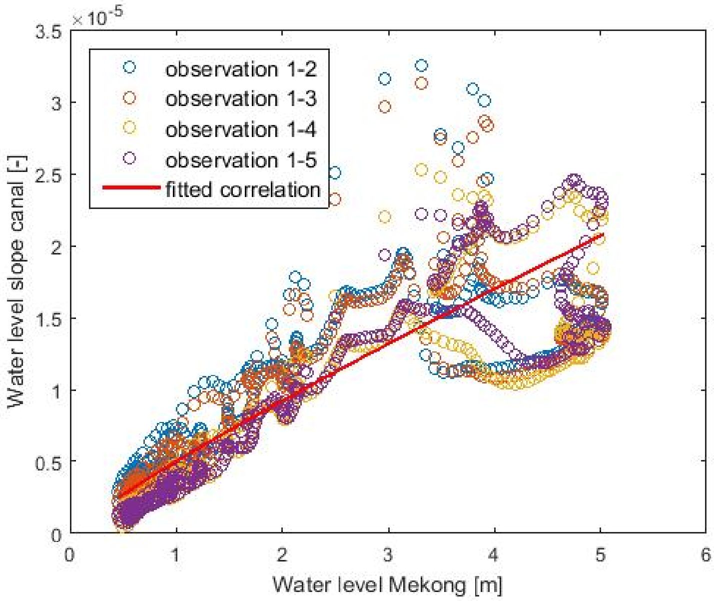


Figure 3.23: Correlation between the water level in the Mekong and the water level slope in the canal

The discharge can now be analytically calculated, using the water level at Tan Chau as the only input. The result of the analytical model is compared with the numerical model. For the Delft3D-FM model, the inflow to the PoR is calculated with: $Q_{PoR} = Q_{TanChau} - Q_{VamNao} - Q_{MyThuan}$. The results are shown in Figure 3.24, in which the red line indicates the situation without inflow to the floodplains and the yellow line including the floodplains. During the first flood peaks, the inundation of the floodplains is overestimated, probably because of damping of the flood wave propagation is not taken into acount. In the analytical model the inflow to the floodplains is spread over a few short periods, while in the numerical model this seems to be better spread over the entire wet season.

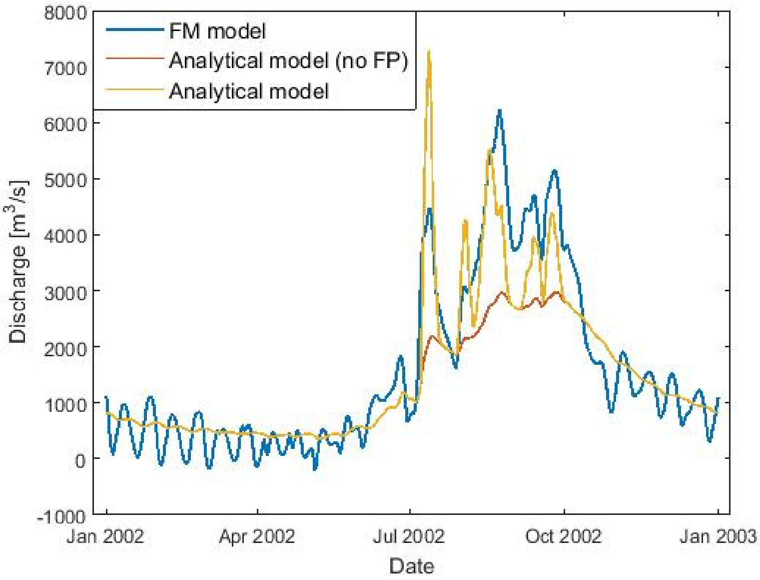


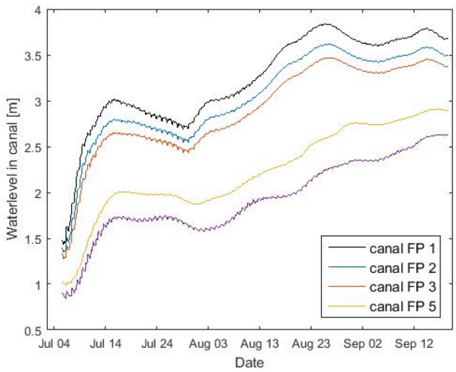
Figure 3.24: Results analytical model compared to Delft3D-FM model

Conceptual model for the inflow of floodplains

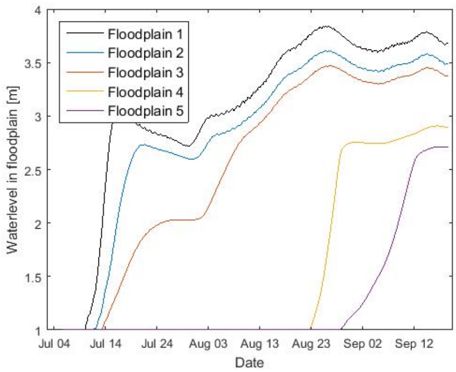
Firstly, the assumption was made that the discharge through the canal decreases by the inflow of the floodplain. In Appendix E, this has been proven to be the case. In Figure 3.25, the results for the water level in the floodplains and canal are shown for all five measurement points (adding the fourth and fifth observation point results in a better view of the process). From these figures the following conclusions can be made:

- The water level variations are dampened and spread in the canals, which decreases the amplitude of water level fluctuations in the Mekong further in the canal, but also delays changes in water levels in the canals. Even when closer to the river the water level in the canal decreases, further away from the river floodplains are inundating.
- Where the analytical model calculated an inundation of the first 30 km in one day, this is clearly not the case if looking at individual floodplains. Inundation occurs plain by plain and is therefore spread over a longer period than indicated by the numerical model. This means that the inundation of a floodplain not only increases the discharge through the canal, but affects the entire hydrodynamics in the canal.
- Just before inundation of a floodplain occurs, the water level difference between the first observation points further in the canal increases. These larger water level slopes were also present in the correlation between water level in the Mekong and slope in the canal. When inundation occurs, the water level difference decreases again, which indicates that the floodwave propagates further into the canal. Besides, it suggests that the length of the floodwave into the canal-floodplain system is dependent on the inundation of a floodplains closer to the river.

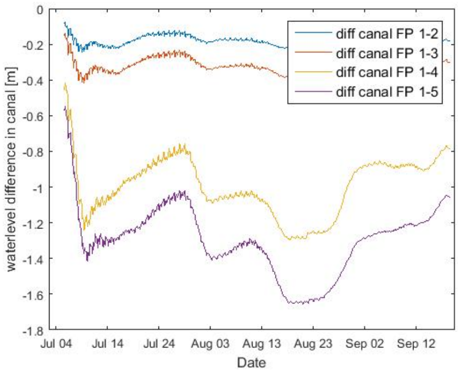
These results follow from the model in which the floodplain is connected only to one channel, while in the rest of the model runs for this research a floodplain is connected to all four surrounding canals. The connection to all canals has several consequences: Because the flood wave arrives from the north, the flood wave will reach the canals on the other sides before it reaches the southern canal, used in the concept model. This will lead first of all to an earlier commence of the inundation of the plain. Besides that, the filling time of a floodplain is decreased, since there are more connections and canals discharging into the plain. Another consequence is when the water level rises above the crest of the dikering overland flow occurs from north to south, also due to higher water levels in the northern canals. This results in a higher discharge in the canal after a floodplain compared to before the floodplain (negative discharge difference), because water flows out of the floodplain even when the water level in the floodplain is rising. The situation with overland flow can be



(a) Water level in the canal



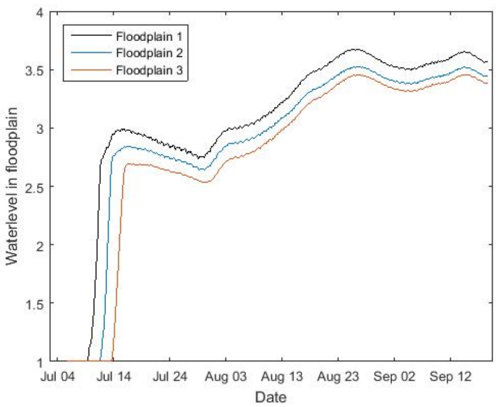
(b) Water level in the floodplains



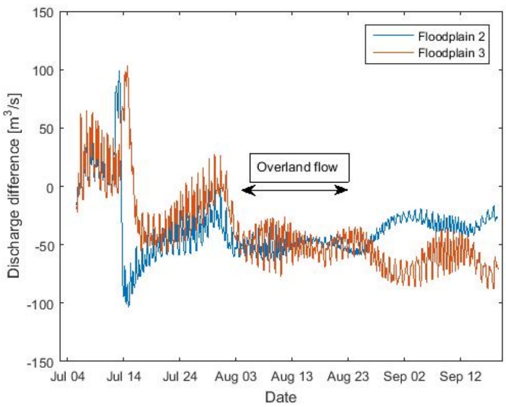
(c) Difference in water level in the canal

Figure 3.25: Results for the floodplains water levels

observed in Figure 3.26 from August 3 to August 23. Due to this overland flow, more water is distributed over the entire floodplain area, because it increases the available conveying area. Subsequently, overland flow enhances the propagation of the floodwave in the canal-floodplain system, which increases the storage volume in the entire floodplain area.



(a) Waterlevel in floodplain



(b) Difference in discharge through canal before and after floodplain

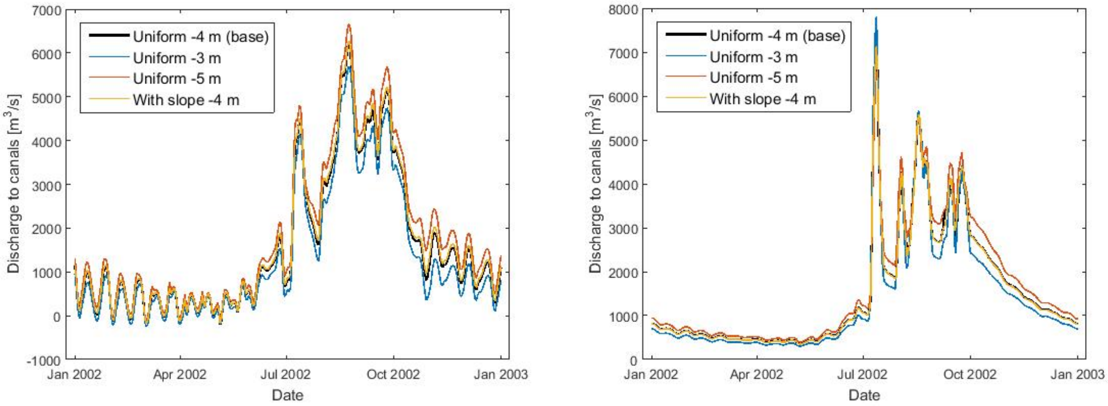
Figure 3.26: Overland flow

3.4.4. Sensitivity analyses

Bed level canals

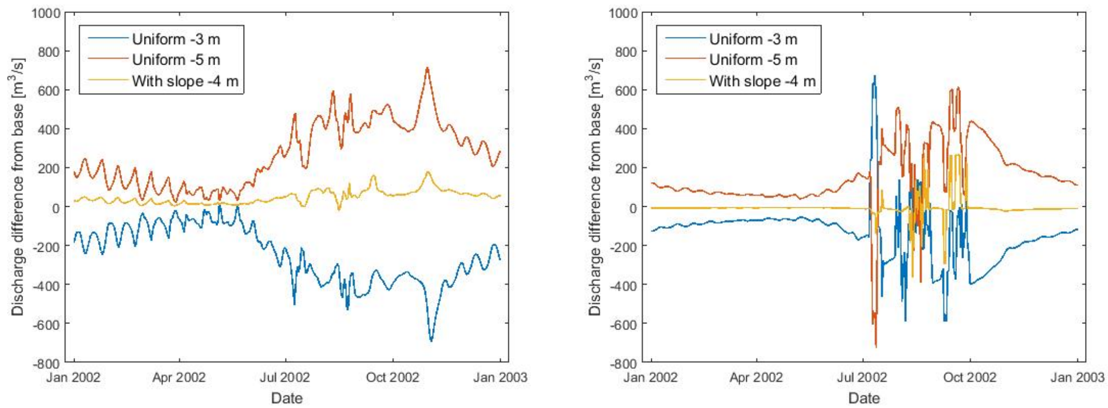
Because no bathymetry data were available for the smaller canals, a uniform bed level of -4 m m.s.l. was estimated. Because the discharge to the canal-floodplain system depends on the cross-sectional area of the canals and the water level slope, the influence of this assumption is assessed. For the sensitivity analyses, the bed level has been varied with +/- 1.0 m and by applying a small bed level slope.

In Figure 3.27 and 3.28, the results are shown for the analytical and numerical model for the different scenarios. By lowering the bed level the discharge to the floodplains increases, because both the cross-sectional area and water level slope (and hereby flow velocity) increase. In the case of a bed slope there is only a small difference, because the correlation between water level in the Mekong and the water slope changes only very little, as can be seen in Appendix D.2. The analytical model shows very similar results to the numerical model for the changes in scenario, except for the first flood peak, where the change is opposite compared to the numerical model. Because the calibration results (Appendix C.2) were better with a bed level in the canals of -5 m m.s.l. in the locations downstream of the floodplain areas, this canal bed level is used for the assessment of the hydropower scenarios and mitigation measures.



(a) Delft3D-FM model (b) Analytical model

Figure 3.27: Inflow to PoR for numerical and analytical model for different scenarios



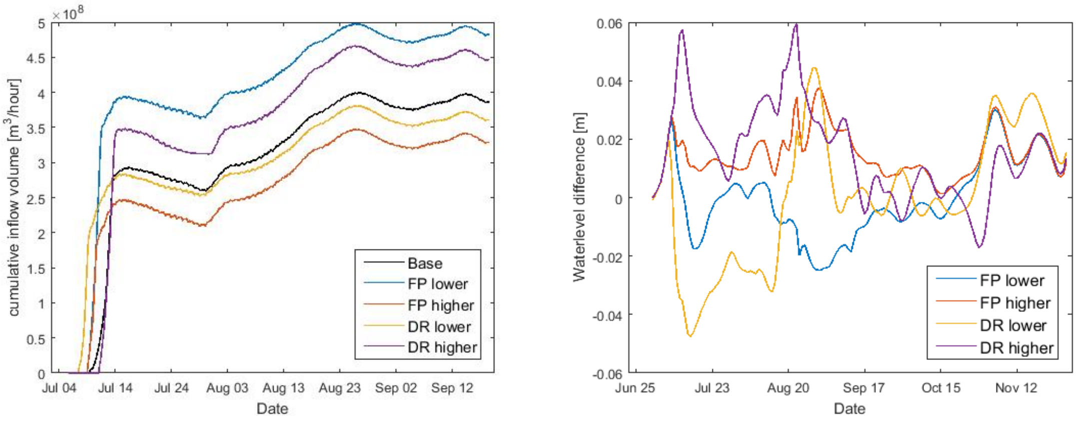
(a) Delft3D-FM model (b) Analytical model

Figure 3.28: Difference in inflow to PoR for numerical and analytical model compared to base scenario

Floodplain geometry

The geometry of the floodplains is also simplified in the model. This is because a lot of data (both topograhic and hydrologic) are necessary to model the areas precisely. In the Delft3D-FM model, the height of the floodplains (+1.0 m m.s.l.) is a uniform value with surrounding dikerings with a height of +2.5 m m.s.l. in the Plain of Reeds (PoR) and +1.5 m m.s.l. in the Long Xuyen Triangle . In order to test what the influence of these parameters on the inflow process is, both parameters have been varied with +/- 0.5 m.

Only looking at the three floodplains closest to the river, the floodplains with the lower floodplains and higher dikerings store the larger volume of water compared to the base scenario as can be seen in Figure 3.29a. Since more storage of water decreases the flood volume in the coastal zone, this is more favorable. However if looked at the complete area of the Plain of Reeds, the area of inundated floodplains and the inundation depth are different for each scenario as can be seen in Appendix D.3. In case of higher dikerings the water levels in the floodplains are deep close to the river, but the inundation has a small extent, because the propagation of the floodwave is much slower. With lower dikerings the whole area is inundated with smaller water depths. This can be explained by the effect of overland flow over dikering height, which is much larger in case of low dikerings compared to high dikerings. For different floodplain heights the extent of inundation is similar, but a lower floodplain is able to store a larger amount of water. The effect of the entire floodplain area can be seen from the water level in the Mekong downstream, which can be found in Figure 3.29b. The higher dikerings of floodplains store less water and therefore increase the water level during the wet season, while lower dikerings and floodplains decrease water levels in the river during the wet season. Also it shows that the extent of flooding has a larger effect compared to inundation depth.



(a) Cumulative inflow volume for first three floodplains

(b) Water level difference from base at My Thuan

Figure 3.29: Effects of different geometry on inflow of floodplains

3.5. Discussion on the system analyses

In order to obtain more knowledge on the system of the Mekong delta, three processes (in- and outflow of Tonle Sap lake, discharge distribution over the branches and inflow to Vietnamese canal-floodplain system) have been researched in depth. To do this, two main tools have been used, namely using a numerical model of the entire delta area and creating conceptual models using simplified geometry and theoretical formulas. These days, the natural flows of most of the largest rivers in the world are influenced by dams (Nilsson et al., 2005) because of increasing energy demands and irrigation systems expand to meet the growing food demands. However, these dams and irrigation systems have large impacts on the river basins flows and ecology, especially in densely populated delta areas. In the delta area many different processes play a role and interact. By splitting up all the processes in a delta area, the important drivers of a processes and influences of anthropological changes on this specific process can be assessed. The interaction between the river system and the process follows from this understanding of the process. This leads to a better understanding of the delta system as a whole.

3.5.1. Applicability of conceptual models

In this chapter, a conceptual model has been created of three important processes, which are chosen because these represent the largest quantities of water flows. Other important processes, such as overland flow, direct precipitation/evaporation and inundation of Cambodian floodplains, are left out of scope. These processes have a smaller influence on the total discharge and from these processes little information and measurements are available.

The analytical models are used primarily to understand the process better and to make a quick assessment of the quantity, but do not represent a process in detail. This is because for an analytical model to work a number of parameters has to be calibrated on available data. As measurements are not always present, more assumptions in the analytical model have to be made. Besides that, processes are often determined by spatial data, and due to variability does this complicate an analytical model too much. Each of the conceptual models has given better insight in the processes. For the applicability of the models the following can be said:

- **Lake Tonle Sap** - The conceptual model of the Tonle Sap is capable of determining the water level fluctuation in the lake and make an estimation of the lake surface area over time. This is useful to determine the impact on agriculture and ecological important wetland areas. The inflow stage is difficult to describe with analytical formulas, because inflow to the lake is determined by downstream conditions, which are influenced by the inflow to the lake as well. The conceptual model is now calibrated, using an inflow discharge related to the water difference with a minimum hydraulic head. Besides, the in- and outflow is independent of the geometry of the Tonle Sap river and the T-factor and head due to friction are determined by calibration. This means that the model cannot be used for situations with a changed geometry of Mekong (change in stage-discharge relation) or Tonle Sap River. Finally, it is difficult to model a smooth transition between the rising and falling stages, because of the imposed boundaries between the stages. These transition errors cause large fluctuations in the discharge in the Tonle Sap river and therefore not considered reliable for an assessment.
- **The discharge distribution over the main branches** - Applying the bifurcation laws at both junctions does give a good representation of the discharge distribution at the bifurcation. If the upstream condition can be retrieved from the analytical model of Tonle Sap lake, the discharge through all main branches can be represented completely with analytical models. Because there are many canals, distributing between the rivers and to the floodplains, it is necessary to know the conditions (preferably including a stage-discharge relation) at the junctions to predict the discharge distribution. These can be estimated by coupling the results of the analytical models together and perform iterations to take the interactions into account. In case of no large scale morphological changes and a known stage-discharge relation, the analytical model can be used as a rapid assessment technique to estimate the discharges through the main branches.
- **The Vietnamese canal-floodplain system** - The analytical model is able to predict the inflow to the canal-floodplain areas based on the water level in the Mekong. The inundation of floodplains is simplified in the analytical model, causing an overestimation during the beginning of the wet season and an underestimation during the final stage of the wet season. Because the inundation of the floodplains is a complicated process, a conceptual model has been tested to see the interaction between the floodplain hydrodynamics and canal hydrodynamics. The results of the conceptual model can be used to improve the analytical model. Besides, by making the water level in the Mekong for the downstream canals dependent on the inflow of the canals further upstream would also improve the performance of analytical model.

In this research, three independent analytical model are created for the described processes. All of the models are dependent on input data (water levels and discharges in the Mekong). When these models are coupled together and iterations steps performed, these input values can be obtained from the analytical model and only a discharge to the delta needs to be provided.

3.5.2. Applicability the Delft3D-FM model

The calibration and validation results of the Delft3D-FM model were quite good, which indicates that indeed the most important flow processes are simulated well. However, a numerical model is never fully able to represent the reality due to simplifications and numerical errors. This does not mean that a model is not applicable, because by understanding the limitations of a model, deviations in the calibration can be understood. These deviations can be taken into account when assessing the results of the different scenarios. Because this model is still in development, certain processes left out. First of all the Delft3D-FM model is made from cross-sections from an old 1D model (2000). When using the model, the possibility that bathymetry has already changed (for example due to sediment mining) must be considered.

- **Lake Tonle Sap** - The process of the bidirectional flow in the Tonle Sap river is modeled quite well. The water level reduces less in the dry season, which can be explained by the coarse grid at the inflow point (Snoc Trau) and the missing evaporation. The maximum water level is simulated well in the model with a difference that is equal to the difference in water level at Phnom Penh. However, the discharge through the Tonle Sap river is underestimated significantly in both inflow as outflow stage. This is shown also in the stage discharge relation in the river, which has less hysteresis and a lower discharge at same water level difference. This indicates that the storage in the floodplain is less in the model compared to reality. If more accurate bed topography data are available for the floodplain areas around the lake and the Tonle Sap river, the in- and outflow through the river can be calculated better by the model. Monitoring the discharge through the Tonle Sap River could improve the calibration of the model as well. Since the water level is calculated accurately, the surface area of the lake can be determined using a relation between water level and surface areas available from data. Also for the processes such as the flow reversal the model works sufficiently. For the assessment of hydropower scenarios and mitigation, it must be kept in mind that the discharge to and from the Tonle Sap lake is underestimated.

- **Discharge distribution over the branches** - The discharge distribution over the branches is well represented with the Delft3D-FM model as was shown in the calibration. However, there are always deviations in a model, these can be explained by missing processes such as:

  - Over a year the bed level in the Mekong changes between the wet and dry season, because of the differences in transport capacity. This is not taken into account, since there are no bed level updates included in the model yet. This would have a small effect on the discharge through most of the delta, because this will lead to sediment waves through the system. However, as explained in Section 2.2.2, the bed level in the estuary mouth does vary by the settling of the fine particles. This would lead to a higher bed level and flow velocities in the mouth of the estuary during the dry season.
  - The Cambodian floodplains are not included into the model since this would require more detailed topography data. Due to the missing of the Cambodian floodplains, a significant amount of water flows in the Delft3D-FM model through the main branches instead of being stored in the floodplains.
  - Direct precipitation and evaporation are not included in the model. For the Vietnamese delta, precipitation varies between 1200 mm/year to 2600 mm/year, of which the majority in the dry season. Evaporation vary between 150 mm/month to 220 mm/month (Deltares, 2011). The annual rainfall in the Cambodian area of the delta lower, around 1300 mm/year. From the drainage basin approximately 25% runs of towards the Tonle Sap lake and Mekong and is included in the tributary discharge. The evaporation is similar to the Vietnamese delta (Kummu et al., 2014). Note that for the Vietnamese delta, the water usage has been estimated taken into account the precipitation (Deltares, 2011). This means that only direct precipitation on the river and Tonle Sap lake must be taken into account.
  - The spreading of water usage in the Vietnamese delta is an unknown factor. During both dry and wet season water is substracted from the river branches which decreases the water level and discharge at the downstream measurement points. In the study of Deltares (2011) the water usages are estimated for the entire Vietnamese delta area. However, the spatial variations are not given. This might lead to a different distribution of discharge over the branches.

  In the downstream data points, the model output deviates from the measurements. However, the measurements are influenced by the tide and, especially during the dry season, strongly oscillating over the spring-neap tidal cycle (measurements are taken on a fixed time of day). From the Delft3D-FM model results it is possible to obtain a daily average of the discharge, which improves the representation of the fresh water discharge, but averaging over a complete tidal cycle would be even better. Therefor quite some analyses, for example salinity intrusion, can be performed better using output from the model compared to the measured data.

- **The Vietnamese canal-floodplain system** - In reality the Vietnamese canal floodplains system acts as storage during the wet season, releasing water when the water level decreases again. In the dry season water is subtracted to the floodplains for agricultural purposes. In this model only the storage function is represented and a number of simplications have been made:

- The Vietnamese canals and floodplains are now modelled with uniform values, a small bed slope is present and canals will have different depths. The bed slope does not influence the inflow to the canal much as shown in the sensitivity analyses. The bed level does influence the inflow to the canal-floodplain system, but the uniform value of the canals has been estimated by calibration of the model output to data.
- The water levels in the floodplains are in reality being controlled by pumps and weirs, while in the model the water flows over the dikerings when the water levels in the canals are high enough. This also means that the water is not able to flow out after the flood.
- The in- and outflow of the floodplains is simplified by applying a 1D-2D connection from a single canal node to a plain, while in reality water is able to flow into a plain from all surrounding canals.
- The second flood peak in the canal system caused by overland flow from the Cambodian floodplains to the LXQ and especially PoR is ignored.

However, the largest influence from the canal floodplain system on the rest of the delta is due to the storing of water in the wet season. This is important for downstream areas, because it reduces water levels and hereby floodrisk. This aspect is included in the model and can be assessed for different scenarios.

4

Hydropower effects

In this chapter the effects of hydropower on the socio-economical and ecological aspects in the delta area will be assessed. First a number of hydropower development scenarios is chosen and after that the assessment criteria are chosen. These criteria are chosen in order to represent the aspects of hydrology that have a direct effect on the socio-economical situation or ecology of the delta, as explained in the methodology. The criteria are based on the three processes analysed in the previous chapter.

4.1. Methodology

4.1.1. Hydropower scenarios

In order to test the effects of hydropower developments different scenarios have been created by the Mekong River Commission (MRC). These are chronological scenarios, that estimate the amount of operational dams. The baseline scenario is the average hydrological conditions up to 2005 (when large scale hydropower developments commenced). At the moment, the hydropower developments already passed the definite future scenario, which include a main stream cascade in the Chinese part of the Mekong. For the Basin Development Plan (BDP) 2030 scenario, all of the planned dams are constructed and operational. This is divided into a scenario excluding and including mainstream dams in the LMB, for ecological and morphological reasons (ICEM, 2010).

Two extra scenarios are added to the MRC scenarios. The first scenario indicates a shift in the hydrograph of the timing for the wet season with approximately one week (ICEM, 2010). In this situation part of the active storage areas of the dams is used to increase power production in the wet season. In this scenario the flow decreases in the rising stage of the wet season. During the highest discharges the flow is equal to the BDP 2030 scenario. During the falling stage, the discharge is increased with the same amount it was decreased in rising stage. The second extra scenario is in the case of a degraded bed level in the main branches (all branches indicated in Figure 3.11). This might occur due to sediment shortage, because of a erosion bedload transport blocking at dams and sediment mining. However, it is expected that this happens only after a long time. Summarized, the following scenarios will be assessed:

1. Baseline scenario - Average hydrological conditions up to 2005
2. Definite future - including dams operational in March 2015
3. BDP 2030 scenario - without mainstream dams
4. BDP 2030 scenario - including mainstream dams
5. BDP 2030 scenario - shift to start wet season
6. BDP 2030 scenario - bed level degraded in the main branches with 1m

The hydrological effects of the hydropower developments on the hydrograph are at the moment still being modelled by the MRC. So far, the results are known up to Pakse (around 150 km upstream of the border between Laos and Cambodia) and for the boundary condition of the model the conditions at Kratie must be known. Between Pakse and Kratie, only the 3S system (Se Kong, Se San and Sre Pok rivers) discharges into the Mekong of the mainstream. These three rivers contribute significantly to the total discharge of the Mekong, especially in the wet season. In these tributary rivers a number of hydropower dams have been planned as well, including a few with large active storage areas. In order to obtain the hydrograph at Kratie, the contribution of the 3S system to the flow of Pakse for the different hydropopwer scenarios must be calculated. This is done using the research done by Piman et al. (2016), who estimated the effects of the MRC hydropower scenarios on the flow of the 3S system. The baseline of the 3S system is calculated for the difference between Kratie and Pakse (with a phase lag of three days) averaged from 2000 to 2006.

4.1.2. Assessment criteria Tonle Sap lake

For the socio-economy of the area around the lake the agriculture and aquaculture are very important, but the area is also ecological a valuable area. The in- and outflow of the lake Tonle Sap plays an important role: First of all, the water level fluctuations cause large areas of natural floodplains to inundate during the wet season. These natural wetland areas are very important breeding places for many species, including fish (Arias et al., 2014). Behind the natural wetlands, large areas of wet season rice fields surround the lake. These areas depend on the water supply of the lake, but also of nutrient supply. The nutrients are natural fertilizer for the rice fields and flow into the lake via the Tonle Sap river (ICEM, 2010). Besides the agriculture, many inhabitants of the region around the lake are depending on fisheries from the lake (MRC, 2016) (Arias et al., 2014). Also the amount of fish in the lake, and the yearly catch, is depending on the hydrology of the lake. This is because fish migrate between the Mekong and the Tonle Sap lake every year, depending on the flow direction of the Tonle Sap river. During the dry season migratory fish use the Mekong as habitat and the flow reversal in the river initiates the migration towards the lake (Arias et al., 2014). Not only the timing of the flow reversal is of importance for the amount of fish entering the lake, but also the total volume that flows into the lake via the river. Besides that the in- and outflow of the lake is important for the water quality and nutrients (ICEM, 2010). Because of the storing function of the lake, the in- and outflow of the lake has a large influence on the rest of the delta area as well. Therefore, the contribution of in- and outflow of lake compared to the Mekong discharge will have a large effect on the downstream delta areas.

From these important socio-economical and ecological aspects, we can assess the effects of hydropower using the following criteria:

- Variation of surface area of the lake (extent of seasonal inundated areas)
- In- and outflowing flowing volume through Tonle Sap river
- Timing flow reversal
- Contribution of Tonle Sap River flow compared to Mekong discharge

4.1.3. Assessment criteria discharge distribution over the main branches

The distribution of discharge over the main branches is not a very important criteria on its own. However, it determines the water quantities available for agricultural purposes, water quality purposes and water levels in the branches. First of all the water is used to compensate for insufficient precipitation during the dry season and is subtracted from the river system. This means that the river has to supply enough water to meet the water usage demands from the surrounding areas. If the river cannot meet the water demands, potential droughts damage livelihood and socio-economy (Deltares, 2011). Besides the water quantities, also the water level in the river is important. In the wet season, too high water levels cause the river to burst outside the banks, causing uncontrolled floodings and endangering the livelihood (Partners for Water, 2013). On the other hand in the dry season, water levels must remain high enough for large vessels to navigate the main river (MRC, 2011). The discharge distribution will be assessed with the following criteria:

- 5-day averaged maximum discharge wet season
- 5-day averaged minimum discharge dry season
- 5-day averaged maximum water levels in wet season
- 5-day averaged minimum water levels in dry season
- Discharge distribution at main branches

4.1.4. Indirect consequences of change hydrodynamics in Delta

The changes in the hydrodynamics in the delta have indirect consequences for the system. These items are mainly related to morphology and water quality. As already mentioned, the bed is expected to degrade due to a decrease in sediment supply. Also the transport capacity is of influence on the degradation and the supply of sediment to the coastal areas. Due to a reduction of the peak flows (which are able to transport the largest part of the sediment transport), this is expected to decrease. Also the fine sediment supply, containing nutrients, to the agricultural areas is very important and depending on the combination of upstream supply and local hydrodynamics. Finally the salt intrusion from the saline sea water is influenced by the fresh water discharge through the branches and mixing due to tidal characteristics. The latter can derived from the discharge variation at the mouth of the branches. Salinity of the river water endangers agriculture in the surrounding areas and undesirable. If more water is discharged through the main branch the saline water is not able to enter the delta branches (ICEM, 2010).
Because the Delft3D-FM software is not completely developed for morphology and salinity, these parameters cannot be assessed using the numerical model. However, in order to estimate the secondary effects of the changed hydrodynamics, the following parameters will be assessed:

- Sediment transport capacity at the measurement locations
- Fresh water velocity at the mouth of the branches
- Tidal characteristics and stratification

4.1.5. Assessment criteria Vietnamese floodplain and canal system

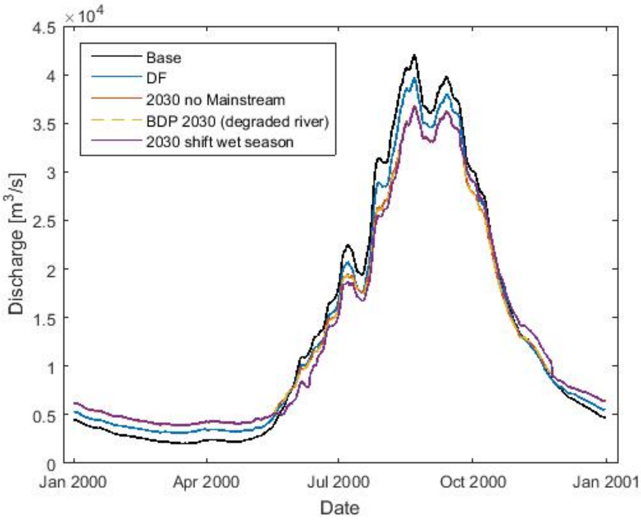
In the areas of the canal-floodplain system in Vietnam, agriculture is the most important driver for the economy. In the areas of PoR and LXQ, the most common crop is rice, which requires large quantities of water for each harvest, which are subtracted from the river (Deltares, 2011). In the wet season these lowlying areas inundate and the areas serve as water storage areas. This has two advantages, first of all the natural flooding of a floodplain deliver nutrients (natural fertilizer) to the floodplains (Hung et al., 2014), which makes chemical fertilizers unnecessary and supplies sediments which compensate for land subsidence (Schmitt et al., 2017). The second advantage is that it reduces water levels and prevents flooding further downstream in the delta, where higher valued crops and areas are located. However, in case of a large flood, the areas are flooded with several meters, which reduces the livelihood in the areas (Partners for Water, 2013). Therefor it is more desirable if the water level does not reach to high above the dikerings (where households are located) and not for a too long period. This lead to the following assessment criteria:

- Volume discharged to floodplain-canal system in LXQ triangle (= $Q_{ChauDoc} + Q_{VamNao} - Q_{CanTho}$)
- Volume discharged to floodplain-canal system in PoR (= $Q_{TanChau} - Q_{VamNao} - Q_{MyThuan}$)
- Inundation extent in PoR and LXQ
- Period of inundation above dikering height
- Maximum water level in floodplain

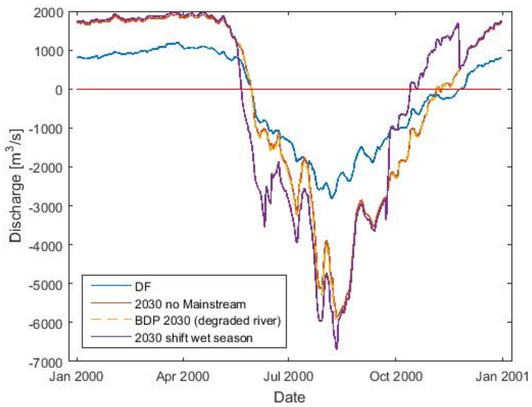
4.2. Hydropower scenarios

All of the hydropower scenarios obtain a new discharge boundary at Kratie. For the scenario with a shift to the wet season the BDP scenario has been changed, shifting the commence of the wet season around one week later, which is compensated at the end of the wet season. For the scenario with degraded branches the hydrograph of the BDP 2030 scenario is used. In Figure 4.1, the hydrographs for the different scenarios have been depicted.

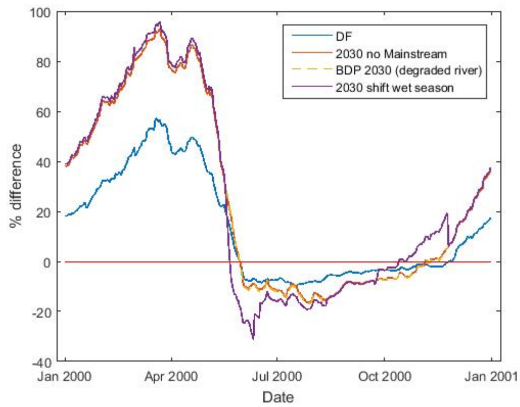
It can be seen that in the dry season the flow increases. Even though the quantitative change is smaller compared to the wet season, the percentual change is much higher, because the total flow is rather low. For the wet season it is the other way around. The scenario with the shift in the wet season has a large quantitative as percentual change during the beginning of the wet season, but after the floodwave has passed a larger percentage compared to BDP. From the Definite Future scenario (2015) to the BDP 2030 scenario, the change almost doubles, which is similar to the amount of active storage that increases (Lauri et al., 2012). Finally it can be seen that the difference between the BDP 2030 scenario with and without mainstream is very small. This is because the mainstream dams have been designed as run of river dams, with only small active storage compared to the daily flow and have therefoer little effect on the hydrograph (ICEM, 2010).



(a) Hydrographs for all scenarios



(b) Difference in discharge from baseline



(c) Percentual change from baseline

Figure 4.1: Hydrograph and changes compared to baseline for the hydropower development scenarios

4.3. Hydropower effects on Tonle Sap lake

The water level in the Mekong river increases during the dry season and decreases during the wet season in the hydropower scenarios. Because the water level difference between lake and Mekong is the most important parameter for the discharge through the Tonle Sap river, the in- and outflow of the lake will reduce. In the dry season the lake will empty less compared to the base line scenario, leaving a larger area permanently inundated. During the wet season less water flows into the lake, causing a decrease in maximum water level and a smaller inundated area. The flow reversal delays in case of a shift to the start in the wet season. In this case the water level fluctuation remains the same, but in- and out flowing volume through the Tonle Sap river decreases. In the case of degraded branches, the flow reversal is delayed for a couple of days, because the discharge has to be higher to reach the same water level. In Table 4.1 the effect on the seasonal inundated areas (difference between maximum and minimum surface area, calculated using the analytical formula used in the conceptual model) is given. Also the annual in- and outflow volume and date of the flow reversal are presented for the different scenarios.

Scenario	Seasonal inundated area [km^2]	Inflow volume [km^3/year]	outflow volume [km^3/year]	Date flow reversal
Base	$6.5 * 10^3$	42.6	70.6	24th May
Definite future	$6.1 * 10^3$	38.5	67.7	24th May
2030 without mainstream	$5.76 * 10^3$	34.9	64.8	24th May
BDP 2030	$5.74 * 10^3$	34.5	64.7	24th May
2030 - Shift wet season	$5.74 * 10^3$	34.2	63.5	30th of May
2030 - Degraded branches	$5.43 * 10^3$	29.4	63.5	27th May

Table 4.1: Assessment parameters of Tonle Sap lake for different scenarios

From these results it is clear that the lake will store less water with hydropower development compared to the case without the hydropower development. This is because the reservoirs of the dams take over the storage process from the lake Tonle Sap. This causes the contribution of the Tonle Sap River compared to the Mekong decreases, which is shown in Figure 4.2.

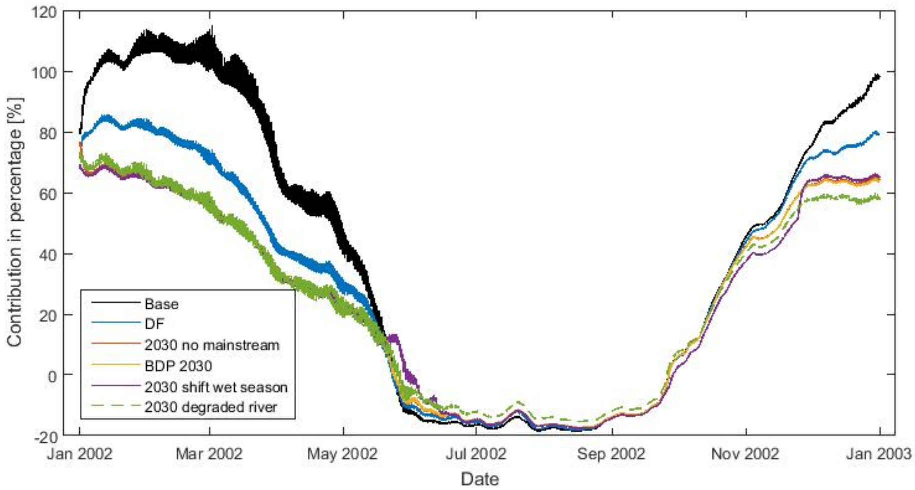


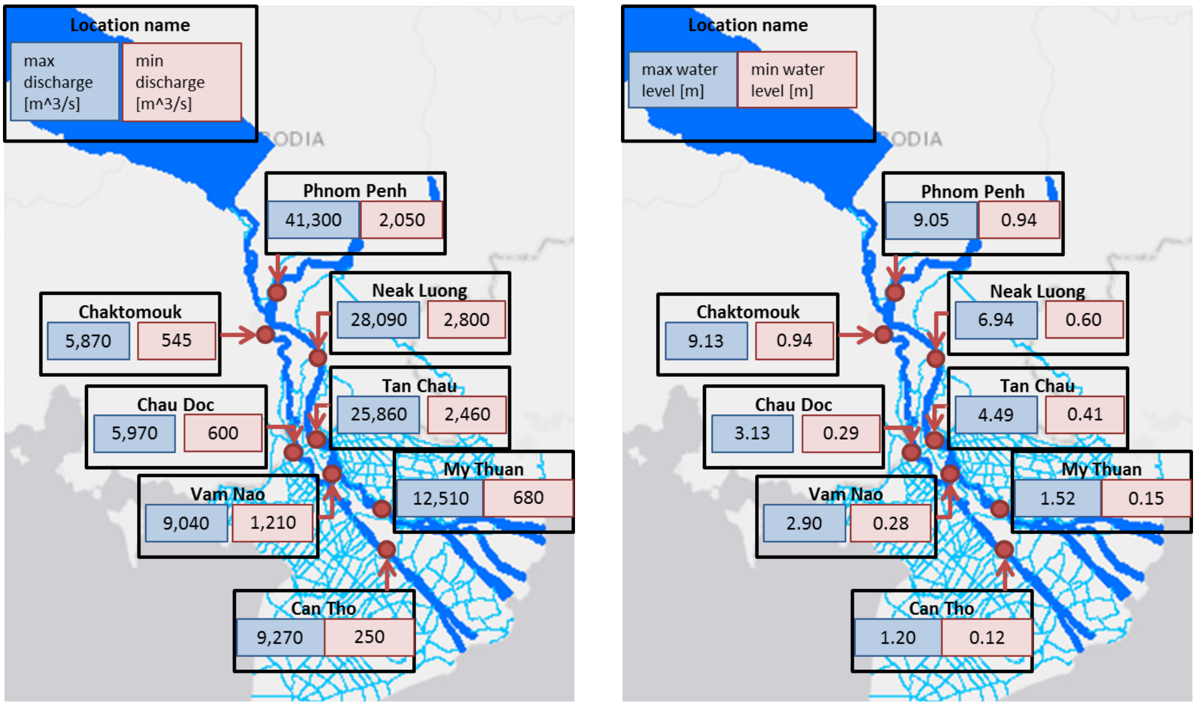
Figure 4.2: Contribution of discharge Tonle Sap River to the downstream discharge

The effects of the changed hydrodynamics can cause the following risks for the ecology and socio-economy:

- Reduction of seasonally inundated areas reduces the surface of ecological rich wetland areas. These habitats are breeding and feeding grounds for many species. This might cause a reduction in both quantity and variety of species in the area of the lake. Consequently, this affects the fisheries and hereby socio-economy as well.
- A decrease of the in- and outflow reduces the exchange and refreshment of the water in the lake. This could have consequences for the water quality.
- A reduction of the inflow reduces the amount of nutrients and fine sediments that enter the lake. This has consequences for the agriculture, since the nutrients are natural fertilizers for the lakes. An alternative for natural are chemical fertilizers, which endanger the water quality.
- The fish migration between the Mekong and the lake will also be influenced. Due to the reduced inflow volume a smaller amount of fish enter the lake via the Tonle Sap river, especially in combination with a delayed flow reversal which initiates the fish migration.

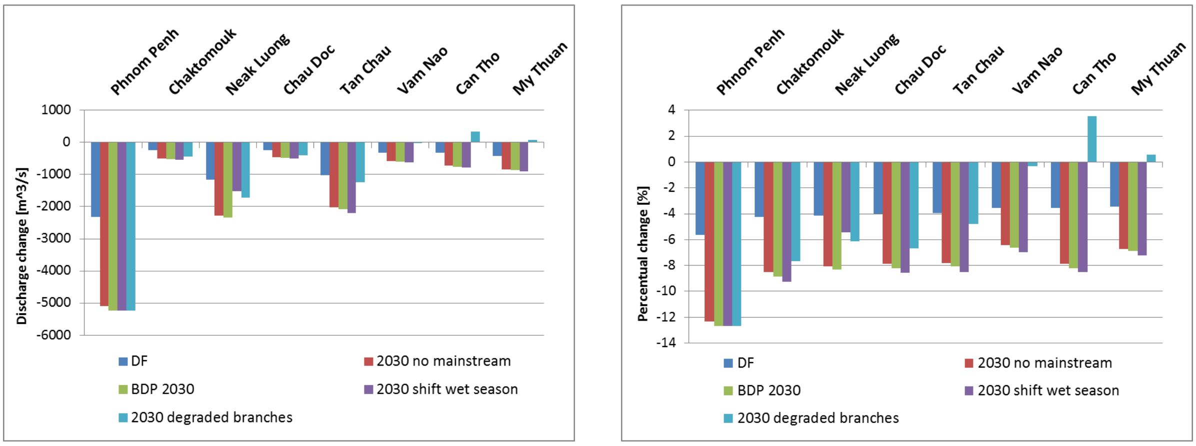
4.4. Hydropower effects on discharge main branches

For each of the measurement locations, the maximum and minimum 5-day average discharge and water level have been calculated for all the hydropower scenarios. Figure 4.3 shows the values for the base scenario and in Figure 4.4, 4.5 and 4.6 the absolute and relative changes are shown for the hydropower scenarios. In Appendix F.3 the annual curves for the discharge and water level are shown for all scenarios and locations. The BDP with a shift in the wet season has the largest changes in maximum discharge. The maximum discharge decreases with a shift in the wet season even further because the flow to the Tonle Sap lake is larger during the peak, to compensate for the later commence of filling. From the Definite Future scenario to the BDP scenario, the changes approximately double. The difference in base line are larger upstream of the bifurcation at Phnom Penh compared to downstream, because the Tonle Sap lake storage area reduces during the wet season and discharges less in the dry season. The changes further downstream decrease even further due to a changes in flow to the canal-floodplain system. In the case of degraded branches, the flow downstream of the floodplain increases even in the wet season, because less water flows to the floodplains. The relative change compared to the baseline is much smaller in the wet season compared to the dry season. However, the absolute changes are much larger and discharge decreases more in wet season than in dry season increases. The changes in maximum and minimum water level are similar in wet and dry season.



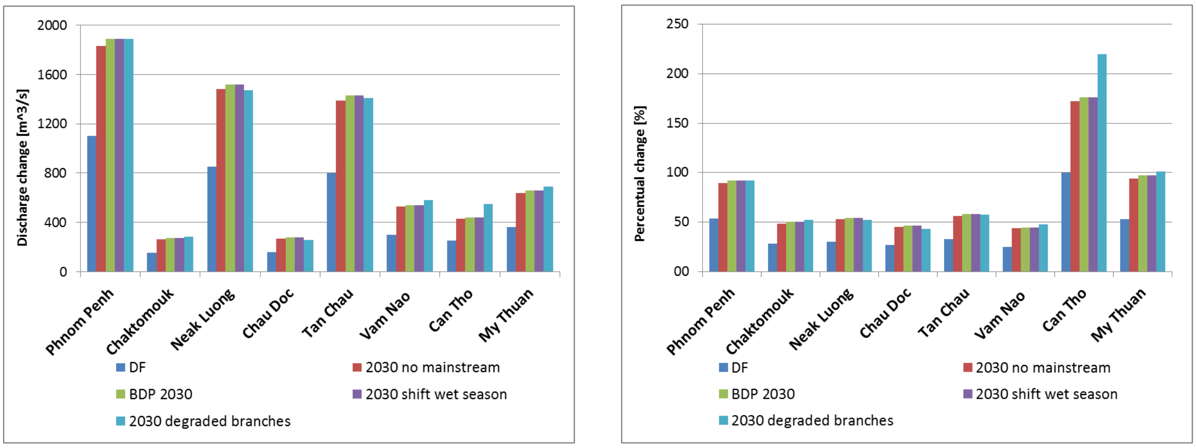
(a) Discharge (b) Water level

Figure 4.3: 5-day averaged minimum and maximum values of discharge and water levels for all measurement locations of the base scenario



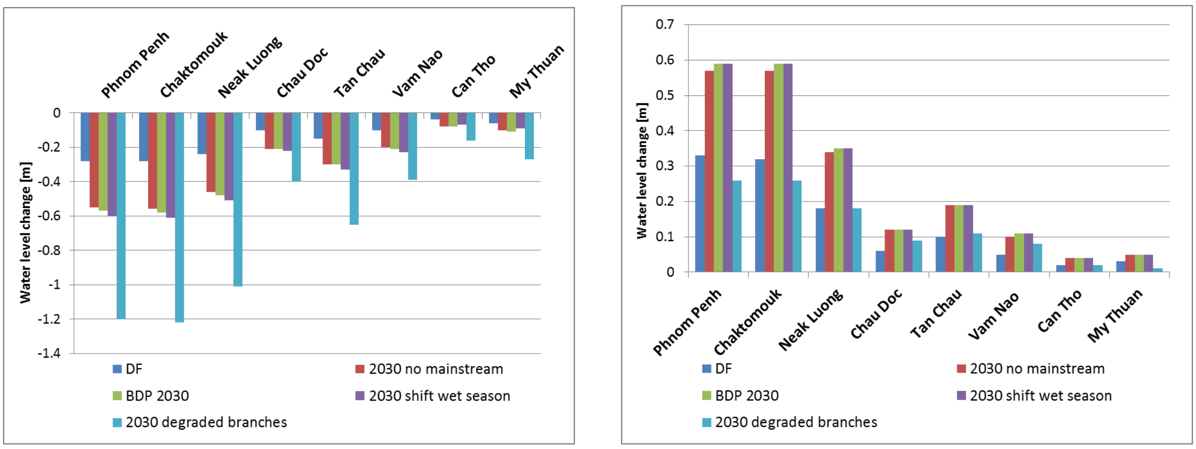
(a) Absolute change discharge (b) Percentual change discharge

Figure 4.4: Change of 5-day averaged maximum discharge for hydropower scenarios



(a) Absolute change discharge (b) Percentual change discharge

Figure 4.5: Change of 5-day averaged minimum discharge for hydropower scenarios



(a) change maximum water level (b) change minimum water level

Figure 4.6: absolute change in 5-day averaged minimum and maximum water levels for hydropower scenarios

At the bifurcations at Phnom Penh and Tan Chau, the discharge distribution changes slightly. The change in the distribution balances the outgoing distribution such that the percentual changes (for the areas upstream of the floodplains) are the same. Downstream of the floodplains the relative changes of the Bassac and the Mekong are different but the absolute changes of discharge are similar. At both bifurcations it can be observed that the contribution to the Bassac (or via Vam Nao to the Bassac) decreases compared to the distribution to the Mekong as can be seen in Figure 4.7 and 4.8.

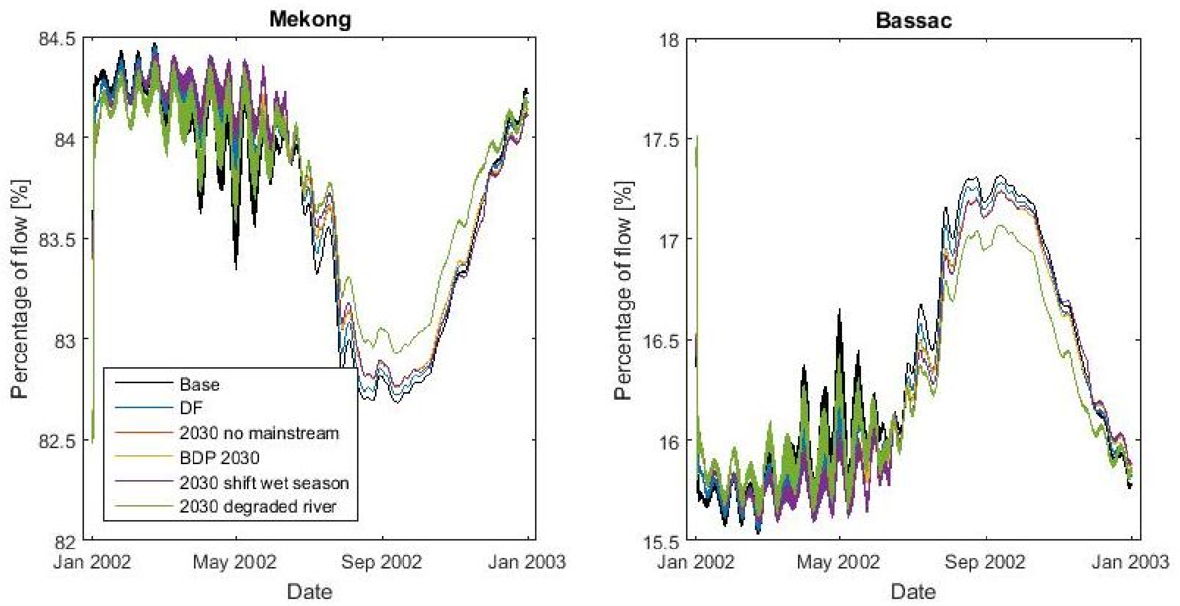


Figure 4.7: Discharge distribution for bifurcation at Phnom Penh

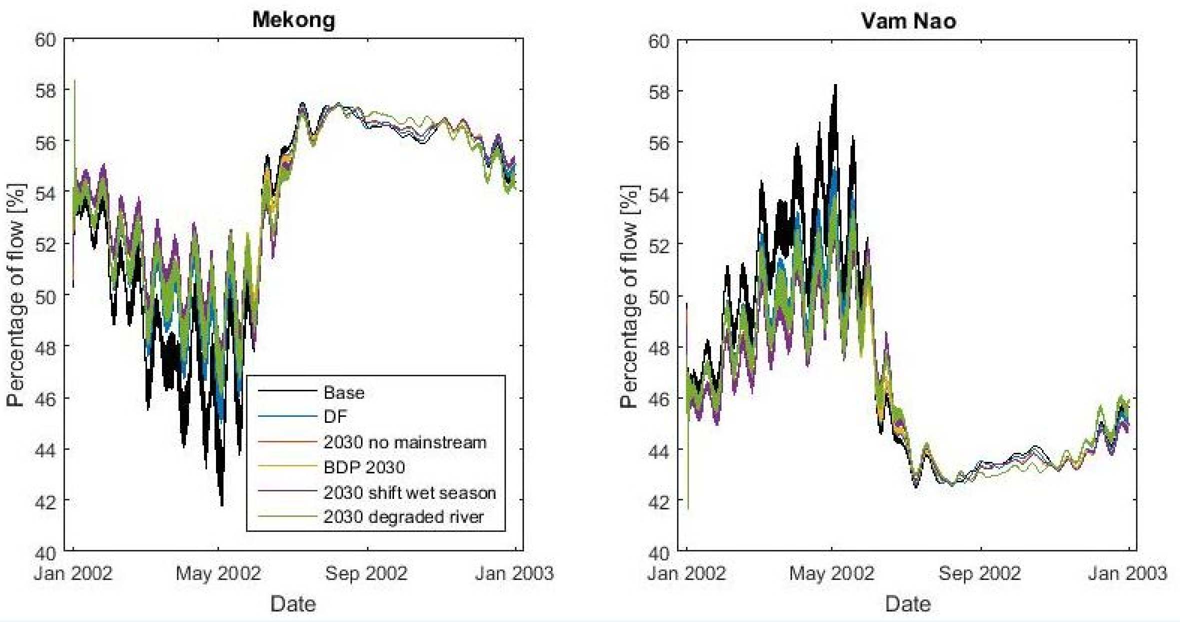


Figure 4.8: Discharge distribution for bifurcation at Tan Chau

The effects of the changed hydrograph are in terms of the socio-economical risks favourable. This is because the water availability in the dry season increases and therefore the risk of drought decreases. The peak of the discharge decreases, causing the risk for flooding to decrease. The discharge distribution shifts only slightly in order to compensate for the changed discharge, which balances the changed distribution over the branches.

4.5. Indirect effects of changed hydrodynamics

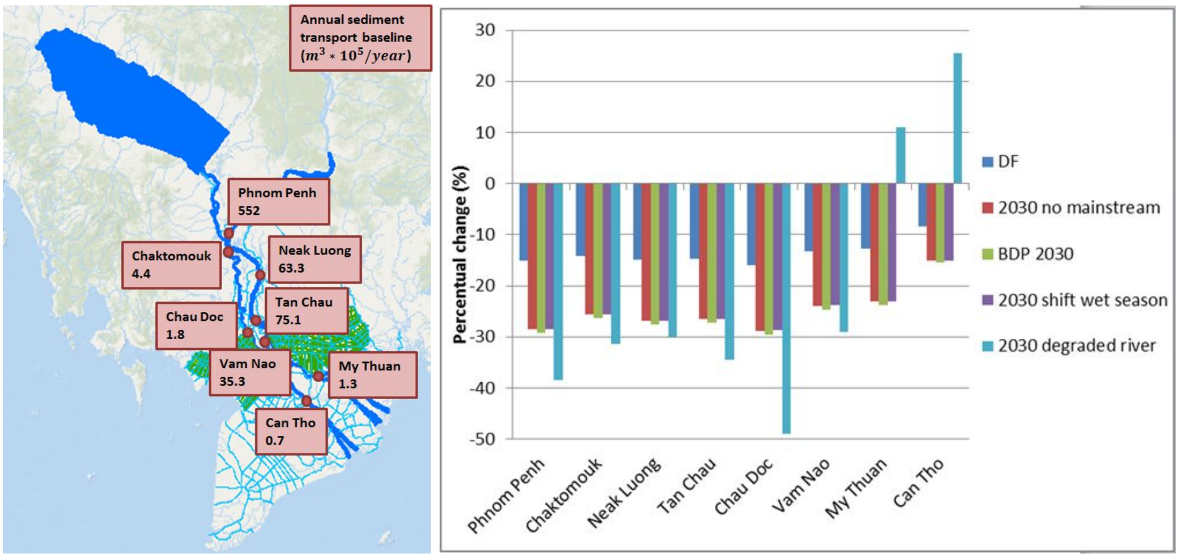
4.5.1. Bed load transport capacity

Even tough the blocking of bed material transport by the dams will affect the delta after a very long period (ICEM, 2010), the changes in hydrodynamics do have an immediate effect on the transport capacity. The bed load transport capacity is estimated from the results of the Delft3D-FM model in the measurement locations. This is done using the formula of Engelund-Hansen, which is suitable for fine to coarse sediments (de Vriend et al., 2011):

$$s = \frac{0.05 * c_f^{3/2}/(\Delta g)^2}{D_{50}} * u^5$$

s	Bed load transport rate per unit width [m^2/s]	c_f	Dimensionless friction coefficient [-]
Δ	Relative density of sediment to water [-]	g	Gravitational constant [m/s^2]
D_{50}	Median grain diameter [m]	u	Flow velocity [m/s]

Because the sediment transport is nonlinear related to the discharge, the higher flow velocities during the peak of the wet season will contribute significantly more to the annual sediment transport. In Appendix F.5, the bed load transport capacity is shown for all measurement locations over the entire year. This shows that indeed the largest sediment transport rates occur during the wet season. In the measurement locations in Cambodia, the sediment transport rate in the dry season is almost zero. Note that due to the applicability range of the Engelund-Hansen formula of $0.07 < \theta < 6$ these might be under- or overestimated by applying formula outside this range. In reality even with small flow velocities, small amounts of sediment transport occur (Hoffmans and Verheij, 1997). In the two most downstream locations (My Thuan and Can Tho) the flow reverses due to tides, which causes negative sediment transport rates in the dry season. The cumulative sediment transport rate is still in downstream direction.



(a) Baseline (b) Percentual change from baseline

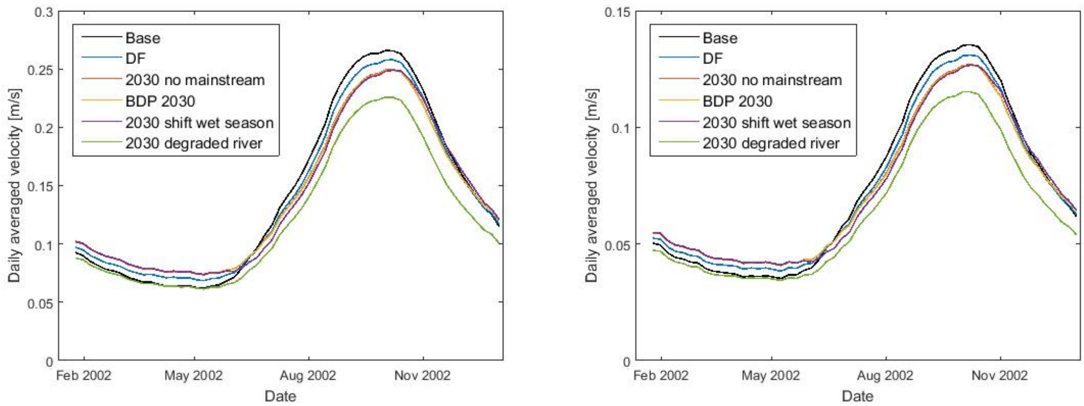
Figure 4.9: Transport capacity at measurement locations for baseline and percentual change for hydropower scenarios

In Figure 4.9, the annual sediment transport rates are given for the baseline scenario and locations and the percentual change from the baseline per scenario. It can be seen that for almost all scenarios and locations there is a clear decrease in the sediment transport capacity, due to the reduction of discharge in the wet season. For the BDP 2030 scenario, the annual sediment transport reduces from 15% - 30% for all locations, with the largest decrease upstream, which becomes smaller further downstream. In the scenario with degraded branches, the sediment transport capacity for the upstream locations reduces even further. However, for the location downstream, Can Tho and My Thuan, the sediment transport capacity increases. This is caused by the increased discharge (less water flows to the canal-floodplain system in this scenario) and the larger tidal fluctuations. Because the scenarios have upstream in the delta a larger decrease in transport capacity than downstream, the supply to the downstream branches is less compared to the transport capacity. This might cause erosion of the downstream branches, especially in the case of degraded branches, for which the transport capacity even increases in the downstream branches. This could increase potential risks for the Tonle Sap lake and floodplain areas even further.

Because the reduced sediment transport capacity in the branches, the supply of the coarser bed material to the coast will decrease. This has consequences on the coastal developments. First of all the areas around the mouth of the estuary with sandy shore lines will erode. Besides that also the height of the coastal planes, the foreshore of the muddy coastlines, further away from the river mouths will decrease. A shorter and steeper foreshore might destabilize the muddy coasts. In combination with a reduced supply of fine material to the coast, the muddy coastlines will erode as well. Erosion of the coastline endangers the mangrove forests. These ecologically important forests are the natural protection of the coastline and have a delicate equilibrium.

4.5.2. Salt intrusion

Salt intrusion is a potential risk for the downstream area of the Mekong delta, because saline water endangers agriculture. The change in fresh water flow velocity is the most important indicator for the potential risk of increased salt intrusion. In Figure 4.10 this flow velocity in the mouth of the estuaries is indicated, using a 6.2-day averaged signal. This average is chosen because in order to obtain the flow velocity for a complete tidal cycle (12 h and 25 min) with model output per hour, at least 12 tidal cycles (or 6 days and 5 hours) are necessary. The figure shows for all hydropower scenarios, except the case with degraded branches, a higher fresh water flow velocity during the dry season. In case of a lower bed level the flow velocity directed to sea is similar to the base scenario in the dry season and much lower in the wet season. Even though the river discharge is higher compared to the base scenario, the discharge is divided over a larger flow cross-section which decreases the average flow velocities to sea.



(a) Bassac (b) Mekong

Figure 4.10: Tidal averaged fresh water discharge in the mouth for different scenarios in both branches

Because the case with degraded branches shows similar average fresh water flow velocities in the mouths of the branches in the dry season, salt intrusion might increase. The flume experiments Rigter performed in 1973 showed that due to an increase of water depth the salt intrusion length increases, as can be seen in Figure 4.11. For the flume experiments, this is a result from a number of effects (Daniels, 2016):

- The fresh water velocity (seawards) and hereby advective transport towards sea decreases because of a larger cross sectional area (NB Q_f is the same in all experiments)
- An increase in flood velocity (similar to tidal velocity amplitude) as a result of an increased tidal prism, because the tidal wave is dampened less in a deeper estuary
- A larger water depth enhances density driven currents

Because the fresh water discharge increases in the case of degraded branches, the fresh water flow velocity remains the same in the dry season. If looking at the flow velocity including tidal fluctuations in the mouth,

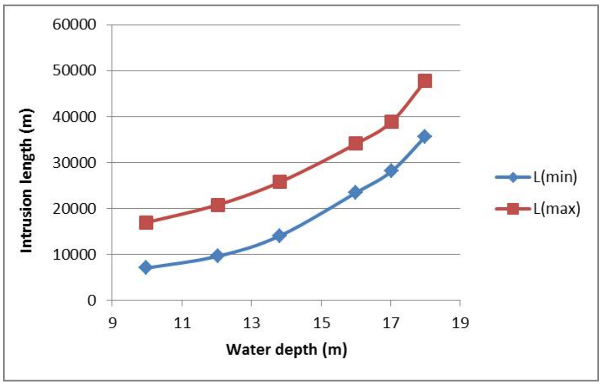


Figure 4.11: Salt intrusion length for varying water depth (results flume experiments 1973)

a difference can be seen in both dry and wet season. The positive ebb velocity (directed to sea), decreases in both cases, while the flood velocity remains similar. This means that the advective transport to sea decreases further compared to the advective transport directed inland, which results in an increase of salt intrusion. This is also the case in the Mekong branch, for which the result is shown in Appendix F.6.

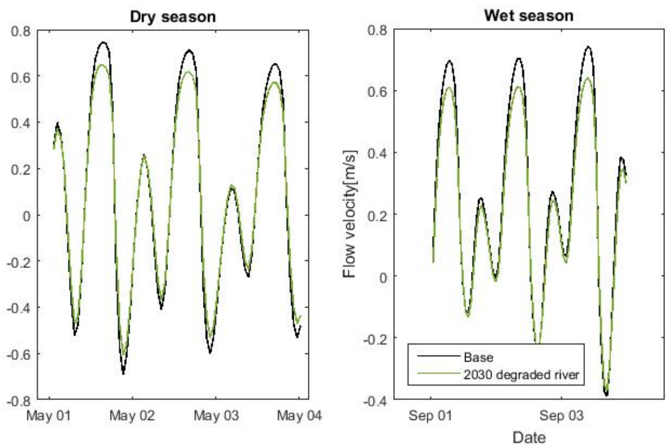


Figure 4.12: Flow velocity in mouth of Bassac for a short period in the wet and dry season

The difference between ebb velocity and flood velocity, the tidal velocity amplitude (v_0) decreases in both branches for both dry and wet season. This is in contradiction with the Rigter flume experiments, where the flood velocity (and hereby tidal velocity amplitude) increased with a larger water depth. This is because with a larger water depth the tidal prism increases, which is also the case in the Mekong Delta. The tidal prism (P_t) is described by:

$$P_t = EA_0 = \frac{v_0 T}{\pi} A_0$$

P_t	Tidal prism [m^3]	E	Tidal excursion length [m]
A_0	Flow cross-section area in mouth [m^2]	v_0	Tidal velocity amplitude in mouth [m/s]
T	Tidal period [h]		

The decrease in tidal velocity amplitude can be explained by the shape of the estuary. In the Mekong branches the mouth of the estuary is very wide and shallow, which converge to a smaller and deeper branches further upstream, while in a flume the cross-sectional area is constant over the entire flume. The decrease in bed level in the mouth of the estuary has a large effect on the cross-sectional area in the mouth, because the mouth is very wide and water depths small. Further upstream, the branches are less wide and deeper and a degradation of the branches has smaller effect on the cross-sectional area. Because the tidal prism increases in the mouth, but the cross-sectional area relative much more, the tidal amplitude in the mouth decreases. Further

upstream in the estuary, at the first observation points at My Thuan and Can Tho, the tidal velocity amplitude does increase. These observation point are located approximately 100 km upstream and not therefore not influencing the salt intrusion. The estuary remains quite wide and shallow over up till 80 km upstream, which means that in this entire area the tidal velocities will change similar as in the mouth. In Appendix F.6, the tidal velocity in the mouth and flow velocities are shown for both mouth as further upstream for a short period in the wet and dry season.
The final reason for the increase of salt intrusion length in the Rigter experiments, is the increase of density driven currents. This is difficult to assess from depth average flow velocities. However, the amount of stratification (calculated using the estuary Richardson number) in the estuary gives a good indication of the potential for density driven currents. The estuary Richardson number (see Section 2.1 for definition) is calculated for both branches and scenarios for 2nd of May and 2nd of September, the periods of Figure 4.12. The estuary Richardson number increases in the case of degraded branches for both branches and seasons. In the wet season the estuary was already stratified and the largest change will be in the seawards directed advective transport. In the dry season, the estuary was of a mixed character and especially in the Bassac, which will change to an almost stratified estuary in the dry season as well.

Branch	Scenario	Season	Tidal velocity amplitude [m/s]	Fresh water flow velocity [m/s]	Water depth in mouth [m]	Estuary Richardson number [-]
Mekong	Base	Dry	0.55	0.038	6.8	0.38
		Wet	0.43	0.126	6.8	2.65
	Degraded	Dry	0.54	0.037	7.8	0.45
		Wet	0.4	0.107	7.8	3.19
Bassac	Base	Dry	0.65	0.068	7.2	0.43
		Wet	0.47	0.254	7.2	4.33
	Degraded	Dry	0.57	0.067	8.2	0.72
		Wet	0.43	0.212	8.2	5.36

Table 4.2: Estuary Richardson number for base scenario and degraded branches scenario in wet and dry season

The hydropower developments cause higher fresh water discharge in the dry season, which would decrease the risk of salt intrusion. In the case of degrading of bed levels (because of sediment mining and reduced supply), the salt intrusion is expected to increase, because ebb flow velocities in the mouth and tidal mixing reduce. However, the expected sea level rise has not been taken into account in this assessment. Because of sea level rise, the average sea directed flow velocities would reduce even further (increase of A_0), causing the potential for salt intrusion to increase. The effects of density driven currents cannot be assessed based on averaged velocities and might have a large influence. However, because the estuary Richardson number increase in all cases, the branches become more stratified, which would enhance density driven currents. The dispersion in analytical models is calibrated on salinity measurements (Nguyen, 2008) and not all dispersion formulations for 1D model respresent the effects of an increased water depth well (Daniels, 2016). In order to assess the density driven currents and salt intrusion effects in more detail a 3D Model is recommended.

4.6. Hydropower effects on Vietnamese floodplain-canal system

The changes of discharge through the main branches also have consequences for the floodplain canal system and the inundation of the floodplains, because the amount of discharge to the floodplain canal system is directly related to the water level in the Mekong. This causes the inflow to the LXQ and PoR to increase during the dry season and decrease during the wet season as can be seen in Figure 4.13 and 4.14. However, the increase of discharge to the canals in the dry season is much smaller compared to the amount of water entering the floodplain area in the wet season. This means that also the storage of water in the floodplain areas reduces during the wet season. The figures also show that in case of degraded branches the discharge to both floodplain areas significantly decreases and even during the begin stage of the dry season a decrease of the inflow will occur.

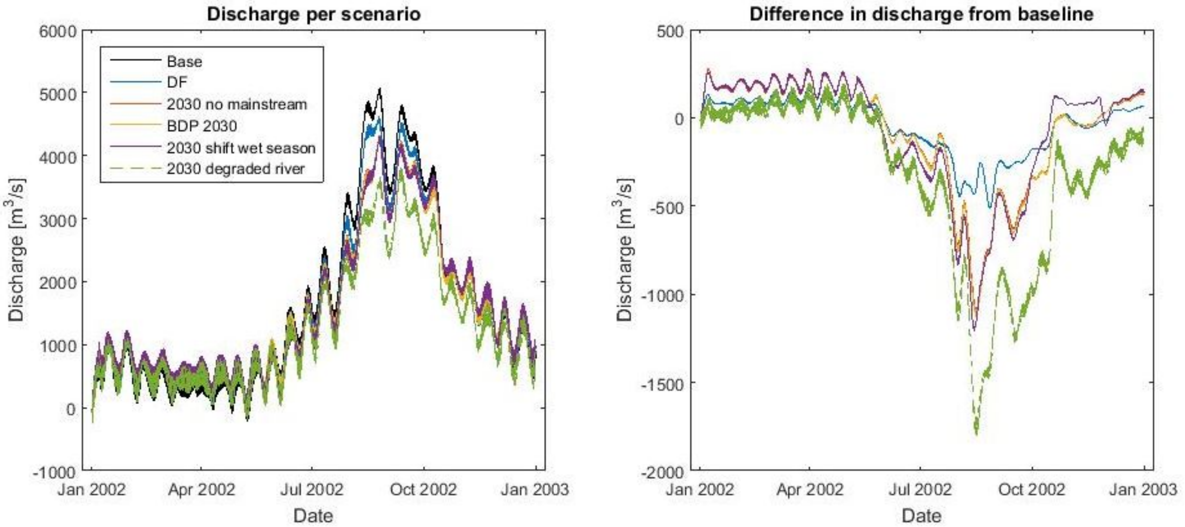


Figure 4.13: Discharge to the PoR floodplain canal system for the different hydropower scenarios and compared to baseline

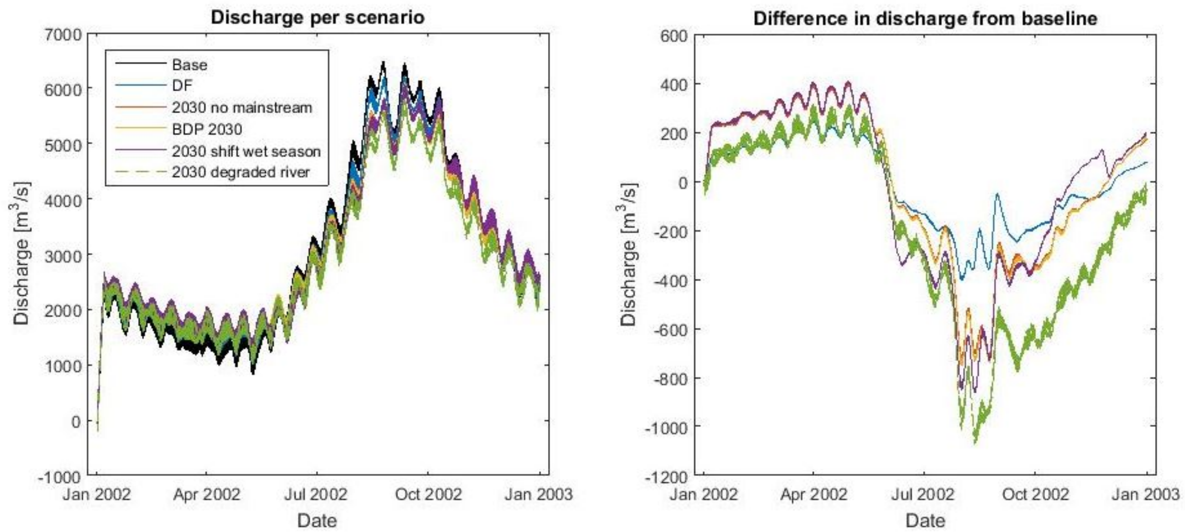


Figure 4.14: Discharge to the LXQ floodplain canal system for the different hydropower scenarios and compared to baseline

From Table 4.3 it can be concluded that indeed the amount of water in the floodplains decreases. Not only in extent (a decrease of 30% in the Plain of Reeds), but also the maximum water level height. The maximum water level height and period occurs in the area the closest to the river. Areas further away from the river are less likely to inundate in the case of the hydropower scenarios. The period that the water remains above the dikering level in the PoR is shortened as well. The amount of inflow and the extent of inundated areas changes less in the area of the LXQ compared to inflow of the PoR. This is caused because even though the percentage of discharge to Chau Doc (Bassac) and Tan Chau (Mekong) changes equally, the water level in the Mekong drops more than in the Bassac. The figures indicating the maximum flooding extent and depth in both PoR and LXQ are shown in Appendix F.4.

Scenario	Inundated area PoR [km^2]	Inundated area LXQ [km^2]	maximum water level in PoR [m]	Inudation period above dikerings [days]
Base	310	190	3.42	89
Definite future	250	160	3.31	78
2030 without mainstream	200	160	3.22	73
BDP 2030	200	160	3.22	73
2030 - Delayed wet season	200	160	3.24	73
2030 - Degraded branches	160	140	3.02	62

Table 4.3: Assessment parameters of Floodplain canal system

The consequences of the changed in- and outflow of the floodplain areas are both positive as negative.

- The increased discharge in the dry season increases the water availability in the period that the water demands are highest, which is favourable for the agriculture and livelihood of the area. Also a decreased maximum water height in the area and shorter inundation period (above dikering level), increases livelihood and decreases the potential hygienic risks.
- Due to a reduction of inundated areas, less nutrients and fine sediments will be spread over the area to fertilize the agricultural areas. If farmers start using chemical fertilizer this will decrease the water quality. Also due to a reduced volume of water flushing the canal system, water quality might reduce.
- The areas will subside when the decrease of inflowing sediments cannot compensate for the natural land subsidence. Due to the groundwater extractions the land subsidence accelerates even further. This will lead to increased flood risk on the long term.
- The seasonally inundated areas are important habitats for many species, a decrease of these areas might endanger a number of these species, which could also have consequences for fisheries.
- Due to a reduced storage in the floodplains less water will be available during the dry season. This is not taken into account in the model, because floodplains are not able to empty below dikering level

4.7. Discussion on the assessment of hydropower effects

4.7.1. Hydropower development scenarios

For the assessment of the hydropower scenarios, a number of scenarios based on the expected developments of the hydropower dams in the LMB has been chosen by the Mekong River Commission. However, there are many uncertainties in these hydropower scenarios: First of all, the development scenarios are based on planned dams; there are still dams that have not been fully designed or licensed for construction by the MRC. So far, the hydropower developments and construction of dams proceed slower than in the estimated scenarios that are used for the assessment (MRC, 2016). Also a number of planned dams meet a lot of resistance, especially from nature conservation organizations, and dam designs are being adjusted in order to mitigate potential negative effects. However, the focus of this resistance is aimed at the mainstream dams, which have little impact on the hydrograph. At the moment there is still a lot of ongoing research and discussion about the cumulative impacts of hydropower developments. When more knowledge is available, the regulations for construction of hydropower dams might become stricter and less dams than planned might be constructed.

Apart from the uncertainty of the eventual developments, the predicted scenarios have been based on long term averages. The contribution of the 3S system with hydropower developments is based on maximum and minimum changes of a research and due to the large contributions of these tributaries this might lead to inaccuracies in the scenarios. However, in reality there are interannual fluctuations, which could be even larger deviations from the average than the difference caused by the predicted hydropower developments. These fluctuations will decrease as well, because peak flows are dampened by the hydropower dams. The effects of the hydropower on the average situation has been assessed, but consequences from the decrease in variability in the hydrograph are not taken into account in the assessment. Finally, the MRC scenarios did not take a shift in the timing of the wet season into account, which is why the extra scenario was introduced. The potential shift in the wet season has been estimated very roughly in order to assess whether it does make a difference, for example on the in- and outflow of lake Tonle Sap. Also the estimate of the shift in the wet season could be severely underestimated, since only a small part of the active storage volume in reservoirs (1/5 dams using 1/3 volume of active storage) is assumed to be filled during transition to the wet season. The operational rules of many of the dams remain very uncertain and estimations of seasonal fluctuations of stored water in reservoir difficult to make.

As for the uncertainties in the hydropower scenarios, there are many other future developments which are not taken into account in this assessment, such as sea level rise and climate change. Not only changes in natural environment, but also the human interferences in the complete Lower Mekong Basin will increase, which is already discussed in the literature review. The development of these aspects in the next 30 years are difficult to predict, because of the dependency on many factors. Important factors that will affect the hydrological processes in the delta area in the future are:

- **Climate change** - As a result of climate change it is expected that both storms and droughts will become more frequent and intense. This will create even more seasonal and interannual variability in the discharge of the Mekong. The reservoir dams are able to reduce these effects, because of the temporal storage of water in the reservoirs.
- **Sea level Rise** - Because the Mekong delta is a very low lying area with a small slope, sea level rise would have a large effect on the hydrodynamics in the delta. The tidal influence would reach further into the branches and the backwater effects will be noticed over longer distances. In the downstream areas, sea level rise would increase flood risk, since it is more difficult for the river to discharge to sea. This would increase water to flow to the floodplains during the flood season. The combination with a decreased flow through the main branches and higher water levels at sea would increase salt intrusion in the main branches and hereby endanger the agriculture in the area. Due to sea level rise the risk for coastal erosion increases, especially in combination with a reduced sediment supply.
- **Irrigation and water usage** - In the Vietnamese delta the irrigation potential is already fully utilized, but in Cambodia and Laos there is still a large potential available for irrigation. The irrigated areas are expected to expand, because of growing food demands due to population and economical growth. Increase of irrigated area would reduce the available amount of water during the dry season downstream, which is undesirable since water demands are growing due to intensified cultivation and population growth. This also causes the amount of ground water extraction to increase and consequently increased subsidence.
- **Sediment extractions** - Even tough the volumes of extractions are difficult to measure, it is estimated that the amount of sediment extractions is still increasing. At the moment there are few effective regulations for sediment mining in the LMB. Because sand and gravel are important construction materials, the amount of extractions is not expected to decrease in the near future. Since the amount of extractions is larger than the total transport capacity in the Mekong at the moment, erosion and bed level degradation are expected.

4.7.2. Assessment of effects

Because a number of processes is not included in the model (or underestimated), this has consequences for the assessment of the effects of hydropower development. First of all the initial water level in the river and lake Tonle Sap are for all scenarios similar. In case of a changed hydrograph, the water level in the lake Tonle Sap would be lower in the end of December, which would decrease the outflow during the first months of the year as well. This would reduce the increase of available water in the dry season, especially in the case of degraded branches. Also the calculated difference in the discharge through the Tonle Sap river, is affected by the model properties. This would reduce the outflow of the Tonle Sap lake in the dry season even further. In reality, a decrease in the wet season inflow of the lake, would mean that the discharge in the rest of the delta, reduces less than the model indicates.

In case of a decrease of the maximum water levels the operations of sluice gates and pump in the canal floodplain system, will adapt to new discharge regime, for example to open the gates with lower water levels. In order to assess the inundation of the floodplains in more detail, the model has to be developed further, including operational rules. In the case of the degradation of branches the change will be largest, because more water will be pumped into the floodplains, hereby increasing the discharge to the floodplains. This would increase potential risk of salt intrusion even further, because less fresh water is discharged to sea through the

main branches.
Several studies show that the salt intrusion is expected to increase due to hydropower developments. In this assessment, only the scenario with degraded branches indicated an increase of expected salt intrusion. The first part of the assessment was based only on the fresh water flow velocity in the mouth of the estuary. Only for degraded branches the flow velocity did not increase in the dry season and the changes of tidal characteristics and stratification have been assessed for this scenario as well. These indicated an increase of the salt intrusion, which could be predicted with a 1D model. For a more detailed view of the effects a 3D model is necessary, because of the change in dispersion processes such as stratification and density driven currents.
In order to make a better assessment of effects on morphology due to the changes in hydrodynamics in all areas of the delta, a numerical model is better suited compared to analytical equations. However, at the moment the Delft3D-FM software is not completely developed with respect to morphodynamics. In addition, to calibrate morphodynamics in a model, a target is necessary that represents the mophological changes under hydrological conditions. For this, more detailed bathymetry data in both time and space is necessary. The suspended sediment plays an important role in the morphodynamics in the coastal region as well. However, there is still no consent on what the actual suspended sediment supply is. This is caused also by the changes in conditions from upstream.

There are both negative as positive effects due to hydropower scenarios. For example, the reduced flood risk is a positive effect, but for many people the decreased flooding and supply of nutrients is a negative side effect. Also the increased water supply in the dry season is a positive effect, but if this keeps up with the increasing agricultural production and water demands is uncertain. Due to the large scale of the area and the amount of people affected by the changes it is difficult to say if there is a cumulative negative or positive outcome. If the cumulative effects of the developments are assessed, it important to include the ecological effects as well. Due to the reduction in natural floodplain inundation, it is expected that many valuable habitats are lost. This would in return also affect the socio-economy in terms of decreased fisheries.

5

Mitigation of potential risks

Now that the effects on the delta due to the hydropower scenarios are assessed and potential risks determined, the final objective of this research is to explore potential mitigation measures. These mitigation measures focus mostly on what can be changed in the delta to reduce the potential risks as consequence of the changed hydrograph.

5.1. Methodology

First all the potential risks, following from the effects from the previous chapter, are listed and ranked based on ecological and socio-economical effects. For each risk it is determined how it is best to deal with it, for which there are three possibilities:

- **Avoidance** - Avoid the potential risk by (large-scale) planning. This will we be applied as much as possible and should also be applied in the case that no mitigation or compensation is possible
- **Mitigation** - Reduce negative impact by local (in time or space) measures. If negative impact cannot be avoided, the second step is to see what can be changed in the design or at the location of impact to reduce potential risks
- **Compensation** - Compensate for the negative impact. When avoiding or mitigation is not possible, it is necessary to compensate for potential risks. This could be applied both for ecological as socio-economical risks, for example by creating new nature areas or helping impacted communities to relocate or find another profession. However, this is the least desirable solution

When for each risk, it has been determined whether avoidance, mitigation of compensation should be applied, the focus will go to the risks that need or can be mitigated. Here we assume that the large-scale hydrological changes are unavoidable, because (most) planned dams will be constructed. For this there will be two steps in coming up with mitigation measures: Based on the important parameters of a process, mitigation measures are proposed.

Modelling of mitigation measures

In order to test the effectiveness of the proposed measures, the mitigation measures are applied using the BDP 2030 scenario and their effects are compared to the baseline. Using the model, local changes in for example bathymetry will be tested, using the same assessment criteria as for the assessment of the effects. First the effects on the subsystem are tested. If a measure seems to be effective on the specific subsystem, the effects on the whole delta system can be assessed using the model.

5.2. Mitigation Tonle Sap lake

5.2.1. Potential risks and strategy

In the area of the Tonle Sap lake all the risks are related to the reduced in- and outflow and hereby smaller water level and inundation fluctuations. Besides that also a potential shift to the wet season is seen as a potential risk for fish migration patterns. These effects are direct consequences of the changed hydrograph, due to seasonal fluctuation of storage in reservoirs. It is not expected that operational patterns of dams will be adapted to avoid potential risks because of different priorities of energy companies compared to environmental institutions and the transboundary effects. Therefore the decrease in water level fluctuation in the lake Tonle Sap should be mitigated.

5.2.2. Mitigate decrease in water level fluctuations

In order to mitigate the decrease of annual fluctuation in the water level, it is necessary to obtain a higher discharge to (and after the wet season from) the lake, with the same water level in the Mekong. It is also possible to increase water levels in the Mekong during the wet season and decrease water levels in the Mekong during dry season to increase the water level difference. In order to obtain a higher in- and outflowing volume the following mitigation measures are proposed:

- Deepening of the Tonle Sap river with 2 m - By increasing the cross-sectional area of the Tonle Sap River, the flow for the same water level difference for both inflow and outflow is expected to increase.
- Widening of the Tonle Sap river with on average 150 m - Increasing the cross-sectional area of the TSR.
- A shortcut canal from further upstream of the Mekong to the lake - Since it is connected to the Mekong further upstream than the bifurcation, the inflow water level is higher and also because it is shorter, it would be able to flow to the Mekong in larger amounts compared to the Tonle Sap river. The canal has a length of approximately 80 km and a bedlevel from +10 m m.s.l to +7 m m m.s.l at connection with the lake, causing water to flow in only during the highest water levels in the rising period. The location and bathymetry can be seen in Figure 5.1. The width of the canal is 100 m.
- Controlling tributary inflow - Since the water level is also determined by the inflow of the tributaries, controlling this inflow might also contribute to increase water level fluctuations. The control can be done with dams planned in the tributaries to the lake. The discharge is reduced in the beginning of the wet season. This would enhance flow velocities to the lake, because it reduces the water level. During the final rising period this retained discharge is released in order to increase the water level in the lake further.

In order to change the water level in the Mekong, only very expensive methods are expected to work. This is because, due to differences in the effects in the wet and dry season and to prevent flooding, only a movable solution is suitable. However, due to the high flow velocities, high sediment concentration and transport and the large geometry of the Mekong, movable solutions would be very costly structures. Besides, the effect of a moving structure is difficult to assess using the Delft3D-FM model. Therefore, these solutions are not considered. The effects of the proposed mitigation measures are listed in Table 5.1. The graphs showing the water levels in the lake and the discharge through the Tonle Sap river can be found in Appendix G.

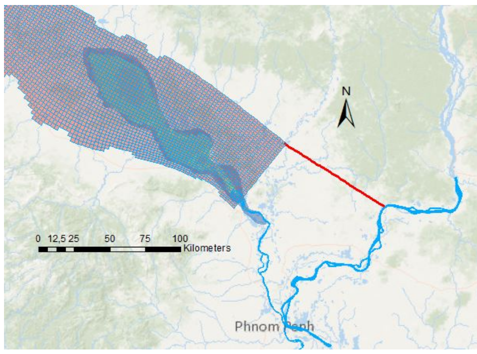


Figure 5.1: Shortcut canal implemented in model

Scenario	Seasonal inundated area [10^3 km^2]	Inflow volume [km^3/year]	outflow volume [km^3/year]	Date flow reversal
Base	6.50	42.6	70.6	24 May
BDP 2030	5.74	34.5	64.7	24 May
Deeper Tonle Sap River	6.23	39.1	72.3	19 May
Wider Tonle Sap River	6.10	38.3	71.2	21 May
Shortcut canal	5.82	32.8 (Tonle Sap River) 3.9 (shortcut canal)	66.2	24 May
Controlled tributaries	5.75	34.9	64.8	23 May

Table 5.1: Assessment parameters of Tonle Sap lake for mitigation measures

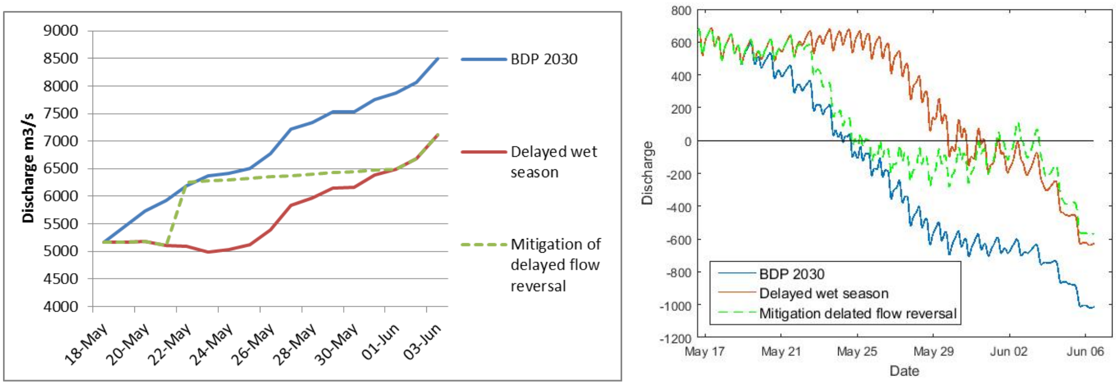
None of these mitigation measures will increase water levels to the same amount as the Base scenario. However, the measures to deepen or widen the Tonle Sap River and create an extra shortcut canal do show improvement. Especially increasing the flow cross section of the Tonle Sap River by deepening or widening is effective, with a higher discharge through the Tonle Sap river. This causes the water level to drop around 40 cm more compared to the BDP scenario and to increase almost 25 cm at the peak of the wet season. Because of a lower minimum water level in the lake, the flow reversal also occurs a couple of days earlier.
From the beginning of July to the end of October water is discharged through the shortcut canal, with a maximum of almost 800 m^3/s. This causes an increase of the maximum water level of 10 cm. Because of this water diversion, the water level at Phnom Penh is lowered with a maximum of 15 cm. In October, there is still a discharge through the canal, while at the same time the flow has reversed back in the Tonle Sap River. The inflow of the canal during this period is much smaller compared to the outflow via the river.
The shifting of discharge by controlling the tributary inflow has only very minor influence. The water level fluctuation remains the same, but in- and outflow volume through the Tonle Sap river increase slightly. This is because the total flow of all tributaries has quite a large influence, but this comes from 11 tributaries and dams are planned in a few. Therefore, only a small change in the tributary inflow is possible.

5.2.3. Mitigate delayed flow reversal

There is little that can be done in the delta area itself to initiate the flow reversal, because it it depending on the difference in water level between the Mekong and the lake. However, as was shown in previous mitigation measures, the control of tributaries and deepening of the Tonle Sap River expedite the flow reversal as well. Another solution is to increase the water level in the Mekong in the beginning of the wet season by changing operations of dams upstream. This can be combined with sediment drawdown flushing of a mainstream cascade in order to release more water at beginning of wet season to initiate the flow reversal. This drawdown flushing is currently under consideration at the MRC in order to decrease sediment blocking by the main dams and empties a reservoir in a short term of 1-2 days. The volume of the floodwave can be calculated following these steps:

- First step is to obtain the expected minimum water level in the lake before the flow reversal. From the BDP scenario this is 1.88 m a.m.s.l., but in reality this might be different due to inter annual fluctuations. Then keeping in mind a minimum head difference between the Mekong and the lake, the necessary water level in the Mekong can be estimated.
- From a stage discharge relation at Phnom Penh and sinks and sources of discharge between Phnom Penh and Kratie, the discharge at Kratie which is necessary to initiate the flow reversal can be determined. This discharge needs to increase slightly over the period of the increased flows in order to prevent a flow back reversal. The extra flood volume must be spread over a period until the normal flow conditions exceed the discharge plus increase over time.
- The travelling speed of the floodwave from Kratie to Phnom Penh can be estimated assuming a prismatic channel as $C_{HW} = \frac{3}{2}\frac{B_c}{B}U$, which is around 1.5-2 days. The drawdown flushing of the mainstream dams, must be planned such that the floodwave arrives at Kratie around 2 days before the flow reversal in the Tonle Sap River must occur.
- The extra volume necessary for the floodwave can be calculated by multiplying the extra discharge by the time this extra discharge is necessary. This means that a larger shift in the wet season, requires in a longer period of increased flows and a larger flood wave volume, which might not be available from the storage of the mainstream dams.

The sediment flushing increases the flow for only a very short period and in order to prevent the flow to return back to outflow it is necessary to increase the flow for a longer period (at least for one week). The volume of the flood wave from a sediment drawdown in the mainstream cascade might not be enough to compensate for the filling of the large tributary reservoirs. In this case the large active storage area, which is present in the current design of the Sambor dam (the dam closest to Kratie) can be used to spread the expected flood wave over a longer period. Besides, it can increase the available water, if the reservoir is completely filled at the end of the dry season, with 465 million m^3. In Figure 5.2b, the discharge at Kratie in the beginning of the wet season is shown for the BDP scenario, the BDP scenario with a delayed start of the wet season and the proposed floodpuls to initiate the flow reversal are shown. In this case the necessary discharge to initiate the flow reversal is around 6,250 m^3/s, increasing with 25 m^3/s each day. The volume of the flood wave for this situation is 640 million m^3. On June 1st, the discharge of the delayed start in wet season has increased enough and no extra volume is necessary to maintain a flow in the Tonle Sap river directed to the lake.



(a) Discharge at Kratie (b) Discharge through Tonle Sap River

Figure 5.2: BDP scenario, scenario with a shift in wet season and the mitigation floodpuls in order to initiate flow reversal

In Figure 5.2, the resulting effect of the floodpuls is shown with the green line. This shows that indeed the flow reversal occurs on the same date as for the BDP scenario. Using a floodpuls, the delayed flow reversal can be antedated by increasing the discharge temporarely. However, after the flow reversal occurs, it can be seen that the flow becomes positive around June 2nd, indicating an outflow of the lake again. This decrease in discharge to the lake is also shown in the other scenarios and is caused by the tidal influence. At this moment a neap tide is present at sea, which enhances the flow to the downstream branches. Because the level in the Tonle Sap lake has risen slightly in the case of the floodpuls, which causes the flow to reverse back for a short period. This must be prevented and not only the water level difference between the lake and river must be taken into account, but also the tidal cycle. This can also be compensated by a larger daily increase, for example 50 m^3/s, which requires a larger volume of the floodwave.

5.2.4. Effects mitigation measures on downstream delta

The deeper and wider Tonle Sap River, increases the outflow during the falling stage of wet season and beginning of the dry season. This causes the floodplain inundation to extent, since the water levels remain higher in the downstream branches for a longer period. However, due to this increased outflow, less water is available for the second half of the dry season in which the lowest discharges occur. Also during the inflow stage of the lake the discharge in the downstream branches decreases.

The effects of a shortcut canal on the downstream branches are smaller, because it only affects the discharge in the wet season. This causes a small decrease in the downstream branches during the rising stage of the wet season. More water is stored in the lake Tonle Sap with this shortcut canal, causing the discharge after the wet season is slightly higher compared to the BDP scenario. The graphs for the effects on the downstream branches for all measurement locations can be found in Appendix G.1.1.

5.3. Mitigation discharge distribution branches

5.3.1. Potential risks and strategy

For the discharge distribution in the branches there were no direct negative effects, since a decreased wet season flow reduces flood risk and the increased dry season flow reduces drought risk. However, the secondary effects of reduced transport capacity and salt intrusion, especially in combination with degraded branches (which is caused by a combination of reduced sediment supply and transport capacity and sediment mining) are potential risks. Increase of salt intrusion both via the main branches as via groundwater flows endangers agricultural production. Because mitigation of degraded branches would require many measures spread over the entire delta area, this is undesirable. Therefore, large scale morphological changes should be avoided as much as possible. Increased salinity would preferably be avoided, but mitigation measures might reduce costs and other negative impacts.

5.3.2. Plan of approach to avoid bed level degradation

In order to reduce the potential for degrading of the branches the reduction of available sediments must be minimized. This can be done only by policy implementation from the Mekong River Commission on the following aspects:

- Reduce the amount of sediment mining in the entire Mekong delta on short term. In order to accomplish this, stricter regulations for sediment mining cooperations must be arranged by the MRC. Besides the regulation also a better monitoring system for sediment extraction is necessary.
- Reduce sediment blocking at main dams and also introduce stricter rules for sediment management in large tributary dams, which did not obtain a license yet. To reduce the blocking of bed material, sediment bypasses can be applied or shallow reservoir basins can be dredged and sediment redistributed downstream of the dam. In order to maintain suspended sediment loads, retention times in reservoirs can be decreased or sediment management options such as flushing can be applied.
- Increase the monitoring of large scale bed level changes in order to keep track of the erosion rates and stabilize erosion areas locally. Besides monitoring of the bed, the suspended sediment concentration in the delta can be monitored in order to optimize dam operations and maintain sediment loads to delta.
- If the branches in the downstream erode due to increased transport capacity it can be possible to increase the discharge in both wet and dry season to the floodplain and canal system by lowering bed levels in the canals. However, this will have consequences for the salt intrusion as well.

5.3.3. Mitigation measures salt intrusion

Because the salt intrusion is expected to increase in the case of degraded bed levels of the branches and sea level rise, measures should be taken to mitigate the risk of increased salinity in the delta branches. There are a number of local meausures that can be taken to decrease the potential for salt intrusion in the delta branches:

- Creating a stair case bottom profile in the branches, which has a constant bed level profile, with sharp transitions to higher bed levels instead of a bed level gradient. This has been applied in the Rhine delta as well (Kuijper and van de Kaaij, 2009) and reduces salt intrusion, because the sharp transitions block the saline water in the lower half of the water column better than a bed level gradient. In the Mekong this is can be applied only in a small extent, because water depth is already small in the mouth of the estuary. However, in the Rhine delta the bottom profile must be maintained regularly because of sedimentation (Kuijper and van de Kaaij, 2009). In the Mekong delta, sedimentation rates will be even higher compared to the Rhine delta, because of the high sediment loads. To apply this measure in the Mekong as well, the feasibility must be investigated.
- Reduce the cross-sectional area of the river in the river by constructing a sill (or movable sill which can be lowered in wet season). This blocks the water with higher salinity concentrations, which is located mostly in the lower half of the water column. Movable sills are applied in lock entrances as well for this reason (Boeters, 2012). Besides, it increases the fresh water flow velocity directed to sea.
- In shipping locks between saline and fresh water bodies, air bubble screens prevent saline water from entering the fresh water body. This is because the upward flow of the air bubbles seperates the saline water in the lock from the fresh water (Boeters, 2012). This air bubble screen can be placed in a location from where saline water is undesirable for short periods. However, this has not been applied in a river and the effect in combination with flowing water is unknown. Besides, the air bubble screen require quite some energy especially in case of a very wide river branch.
- Placing groynes along the side of the river to increase the turbulence and increase fresh water velocity to sea. This method is applied in the Dutch Rhine delta and is also suitable to increase navigability (Verkerk et al., 2010). This is also applicable in the Mekong delta, but more research is necessary on sedimentation between the groynes and the consequences for flood risk during the wet season by decreasing the discharge potential.
- Increasing the roughness of the bed to increase turbulence and reduce the near bed velocities which are more often directed landwards. In the Rigter experiments, it was shown that by increasing the bed roughness, the salt intrusion lengths decrease (Daniels, 2016). However, there are no available cases in

where an increase of bed roughness is applied and therefore the feasibility of this solution is uncertain. Research has been performed by Haralambidou et al. (2003) for an estuary in Greece with a numerical model, showing indeed a small decrease in salt intrusion. Examples to increase bed roughness are applying rough bed material, such as concrete blocks or rocks. Also the idea of flexible slats, attached to the bottom, was brought to the table in the Netherlands (Verkerk et al., 2010).

- In case of severe increase of salt intrusion, a closure of one of the delta branches can be proposed. By closing a branch, the salt intrusion is entirely blocked in the closed branch and because of the increase in fresh water discharge through the non-closed branches, the salt intrusion decreases there as well. In the Rhine delta in the Netherlands, the Haringvliet estuary was closed in 1970 to compensate for the increased water depth in the main branch for navigation to the port of Rotterdam (Verkerk et al., 2010). However, this caused severe erosion in the Oude Maas and Spui branches due to increased tidal flow velocities (Sloff et al., 2011). Tromp (2013) investigated possibilities for closing a branch in the Mekong estuary. This showed indeed lower salinity values, but also enhanced erosion in the connecting rivers between branches. While the flood protection improved with respect to storm from sea, the upstream water level and hereby flood risk from the river increases. Besides, the closure of a branch could have large consequences for ecology and morphology of the river.

However, all of these measures are difficult to apply and expensive on a large scale such as the Mekong delta. Besides, the constructions must be designed very robust because of the high flow velocities and sediment concentrations in the wet season.

Besides these local measures, the salt intrusion can be reduced by enhancing the advective transport to the sea by temporarily increasing fresh water discharge. During critical salt intrusion events, a small flood wave of fresh water can be supplied to the delta (using the volumes of water in the active storage areas in for example Sambor dam). In order to execute this measure it is necessary to measure the salinity concentrations in the branches in order to determine when salt intrusion becomes critical. Because salt intrusion is a slow process, a critical event can be predicted in advance especially in combination with weather forecast (increased salt intrusion due to wind set up) and tidal predictions. During the dry season fresh water flow velocities are quite low and vary from 0.4 m/s upstream of Phnom Penh to less than 0.1 m/s in the estuary of the mouth. Due to these low flow velocities and reverses due to tidal wave propagation, the flood wave is expected to travel quite slow, because of the relation: $C_{HW} = \frac{3}{2}\frac{B_c}{B}U$. To make a conservative estimate for the travelling speed of this floodwave in a stretch of river, the average flow velocity in the downstream measurement point in base scenario is used. The flood wave is probably necessary in the driest period, which is the end of the dry season around April, when flow velocities are lowest. The flood wave will propagate from Kratie to the mouth of the Mekong in approximately 18 days (10 days from the Vietnamese border). This is quite long and a short flood wave will be dampened severely, because of the spreading over the branches and canals. An increase of discharge will be necessary over a longer period of at least a week in order to increase the flow velocities in the mouth of the estuary. However, this is compared to the previous solutions quite a cheap solution, which does not need extra infrastructure. Therefore, more research is required in order to optimize the flood wave and make this solution feasible.

The risk of increased salt intrusion is not only caused by salinity in the surface waters, but also from salt concentrations in the ground water. Due to the ground water extractions, the hydraulic head (ground water level) declines and therefore the saline water is able to penetrate further into the delta. The increase of saline groundwater flows can be reduced by reducing large scale ground water extractions. To accomplish this ground water extractions must be regulated more strictly and a more sustainable system for drinking water is necessary.

5.4. Mitigation floodplain areas

5.4.1. Potential risks and strategy

For the floodplain areas in Vietnam, the Plain of Reeds (PoR) and Long Xuyen Quadrangle (LXQ) the floodplain inundation is important, because it fertilizes the floodplains and hereby enhances the agricultural production. Due to the decreased maximum flow, the yearly inundated area will decrease, which reduces the inflow of the floodplains and hereby nutrients supply. Also ecologically speaking the reduction of inundated areas is a risk, because these are important habitats. Similar to the Tonle Sap inundation area, the extent of inundation is dependent on the maximum discharge in the wet season. This cannot be avoided because of the hydropower developments and should therefore be mitigated.

5.4.2. Mitigation of decreased extent of flooding

In order to increase the inundation extent, extra water must be discharged to the floodplain areas in the wet season, while the maximum water level and discharge in the river decreases. In order to increase the inundation of the floodplains the following mitigation measures have been tested:

- The lowering of the dikerings - because this has already been proven to increase the extent in Section 3.4.4.
- Extra canals to the floodplain area - because water currently enters the floodplain area mostly from the river side, the extent is limited. However, if water is supplied from more directions into the floodplains the inundation will be more spread over the area. For both floodplain areas a canal connected to the river in Cambodia to the North West side of the floodplain area is created.

Scenario	Inundated area PoR [km^2]	Inundated area LXQ [km^2]	maximum water level in PoR [m]	Inudation period above dikerings [days]
Base	310	190	3.42	89
BDP 2030	200	160	3.22	73
Lower Dikerings	380	210	3.01	69
Extra canals to FP	220	160	3.22	74

Table 5.2: Assessment parameters of canal-floodplain system for the BDP 2030 and base scenario and mitigation measures

The results of the assessment criteria are shown in Table 5.2. In case of lowered dikerings the flood extent is even larger compared to the base scenario, but with lower maximum water levels and a shorter inundation period. The extra canal to the Plain of Reeds does help to inundate a couple of the floodplains closest to the Cambodian border. The canals have a maximum discharge of around 200 m^3/s during the wet season, but in the LXQ does this not inundate more floodplain areas. This could be caused by the uniform values of dikerings and canal bed levels applied in the area. Especially in the PoR the lower dikerings increase the flow to the area and store larger amount of water. This also causes a small decrease in inflow at the end of the wet season, when the volume stored in the floodplains is released as can be seen in Appendix G.2.

5.5. Discussion on potential mitigation measures

The mitigation measures tested are no detailed designs but are giving a global indication for possibilities to reduce negative impacts with measurements within the delta. For some of the mitigation measures large scale changes have to be made and whether these are feasible (both economical and ecological) solutions is uncertain. Measures that need hard solutions are in a river such as the Mekong very expensive, because of the high river discharges and flow velocities. The solution needs to be sustainable and able to cope with the large suspended sediment concentrations and flow velocities.
Because many of the given solutions change the natural state of the river, research on the ecological consequences of the measures is necessary. Because of the interaction between socio-economy and ecology, a mitigation measure might turn out to be negative for the socio-economy, because of unexpected ecological consequences. For example in case of a shortcut canal to the lake Tonle Sap or a deepening of the Tonle Sap river, the migrating fish could be affected.

For the lake Tonle Sap, the proposed measures did increase the annual water level fluctuations significantly, but none reached the fluctuation present in the base scenario. In order to fully mitigate the hydropower scenarios to baseline, a combination of the given measures can be explored.
In the floodplain area it might be interesting to investigate in solutions in the operations of the sluice gate and pump operations. An earlier opening of the sluice gates increases the floodwave propagation. This would be cheap solutions that would not require large contructions, which might damage ecosystems. However, in the present model these operations are not implemented yet. Besides, the efficiency of use of water resources can be improved as well, which could lead to a decrease in water usage.

As could be seen in the mitigation measures of the Tonle Sap lake, mitigating one negative impact enlarges the problem in the rest of the system. During the wet season, extra water is directed to the lake, causing an even larger decrease in the downstream branches, compared to the situation without mitigation. Also in case of mitigating the flood to the canal-floodplain system this might be the case for the transport capacity and salt intrusion. To maintain a sustainable ecosystem over the entire delta, it might be necessary to compensate for some negative impacts instead of mitigate on the expense of other areas in the delta. In order to make these decisions it is necessary to set boundary limits for potential risks in each area and assess whether these limits are not exceeded.

Because it is clear that to completely mitigate negative impacts is difficult, also compensation measures need to be explored. This means that less people are able to work in the agriculture or fisheries. On the other hand, the economy in the entire Mekong delta area is growing. This might create opportunities to compensate for people losing employment due to the hydropower projects.

6

Conclusion and recommendations

6.1. Conclusions

Because of the economical and ecological importance of the Mekong delta, the effects of the rapid hydropower developments might have large consequences for its inhabitants. Therefore, the objective of this research was to determine the effects of the proposed hydropower developments on the hydrodynamics in the Mekong delta and indicate potential risks for ecology and socio-economy. Secondly, an objective is to explore potential mitigation measures in the delta to reduce the potential risks. In order to reach these objectives the following research questions are answered:

1. *How can the hydrodynamical processes be described and modeled to understand how different processes interact and predict the effects of changes to the system?*
   The influence of the individual processes, in this case the three most important processes for the discharge distribution in the delta, has been assessed using two tools; firstly the numerical model, calibrated using measurements, and secondly a conceptual model based on simplified geometry and theoretical formulas. The numerical model calculates the flows for the entire delta system and is able to provide output on locations where no measurements are available. The output of the model can therefore be used to increase the understanding of processes. The conceptual model can be applied for rapid assessment of a certain process. The results of the conceptual models can be coupled together with other subsystems or processes in order to obtain flows for the entire system. By explaining a process using theoretical formulas the main drivers and important parameters can be found. Together, these tools can be used to provide more knowledge on how the processes work and interaction in the entire delta system and assess the impacts of changes to the natural river. This method, which combines these tools, can be used for other delta areas facing anthropological influences, such as damming of natural floodplains, closing of estuary branches or hydropower scenarios.
   In the Mekong delta it was found that the processes interacted with the system as a feedback loop with two boundary conditions; the upstream boundary condition determining the supply (both water and sediment), the downstream boundary the water level including tidal fluctuations. In between the processes are affected or initiated by incoming hydrodynamical conditions and influencing downstream hydrodynamic conditions. Besides, the interaction between hydrodynamics and morphology can be taken into account by assessing the sediment transport capacity.

2. *What are the effects on the hydrodynamics of the Tonle Sap lake?*
   A reduction of water level fluctuation due to an increase of the minimum water level of 35 cm and a decrease of the maximum water level of 50 cm. This causes the area that seasonally inundates (and is therefore ecologically very important) to reduce with approximately 750 km^2 for the BDP 2030 scenario. The inflow volume reduces significantly by 20% for the BDP scenario, causing a decrease in supply of nutrients to the lake and a smaller potential for fish to swim to the lake. In case of a shift in the timing of the wet season flows, which is caused by filling of reservoirs to increase energy production, the flow in the Tonle Sap river is delayed as well. As the fish migration is initiated by this flow reversal, the number of fish in the lake will decrease even further. A degradation of bed level in the Mekong at Phnom Penh magnifies these effects even more. Because the water level in the lake is directly related to the water

level in the Mekong, degradation of bed level in the Mekong causes an even lower maximum water level and inflow volume than the other scenarios.

3. *What are the effects on the discharge distribution over the delta branches?*
In the downstream branches the discharge decreases in the wet season and increases in the dry season, which is positive because this decreases the risk of floods and droughts. This effect is strongly reduced by the smaller storage of water in the Tonle Sap lake and decreases further downstream. However, the change in discharge distribution has also effect on the sediment transport capacity and salinity in the branches. Due to the decrease of high discharges in the wet season, the sediment capacity decreases. The decrease of the transport capacity is largest in the upper branches and decreases further downstream. This difference in change causes a shortage of sediment supply in the downstream branches and hereby erosion. In the scenario with degraded branches the flow velocity decreases, because the discharge is spread over a larger cross-sectional area. Also the tidal characteristics in the estuary change and the branches become more stratified. This is expected to cause an increase of the potential of salt intrusion, which endangers the agriculture in the delta.

4. *What are the effects on the canal-floodplain system in Vietnam?*
The inflow to both floodplain areas increases slightly during the dry season, which is favorable for agriculture. However, in the wet season the decrease of the inflow is much larger, causing a smaller area to inundate. This has a negative effect for the rice production, because the production of the rice paddies depends on the supply of nutrients (as fertilizer) by inundation. Besides, land subsidence rates will increase, because the natural subsidence is no longer compensated by the supply of sediments.

5. *What are mitigation measures to decrease the potential, socio-economical and ecological, risks?*
In order to reduce the hydropower effects, several solutions have been proposed for measures to be taken in the delta. For the Tonle Sap lake possibilities to increase the water level fluctuations can be found in increasing the flow to the lake, by increasing the conveying cross section of the Tonle Sap River or creating an extra canal from the Mekong (higher upstream) to the lake. A delayed flow reversal can be mitigated by releasing extra volumes of water (using sediment draw downs or the active storage area of the Sambor dam) to increase the water level at Phnom Penh temporarily. However, these measures do reduce the maximum discharge in the wet season downstream of the lake even further. In order to increase the flood extent in the floodplains, the lowering of the dike rings (can be done by opening the sluice gates with lower water levels as well) is the easiest solution to implement. Bed level degradation, caused by changed transport capacity and supply, is difficult to mitigate. However, due to the negative impacts it is necessary to avoid bed level degradation as much as possible. Avoidance measures focus mostly on maintaining the supply of sediment to the delta, which should be done by implementing regulations. Because of the large scale of the changes, it is not possible to mitigate all effects in the delta itself.

6.2. Recommendations

- To prevent large scale morphological changes, which increase the negative effects of the hydropower dams it is necessary to reduce the amount of sediment extracting. This must be done in short term, because of the large volumes that are annually extracted from the river bed. To reach this regulations have to be implemented and extraction sites monitored more often. The same holds for groundwater extractions, which cause land subsidence in large areas of the Vietnamese Delta.

- The conceptual models are very useful for the understanding of processes and can be applied as rapid assessment for estimation of inflow volumes and inundation areas of the Tonle Sap lake and the Vietnamese floodplains for different hydrographs. These conceptual models do need some improvements as mentioned in Section 3.5. Now, the conceptual model represent only a single process and is dependent on measurements for input. However, by coupling these different models together, the most important hydrodynamical processes in the delta are represented and the input of a singular process can be obtained from the output of the upstream process. Because hydrodynamical conditions upstream influence both process and downstream conditions, a number of iterative steps must be performed to obtain the final results which balances all processes.

- The Delft3D-FM model performs already quite well and can be used for assessments, keeping in mind that the results deviate due to the smaller in- and outflow of Tonle Sap and the missing Cambodian floodplains. For further assessment of salinity and morphological changes and other research possibilities, it is recommended to further improve and develop the Delft3D-FM model as follows:

  - Include natural floodplains and overland flow processes in Cambodia based on topography data
  - Improve the accuracy of the Vietnamese canal-floodplain system by using measured bathymetry and topography of floodplains, dikerings and canal depths. Also implement rules of operation for sluice gates and pumps in the area.
  - Investigate and improve the representation of the in- and outflow of lake Tonle Sap
  - Use a 3D-grid in the sections of branches affected with salt intrusion
  - Include morphology, both suspended load transport and bed load transport, and bed level updates.

- In order to gain more insight in the effects with annual fluctuation, research is required using longer time series. In order to obtain the discharge from upstream, the operational patterns of the dams must be known and implemented in accordance with the measured precipitation and discharge patterns.
- In order to reduce the effects of hydropower scenarios it is recommended not only to mitigate effects in the mainstream dams, but especially in the large tributary dams. Especially in basins such as the 3S system, which are important for the sediment supply to the delta, sediment management measures need to be applied in dams that are not yet constructed. Also the reduction in active storage volume can be decreased in order to reduce the effects of the hydrograph.
- Set up a system that predicts and monitors the discharge in the different subsystems in the Mekong river. Use this system to optimize operations of dams in order to reduce the cumulative effects of hydropower dams on the hydrograph without a decrease in energy production. Also optimize sediment management methods by flushing/draw down in series instead of per dam. For this it might be useful to further develop the analytical models and use these as rapid assessment tools for the operational system of dams.

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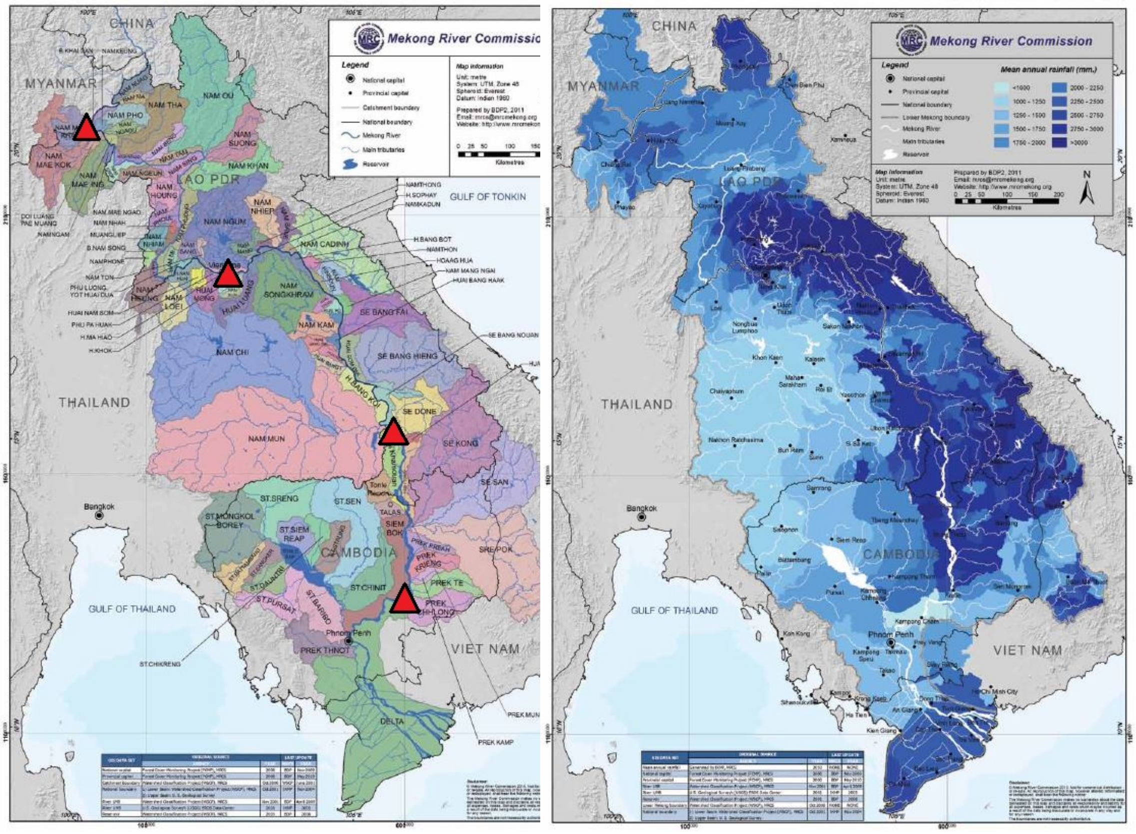
Appendices

A

Tributaries and precipitation Lower Mekong Basin



(a) Tributary systems and discharge measurement stations

(b) Annual precipitation in LMB

Figure A.1: Tributary catchments and annual precipitation

B

Background theory

B.1. Theory on flows

The flow in a river can be characterized by the combination of the continuity equation and the momentum equation. For simplicity the inertia terms of the momentum equation are neglected and the discharge is stationary (Battjes and Labeur, 2014):

$$B\frac{\partial d}{\partial t} + \frac{\partial Q}{\partial s} = 0$$

$$gA_c\frac{\partial d}{\partial s} + c_f\frac{Q^2}{A_c R} = 0$$

B	Width of river branch [m]	d	Water depth [m]
Q	Discharge [m^3/s]	g	gravitational acceleration constant [m/s^2]
A_c	Conveying cross section of branch [m^2]	c_f	Friction coefficient [-]
R	Hydraulic radius [m]		

For uniform flow conditions the equilibrium depth is characterized using the Chézy equations by:

$$d_e = (\frac{c_f q^2}{g i_b})^{\frac{1}{3}} = (\frac{q^2}{C^2 i_b})^{\frac{1}{3}}$$

d_e	Equilibrium water depth [m]	q	Discharge per unit width [m^2/s]
i_b	Bed slope [-]	C	Chézy coefficient [$m^{1/2}/s$]

The water depth is not always equal to the equilibrium flow depth, for example when a river enters the sea or has a sudden change in discharge. Then a so called backwater curve will be the transition between the disturbed water depth and the equilibrium water depth. These shapes of backwater curves are depending on the Froude number. For a mild bed slope and subcritical flows ($Fr < 1$), the backwater curves are found upstream of a disturbance. The slope of the curve is exponential and the following formulas apply for the height of the water level and the length for which the water level change due to backwater is half (de Vriend et al., 2011).

$$h' = h_0 exp(-\frac{3 i_b x}{(1 - Fr_0^2) d_e})$$

$$L_{\frac{1}{2}} = \frac{d_e}{i_b}(\frac{h_0}{d_e})^{\frac{4}{3}}$$

h'	Deviation from equilibrium water depth [m]	h_0	Water level deviation due to changed river conditions [m]
x	Distance from start back water [m]	Fr	Froude number $\frac{u}{\sqrt{gd}}$ [-]
$L_{1/2}$	Half length of backwater curve [m]		

Flood waves
Since the wet season can be characterized as one large flood wave, the water level slope is not constant. The momentum equation can be rewritten taken into account both bed slope and surfacce slope:

$$\frac{\partial d}{\partial s} - i_b + c_f \frac{Q^2}{g A_c^2 R}$$

The difference between the water surface slope and the bed slope is neglected, using the quasi uniform approximation. Using this assumption, uniform flow conditions simplify the equations for the slope and propagation of the flood wave to (Battjes and Labeur, 2014):

$$\frac{\partial d}{\partial t} + \frac{1}{B}\frac{\partial Q_u}{\partial d}\frac{\partial d}{\partial s}$$

$$Q \equiv A_c \sqrt{\frac{gRi_b}{c_f}}$$

Q_u	Quasi uniform discharge [m^3/s]

The wave speed of the flood wave can be expressed as the speed where the depth and discharge do not change in time. By assuming $A_c = B_c d$ and a prismatic channel ($R = d$) the equation can be further simplified as follows (Battjes and Labeur, 2014):

$$C_{HW} = \frac{1}{B}\frac{\partial Q_u}{\partial d}$$

$$\frac{\partial Q_u}{\partial d} = \frac{3}{2} B_c \sqrt{\frac{gdi_b}{c_f}} = \frac{3}{2} B_c u$$

$$C_{HW} = \frac{3}{2}\frac{B_c}{B} u$$

C_{HW}	Propagation speed flood wave [m/s]	B_c	Conveying width of river branch [m]
u	Flow velocity [m/s]		

This means that the flood wave travels more slowly than the long wave speed ($\sqrt{gd}$) and if $B_c/B < 2/3$ the flood wave propagates even slower than the flow velocity. The propagation speed of the flood wave is dependent on the waterdepth, causing a steepening of the front of the flood wave (leading edge) when it progresses downstream and a flattening of the trailing edge of the flood wave. Due to the steeper water slope at the leading edge, the flow velocity is higher in the rising stage and smaller after the peak has passed. This phenomenon is called hysteresis and causes a difference between the stage-discharge relationship for the front and the back of the flood wave as can be seen in figure B.1. Since the discharge is larger in the leading edge of the flood wave, the flood wave spreads out in length and decreases in height. In other words, the flood wave has a diffusive character as it propagates downstream. Taking hysteresis into account the discharge relationship becomes (Battjes and Labeur, 2014):

$$Q = A_c \sqrt{\frac{gR}{c_f}} \sqrt{1 - \frac{1}{i_b}\frac{\partial d}{\partial s}} \approx Q_u (1 - \frac{1}{2 i_b}\frac{\partial d}{\partial s})$$

Taking the spatial derivative of the discharge and filling in in the continuity equation the diffusive propagation of a flood wave can be described as:

$$\frac{\partial d}{\partial t} + \frac{1}{B}\frac{\partial Q_u}{\partial d}\frac{\partial d}{\partial s} - \frac{Q_u}{2 i_b B}\frac{\partial^2 d}{\partial s^2} = \frac{\partial d}{\partial t} + C_{HW}\frac{\partial d}{\partial s} - \kappa\frac{\partial^2 d}{\partial s^2} = 0$$

κ Diffusion coefficient [m^2/s]

In this formula the final term is the diffusion term, which represents the flattening and elongating of the flood wave as it propagates further downstream.

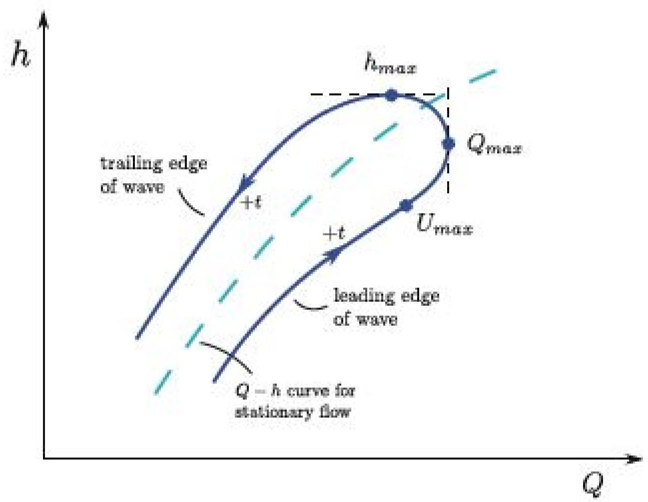


Figure B.1: Hysteresis effect on stage-discharge relation (Battjes and Labeur, 2014)

Confluences and bifurcations
Upstream of the delta, many tributary rivers flow into the main stream of the Mekong. For these confluences the physics with respect to the discharge and morphology is relatively simple and both the discharge and sediment load of the two upstream rivers can be summed up for the downstream conditions (de Vriend et al., 2011):

$$Q_{Mekong,down} = Q_{tributary} + Q_{Mekong,up}$$
$$S_{Mekong,down} = S_{tributary} + S_{Mekong,up}$$

S Sediment transport volume [m^3/s]

In the delta, when the river approaches the sea, the main stream bifurcates into a triangle shaped delta. Also in the case of a bifurcations the continuity conditions must hold for both discharge and sediment. Besides continuity, the waterlevel in the three branches at the bifurcation are equal, assuming there are no rapids:

$$Q_{up} = Q_{down,1} + Q_{down,2}$$

$$S_{up} = S_{down,1} + S_{down,2}$$

$$h_{up} = h_{down,1} = h_{down,2}$$

How the water and sediment is distributed over the branches is dependent on the geometrical parameters of the downstream branches:

$$Q_{down,1} = B_1 C h_{e1}^{3/2} i_{e1}^{3/2}$$

$$Q_{down,2} = B_2 C h_{e2}^{3/2} i_{e2}^{3/2}$$
$$S_{down,1} = B_1 m C^n h_{e1}^{n/2} i_{e1}^{n/2}$$
$$S_{down,2} = B_2 m C^n h_{e2}^{n/2} i_{e2}^{n/2}$$

i_e	equilibrium water slope [-]	m	Sediment transport factor, depending on applied transport formula [$m^{3-n}s^{n-1}$]
n	Sediment transport linearity factor [-]		

These sediment distribution holds in case of an equilibrium situation, which is not always the case. In order to solve the sediment distribution, one more relation is necessary, which is the nodal point relation ship. This relates the amount of sediment to the discharge flowing to the downstream branches to the power k. In case that $k < n/3$, the equilibrium situation lead to a closure of one of the branches in case of stationary conditions. If $k > n/3$, both branches will remain open in the equilibrium situation.

$$\frac{S_{down,1}}{S_{down,2}} = \frac{B_1}{B_2}(\frac{Q_{down,1}B_2}{Q_{down,2}B_1})^k$$

B.2. Theory on sediment transport capacity

Bed load transport

Bed load transport are particles that are in contact with the river bed, but where the shear stress from the flow exceeds the friction from the bed on the particle to move. Therefore, an important parameter for bed load transport is the mobility parameter and the critical shear stress. Shields defined the mobility parameter (θ) as a function of the shear velocity of the bed (u_*):

$$u_* = \sqrt{\frac{\tau_b}{\rho_s}} = \frac{\sqrt{g}}{C}\bar{u}$$

$$\theta = \frac{u_*^2}{\Delta g D}$$

u_*	Shear velocity [m/s]	τ_b	Bed shear stress [kg/m/s^2]
rho_s	Density of sediment [kg/m^3]	$\bar{u}$	Depth averaged flow velocity [m/s]
θ	Shields parameter [-]	Δ	Relative density $\frac{\rho_s-\rho}{\rho}$ [-]
ρ	Density of water [kg/m^3]	D	Grain size [m]

Shields defined the critical motion for different flow patterns based on the Reynolds number (Re_*). This leads to the Shields curve in which the mobility parameter, also called the Shields parameter, is defined for different flow regimes. The Shields curve is shown in figure B.2 and the formulas for the Reynolds number and dimensionless grain parameter are as follows:

$$Re_* = \frac{u_* D}{\nu}$$

$$D_* = (\frac{\Delta g}{\nu^2})^{\frac{1}{3}} D$$

Re_*	Dimensionless Reynolds number [-]	ν	Kinematic viscosity [m^2/s]
D_*	Dimensionless grain diameter [-]		

There are several sediment transport formulas all derived empirically from experiments. Since many different parameters have an influence on the sediment transport, it has so far not been possible to derive a generally applicable formula. Also local effects such as armouring and turbulence effects are of importance and the applicability of a sediment transport formula has to be assessed per individual case. For modelling cases the type of formula is chosen based on the applicability range of the grain size per formula and calibration via a target erosion/sedimentation pattern. It is important to note that formulas using the Shields parameter might underestimate the bed load transport load. This is because it uses the critical mobility parameter from Shields, in which the sediment is moving only when there is permanent movement at all locations. Especially in the dry season occasional transport will contribute to the total sediment load (Hoffmans and Verheij, 1997).

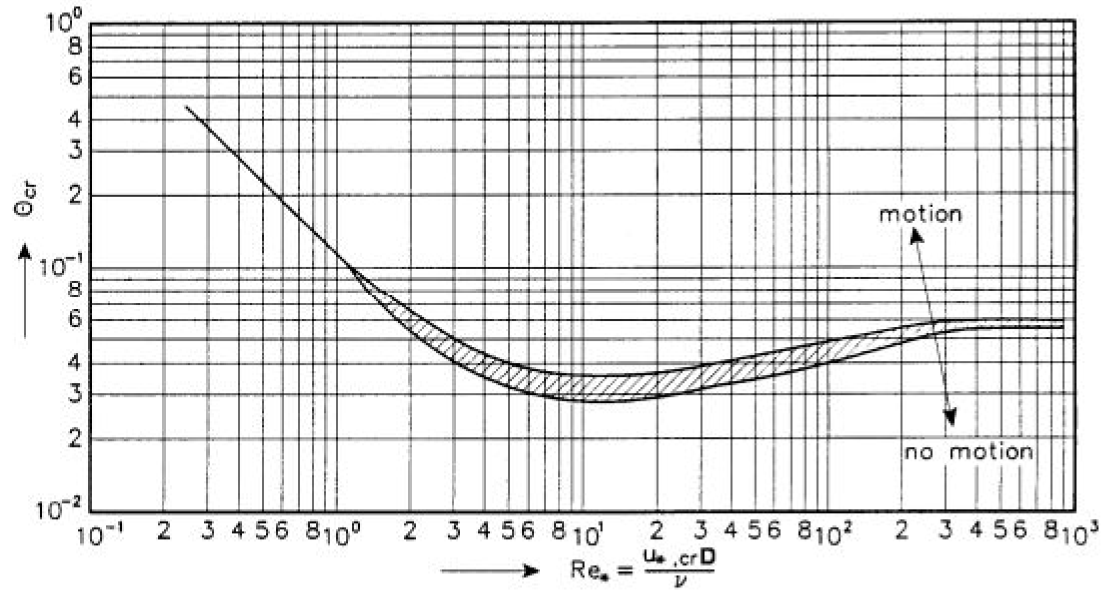


Figure B.2: The Shields curve with the Reynolds number (de Vriend et al., 2011)

Suspended load transport

For suspended load transport particles in suspension are transported with the flow velocity and the load is therefore dependent on the number of grains in suspension. The balance between the settling velocity of a particle and the upward turbulent flux determines the sediment concentration. The settling velocity depends mostly on the shape and grain size of the material and the upward turbulent flux by the flow velocities. Because turbulent fluctuations vary over the vertical water column (parabolic eddy viscosity profile) and the settling velocity, the concentration varies over the vertical, which is called the Rouse profile. The concentration over the depth can be estimated by (de Vriend et al., 2011):

$$c = c_a\left(\frac{a}{d-a}\frac{d-z}{d}\right)^Z$$

c	Depth dependent concentration sediment [kg/m^3]
c_a	Near bed concentration $c_a = \alpha \frac{D_{50}}{a} \frac{(\frac{\tau}{\tau_c}-1)^{1.5}}{D_*^{0.3}}$ [kg/m^3]
a	Near bed location depending on bed forms $a \approx \frac{1}{2}\Delta_{bedform}$ [m]
z	depth location in water column [m]
Z	Rouse number $Z = \frac{w_s}{\kappa u_*}$ [-]

The total flux can be calculated by multiplying the concentration with the flow velocity. However, the Rouse profile will occur in stationary and uniform conditions with a constant sediment supply. This is in natural situations not the case and instead of a Rouse profile a shape factor for the concentration is used in empirical formulations for the suspended sediment transport (de Vriend et al., 2011).

Sedimentation of erosion of the river bed
Sedimentation or erosion occurs when there is a spatial change in the transport flux which causes a bed level change over time. This can happen either because the transport capacity changes (due to for example hydraulic conditions), or because the sediment availability from upstream changes (Mosselman, 2014):

$$\frac{\partial z_b}{\partial t} + \frac{\partial q_s}{\partial s} = 0$$

z_b	Bottom level [m]	q_s	Sediment transport per unit width [m^2/s]

Due to a sudden change in the flow conditions or a withdrawal/supply of sediment an erosion or sedimentation front can occur. This sedimentation front does not have the same propagation speed as a water disturbance, since bed load sediment transport travels much slower. Via a 1D analysis of characteristics this speed can be defined from the conservation of sediment mass formula as follows in which n is the degree of nonlinearity between q_s and u (de Vriend et al., 2011):

$$\frac{\partial q_s}{\partial s} = n\frac{q_s}{u}\frac{\partial u}{\partial s}$$

$$C_{sediment} = \frac{nq_s}{d}$$

$C_{sediment}$	Propagation speed of sediment front [m/s]

C

Description and calibration of Delft3D FM model of the Mekong delta

C.1. Model description

In order to quantify the contributions of the processes better a sensitivity analyses is done, using an Delft3D FM model of which the grid can be found in C.1, which will also be used for the assessment of the hydropower scenarios. The model has been set up by Vo Thanh from UNESCO-IHE. It is a combined 2D/1D model, in which the main branches, lake and sea is modelled 2D depth average and the canals and smaller side branches are modelled in 1D. The largest branches are modelled using 8 grid cells per width and smaller branches such as Tonle Sap river and upper Bassac with 4 grid cells in the width. The width of the cells is depending on local river geometry and the length of the cells is around 650 m, excluding more complicated areas such as bifurcations and confluences. In the lake and sea area the grid cells are large up to 2000 m x 2000 m. The bathymetry is interpolated from the 1D ISIS model cross sections from 2000. The 1D canals are modelled with a distance between nodes of 400m, however since little data is available, the width of the canals is uniform in the model. The depths of the canals were at first interpolated over the rest of the bathymetry of the model and the floodplains in Vietnam were not yet included. The friction coefficient of the entire model was set on 65 $m^{1/2}/s$ The model was not calibrated yet, and therefor the following adaptations have been made in order to resemble the discharge distributions from the hydrologic data provided by the Mekong river commission. For the calibration of the model the hydrological year of 2002 has been used, since most data were available for this year. For the calibration the measurement stations used for data analyses were inserted into the model as both observation points as observation cross sections.

1. Bathymetry updates have been done in some areas in order to improve discharge distributions and at location where logical wise the bathymetry was incorrect, such as Snoc Trau and upper Bassac.
2. Floodplains included in PoR and LXQ between canals as 2D surfaces between the canals. The height of surrounding dikes in PoR is on average +2.5 m a.m.s.l. and for the LXQ this was estimated to be based on water levels around Bassac river +1.5 m a.m.s.l.. At first the depth within the floodplains was estimated everywhere to be +1.0 m a.m.s.l. and the connections with the canals where made using a connection to a single 1D node in the middle of the plain.
3. The canal depths in Vietnam are taken as uniform depths of -5 m a.m.s.l. and also the width
4. The tributaries flowing into Tonle Sap lake have been estimated using the discharge graph from Kummu (2014) for an average year and added as a single source to the lake.

The adaptations to the model were made in steps in order to obtain better results. When the results of calibration were adequate, the model has been validated with year 2005. The results of calibration and validation can be found in appendix C.2. Since quite some assumptions are made and might be rather rough, a sensitivity analyses is performed on a couple of aspects of the model. This does not only give a better overview of the correctness of the model and model assumptions, but also give a better feeling of the system interaction and sensitivity of certain processes, including human induced processes.

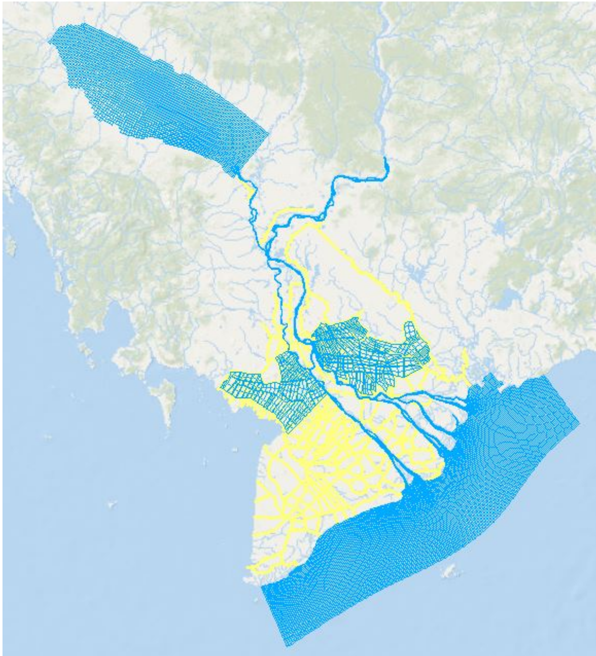
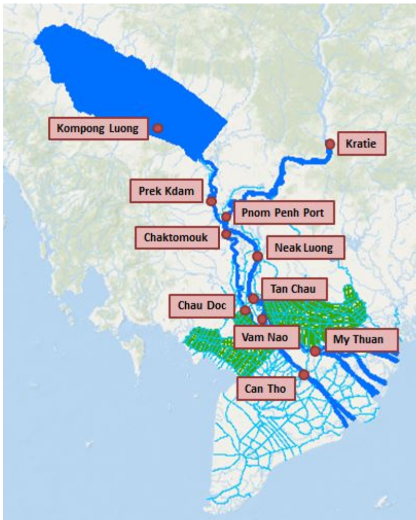
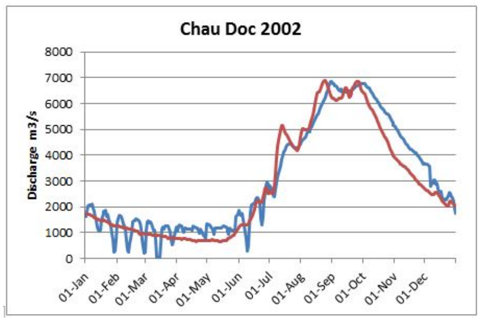


Figure C.1: Grid of Delft3D FM model (with blue 2D grid and yellow 1D)

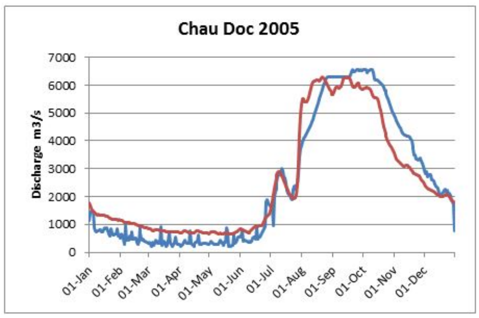
C.2. Discharge calibration and validation results

Calibration of the model has been done using the hydrological year 2002. In this year most measurement data were available from the stations shown in the figure on the right. When results were adequate, a validation run has been done for the year 2005. The figures below depict the discharge and/or waterlevels of the measurement stations over the time. In every figure the blue line is the data following from measurement stations (per day) and the red line is the model output, where all output values from one day are averaged to obtain a daily average. Not all the measurement stations have data available for the calibration year, but this was after 2002 still the most. For not all stations both discharge and water levels are known. All the waterlevel data are relative to mean sea level.



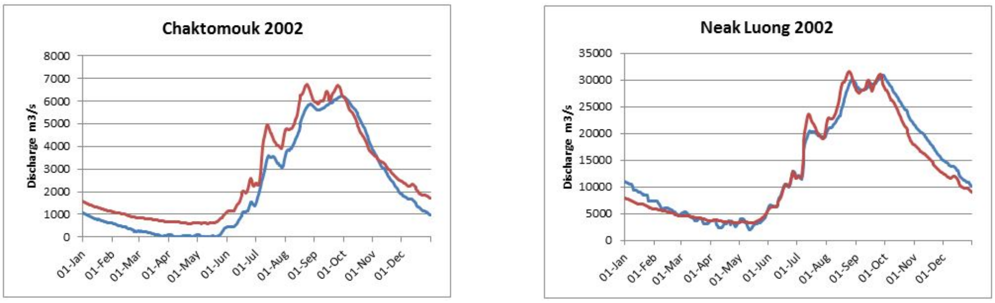


(a) Calibration



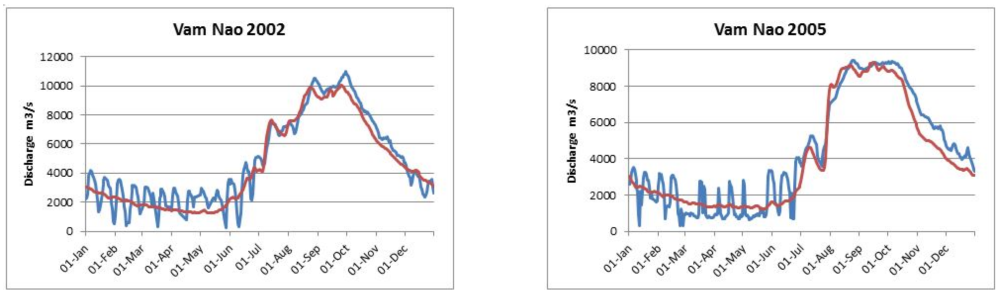
(b) Validation

Figure C.3: Discharge at Chau Doc



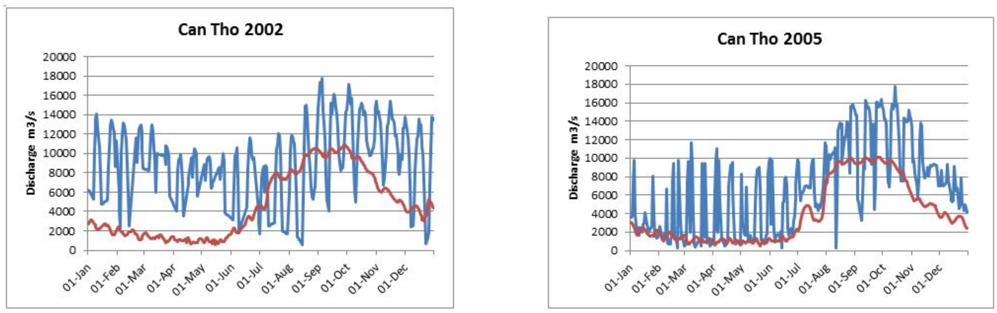
(a) Chaktomouk (b) Neak Luong

Figure C.4: Discharge calibration Chaktomouk and Neak Luong



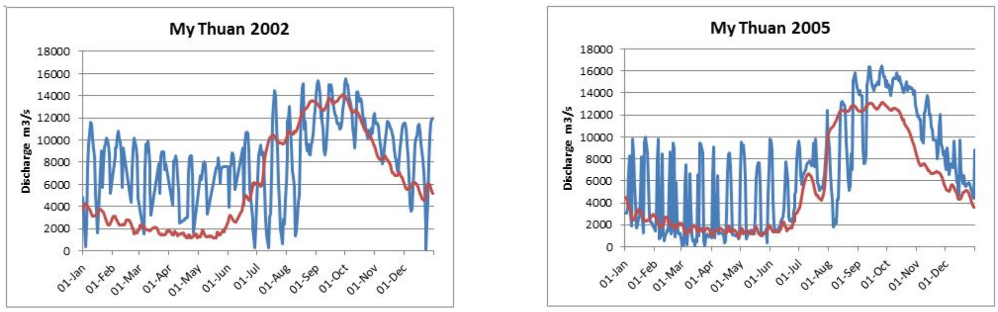
(a) Calibration (b) Validation

Figure C.5: Discharge at Vam Nao



(a) Calibration (b) Validation

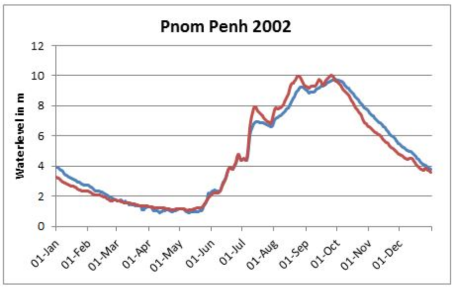
Figure C.6: Discharge at Can Tho



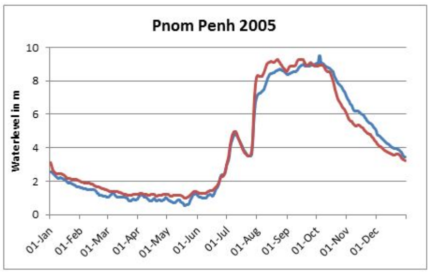
(a) Calibration (b) Validation

Figure C.7: Discharge at My Thuan

C.2.1. Waterlevel calibration and validation results

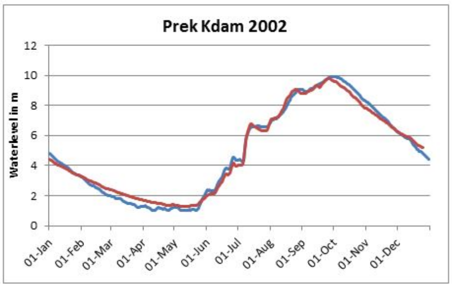


(a) Calibration

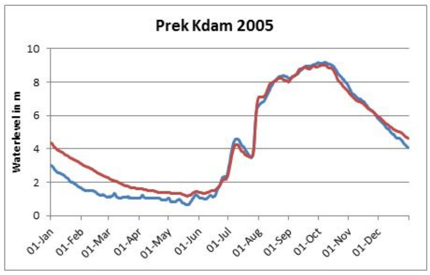


(b) Validation

Figure C.8: Waterlevel at Pnom Penh

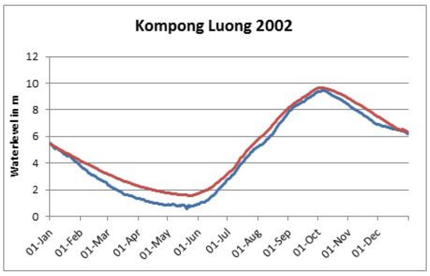


(a) Calibration

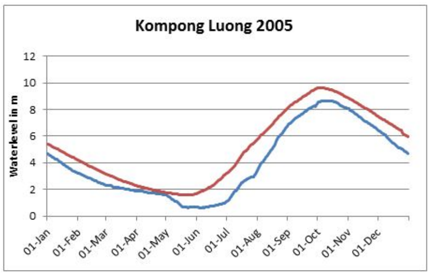


(b) Validation

Figure C.9: Waterlevel at Prek Kdam

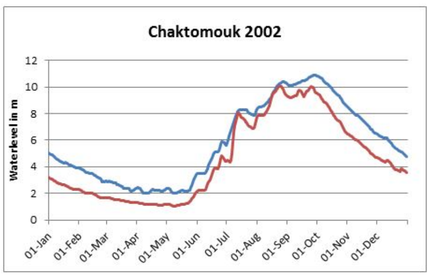


(a) Calibration

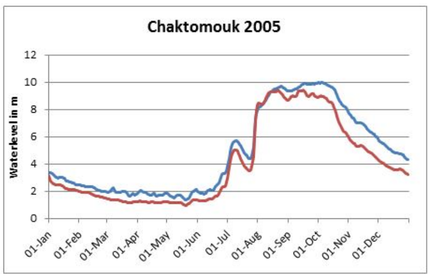


(b) Validation

Figure C.10: Waterlevel at Kompong Luong

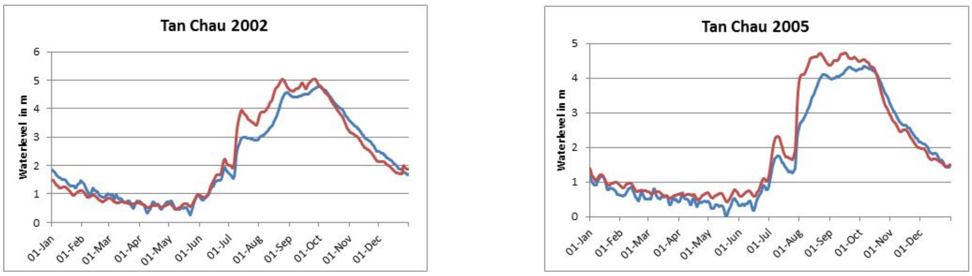


(a) Calibration



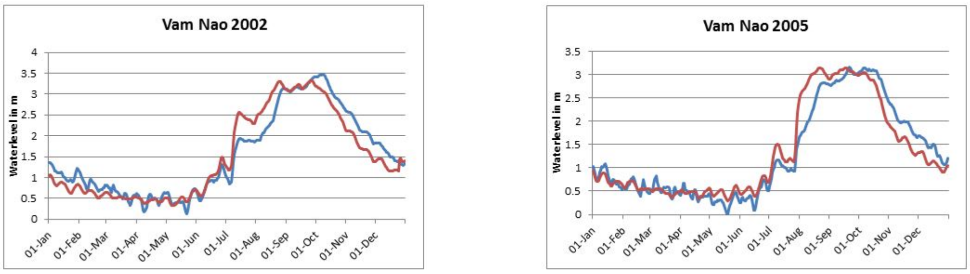
(b) Validation

Figure C.11: Waterlevel at Chaktomouk



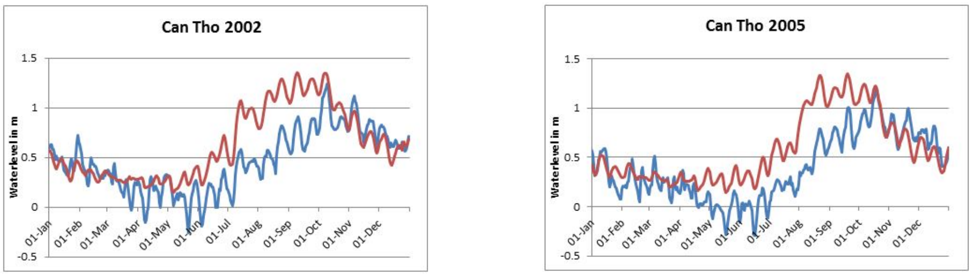
(a) Calibration (b) Validation

Figure C.12: Waterlevel at Tan Chau



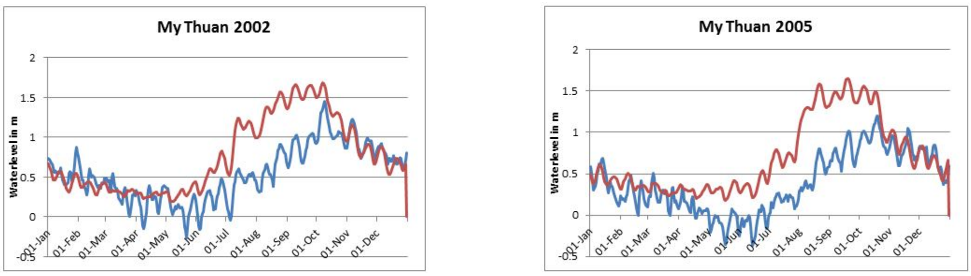
(a) Calibration (b) Validation

Figure C.13: Waterlevel at Vam Nao



(a) Calibration (b) Validation

Figure C.14: Waterlevel at Can Tho



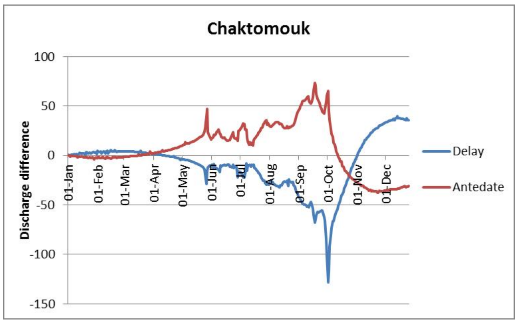
(a) Calibration (b) Validation

Figure C.15: Waterlevel at My Thuan

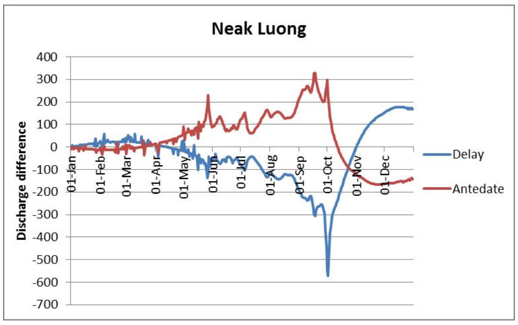
D

Sensitivity analyses

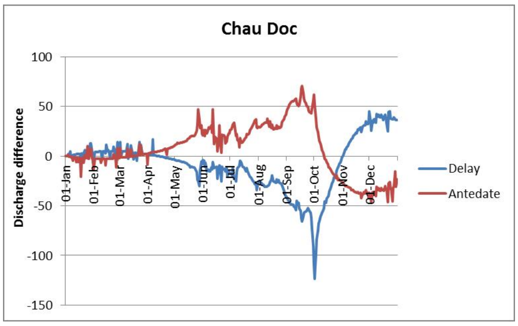
D.1. Sensitivity lake Tonle Sap



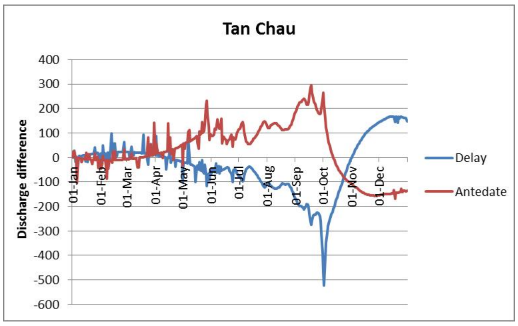
(a) Chaktomouk



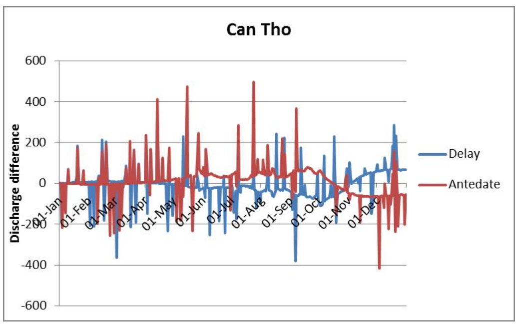
(b) Neak Luong



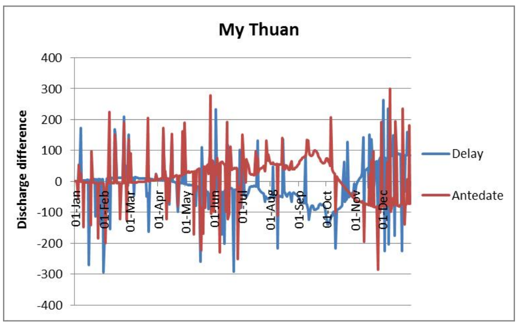
(c) Chau Doc



(d) Tan Chau



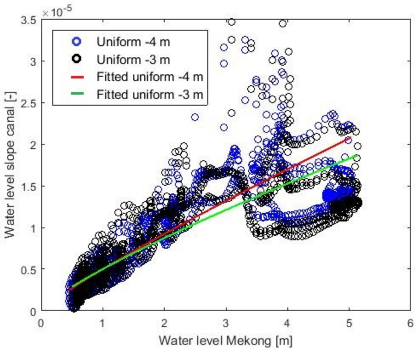
(e) Can Tho



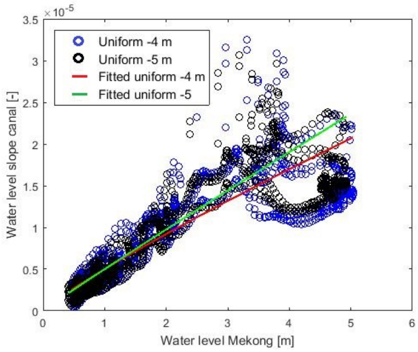
(f) My Thuan

Figure D.1: Discharge difference compared to baseline for different timings of tributaries

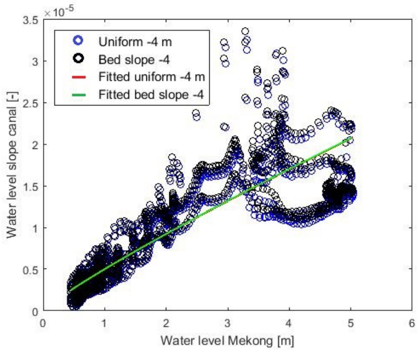
D.2. Sensitivity bathymetry canals



(a) Higher bed level



(b) Lower bed level



(c) With bed slope

Figure D.2: Correlation water level Mekong and water level slope in canals for bed level

D.3. Floodplains and dikerings

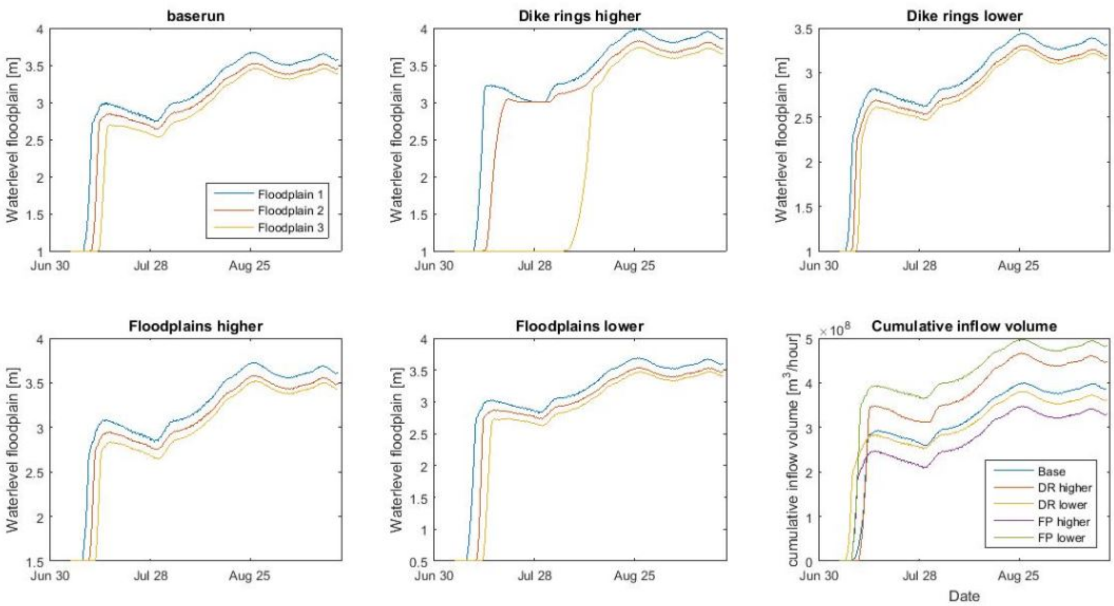
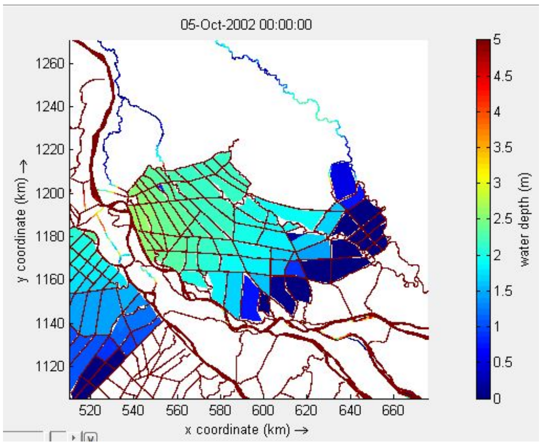
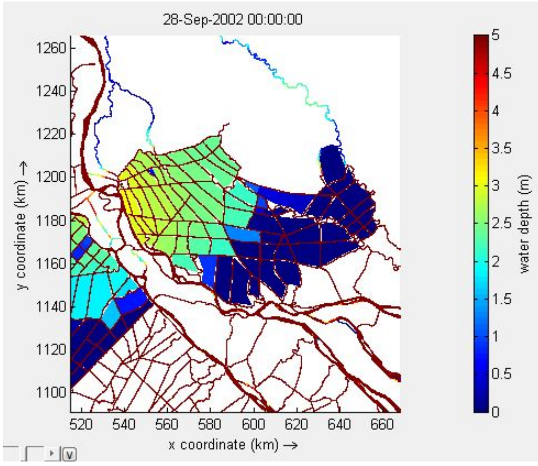


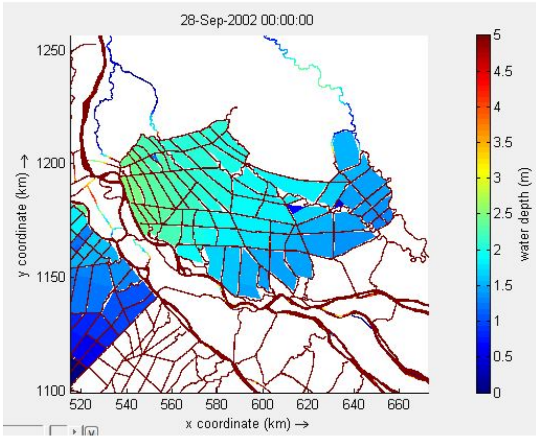
Figure D.3: Waterlevel in floodplains and inflow volumes for different scenarios



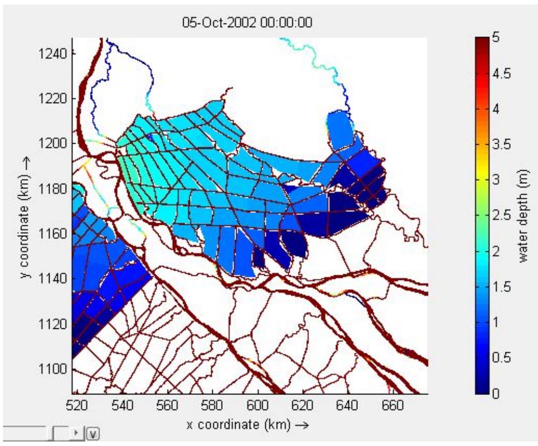
(a) Baserun



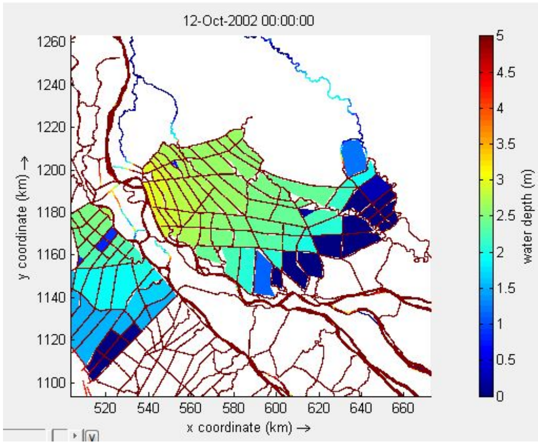
(b) Dikerings higher



(c) Dikerings lower



(d) Floodplains higher



(e) Floodplains lower

Figure D.4: Maximum extent and waterdepth

E

Conceptual model inflow floodlains

The inflow volume in the floodplain is indeed equal to the difference in discharge through the canal before and after the inflow point. This is indeed the case as can be seen in figure E.1 which shows the relation between the inflow volume per hour and the difference in discharge for the 2nd and 3rd floodplain from half of July to end of August. For the third floodplain a discrepancy can be seen when there is no inflow in the plain (inflow volume is 0), but a difference in discharge is present. This can be explained by the tidal variation, which is dampened in the canal system. Each floodplain is modeled with 4 grid cells and the water level from the model is given only in one grid cell. A small deviation of water levels between the cells causes a large difference in the calculated inflow volume, which explains discrepancies during the inflow stage.

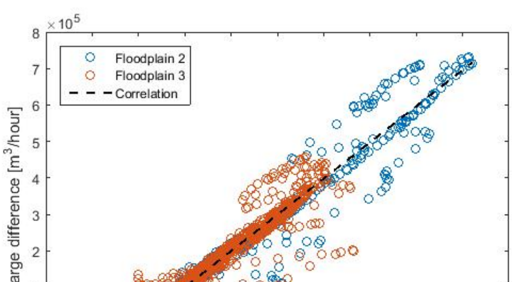
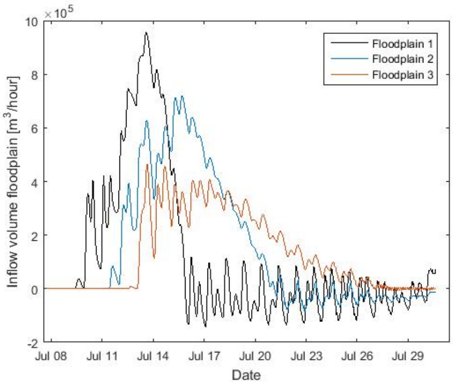
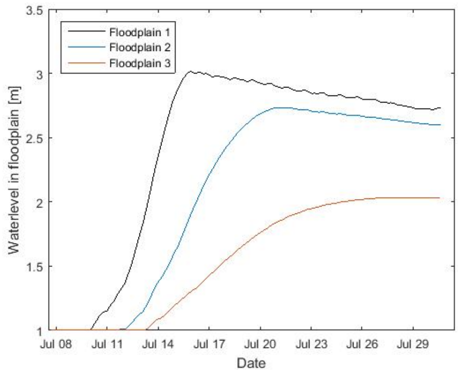


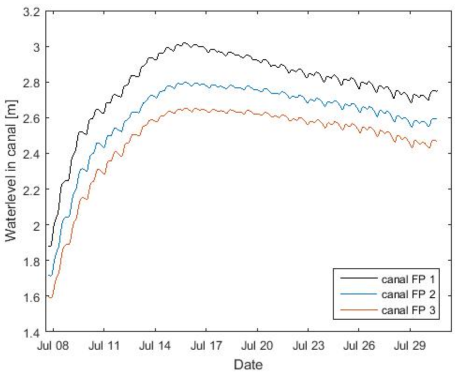
Figure E.1: Correlation inflow volume and discharge difference



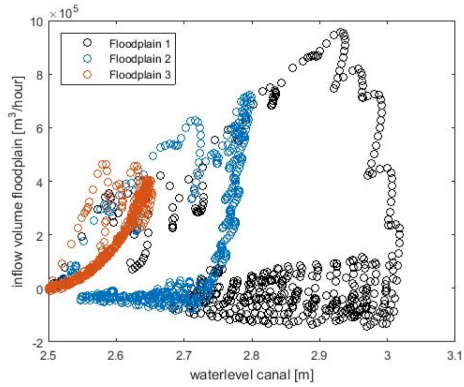
(a) Inflow volume floodplain



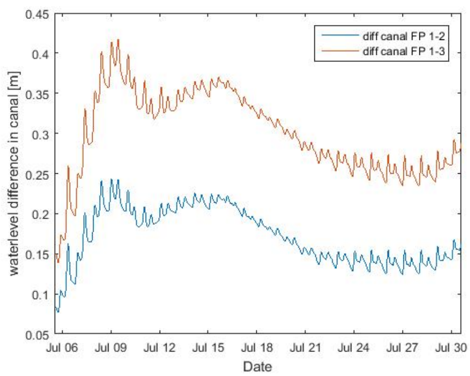
(b) Waterlevel in floodplain



(c) Waterlevel in canal



(d) correlation water level canal and inflow volume



(e) difference in water level canals

Figure E.2: Results inflow floodplain

F
Hydropower Effects

1. Baseline scenario - hydrologic year 2005
2. Current state - including dams operational in March 2015
3. 2030 scenario - without mainstream dams
4. 2030 scenario - including mainstream dams except Sambor
5. 2030 scenario - including Sambor

F.1. Alterations in the hydrograph

The alterations in the hydrograph at the upstream boundary of the model (Kratie) have been calculated by combining the available researches and information on the dams from the Mekong River Commission. The changes for the Basin development Plan 2030 scenario (BDP 2030), excluding mainstream dams, compared to the baseline have been calculated up till Pakse by the MRC. Between Pakse and Kratie only the 3S system (Se Kong, Se San and Sre Pok) is tributing to the Mekong river. Also for these tributaries plans for large scale hydropower development have been made, and due to the downstream location and large contribution the effects of dams in this system can be significant to the hydrograph. In order to find the hydrological alterations for the other scenarios at Pakse, the changes have been interpolated for the current state (2015) scenario and extrapolated to include the active storage areas from the mainstream dams. This can be done since the alterations to the hydrograph are proportional to the cumulative active storage volumes. The hydrograph at Pakse for the different scenarios can be found in figure F.1.

In the research of Piman et al (2016), the hydrological alterations due to the proposed dams have been calculated for the same scenarios, but also for 7 of the largest proposed dams seperately. In order to calculated the average contribution of the system, the difference discharge between Pakse and Kratie discharge from 2001-2006 has been averaged per day. The travelling time between Pakse and Kratie has been estimated to be 3 days, which gave the least extreme values. Also a moving average has been applied in order to obtain a smooth hydrograph. From the study the increase and decrease of average wet and dry season flow and maximum and minimum values follow. Furthermore, the time of storing water, mostly during beginning of wet season is also taken into account by applying the larger difference values in the rising period. The total volume during the year discharged by the 3S system is not changed for the scenario, see figure F.2s. Finally the scenarios from Pakse and the 3S system are combined to obtain the hydrographs for the scenarios at Kratie.

As can be seen in both figures is that the contribution of the mainstream dams to the hydrological alterations is relative small. This is because these dams are mostly designed as run of river and do not have large active storage areas. Furthermore the increase of the average dry season flow and decrease of the maximum flows is visible in both graphs, but due to the large difference between wet and dry season flows it seems a small difference. However, the average dry season flow is almost doubled and the maximum flow decreases by about 25% as well.

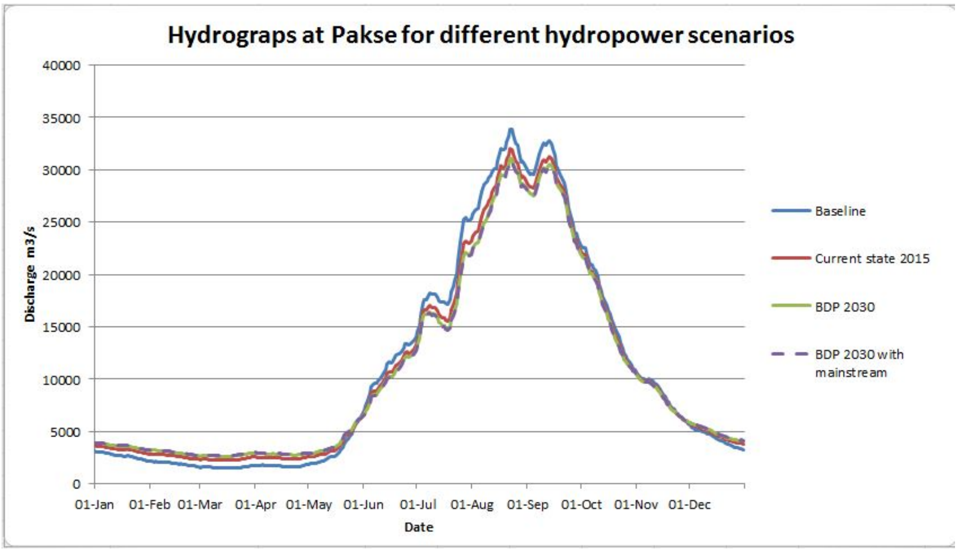


Figure F.1: Annual hydrograph for different scenarios at Pakse

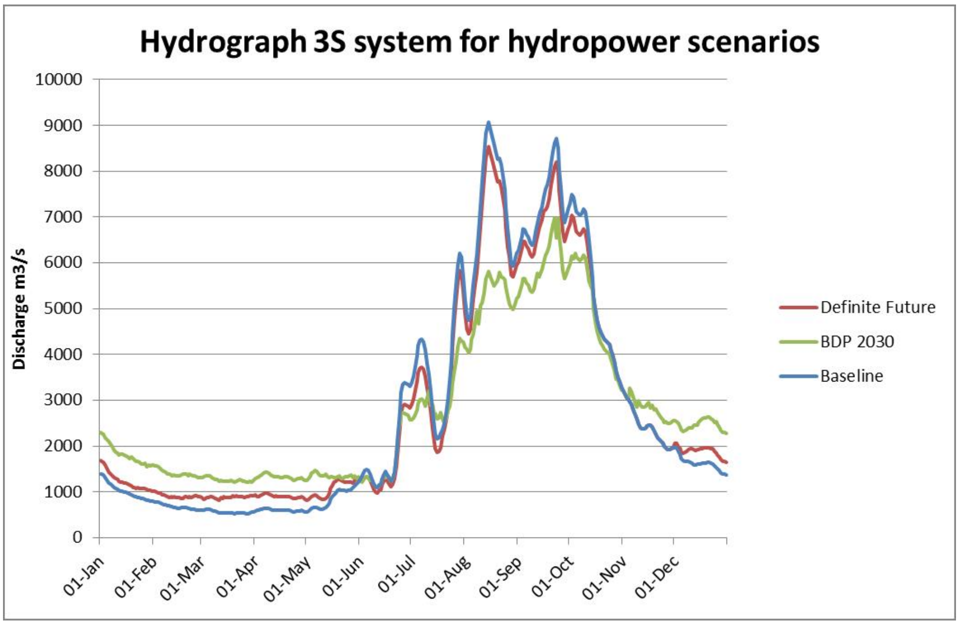
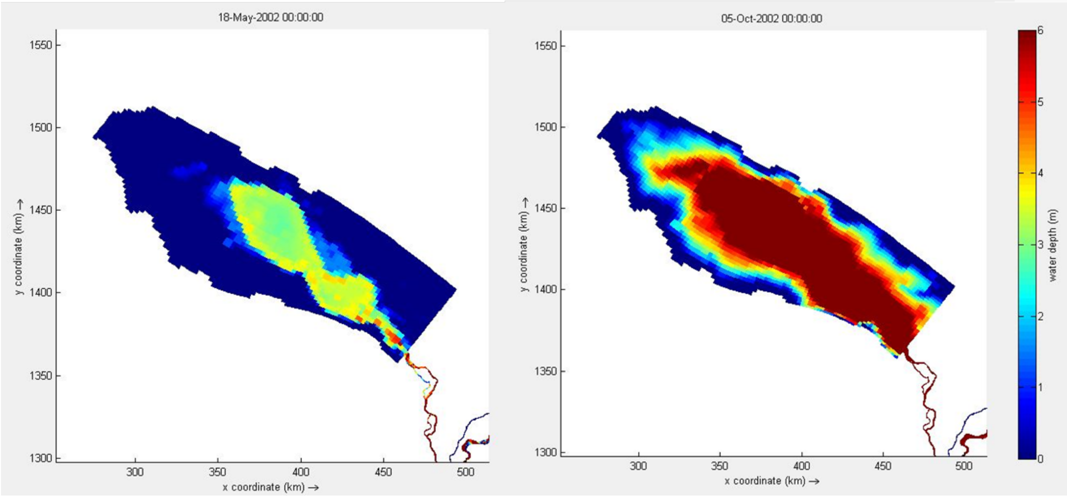
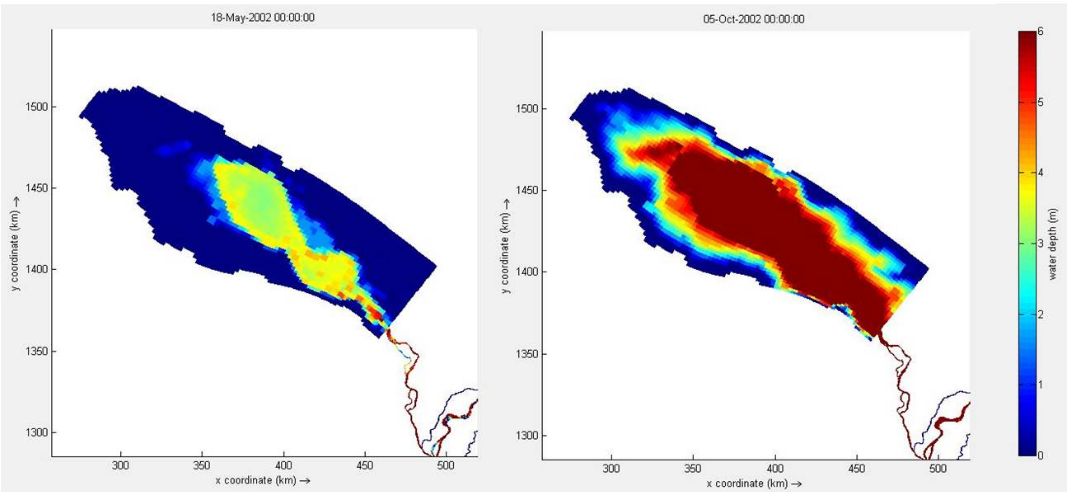


Figure F.2: Annual hydrograph of the 3S system for different scenarios

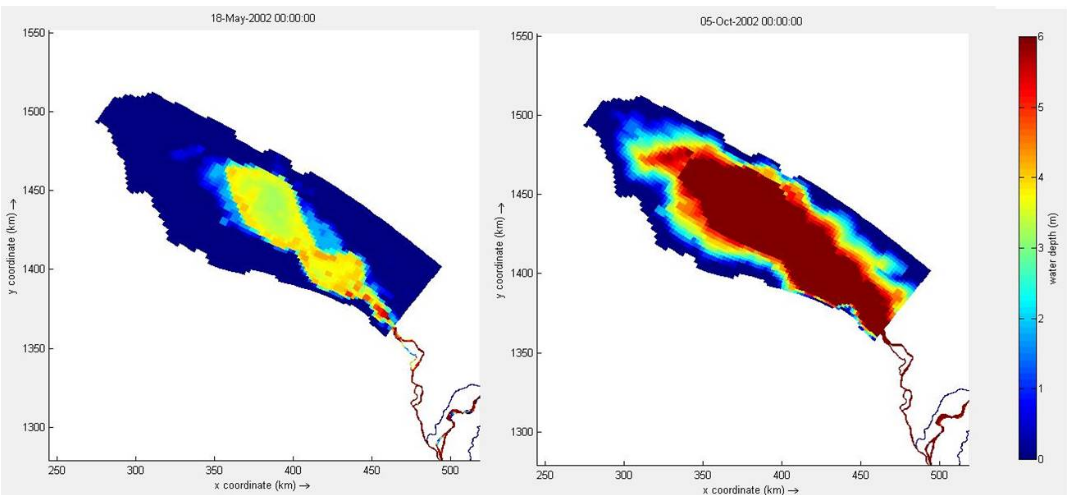
F.2. Effects on Tonle Sap lake



(a) Baserun

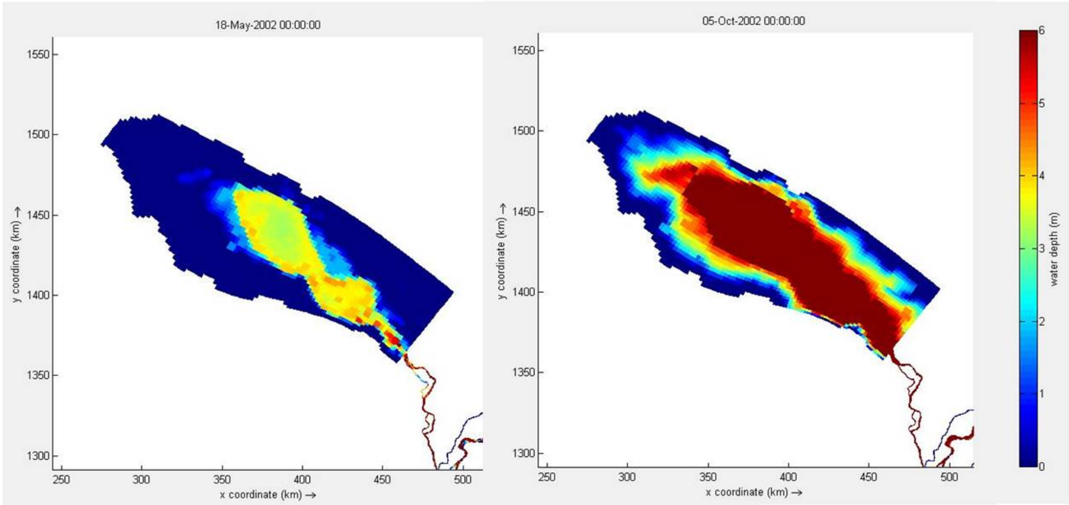


(b) Definite future

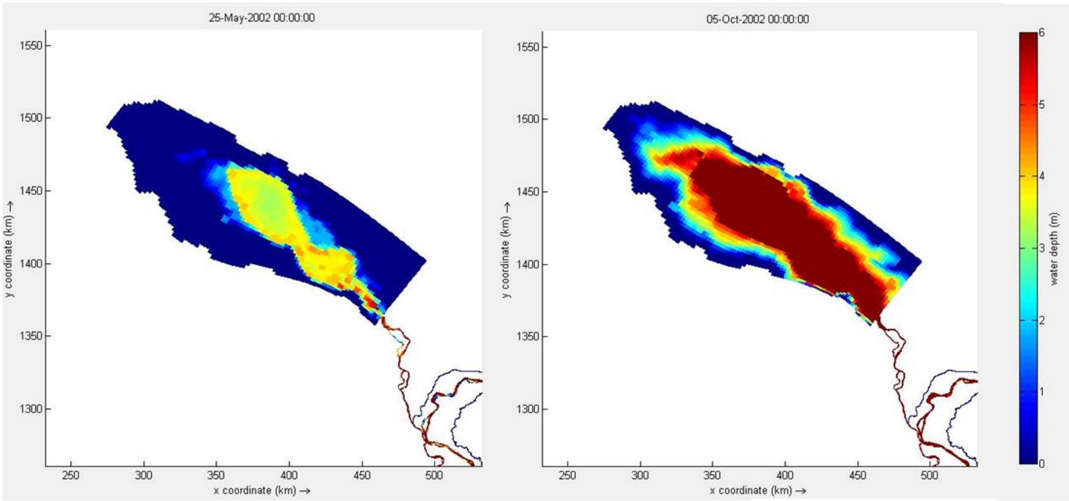


(c) 2030 no mainstream

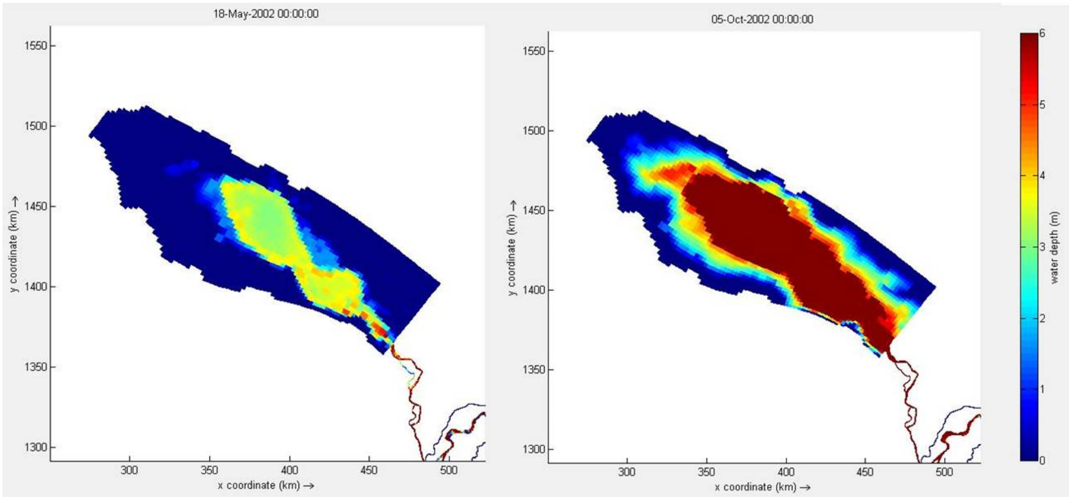
Figure F.3: Minimum and maximum waterdepths in Lake Tonle Sap for different scenarios (1)



(a) BDP 2030



(b) 2030 Shift wet season



(c) 2030 degraded river

Figure F.4: Minimum and maximum waterdepths in Lake Tonle Sap for different scenarios (2)

F.3. Effects on discharge distribution

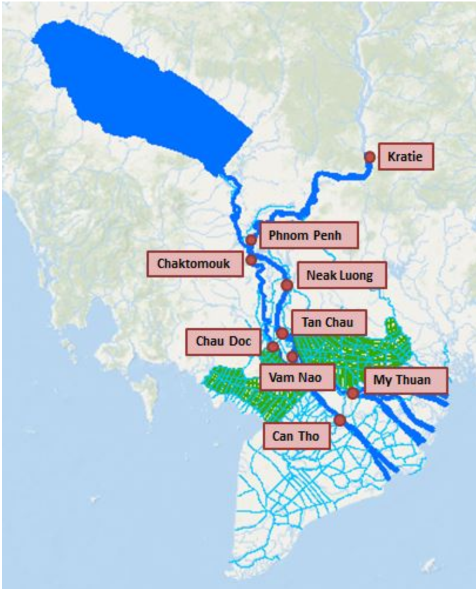
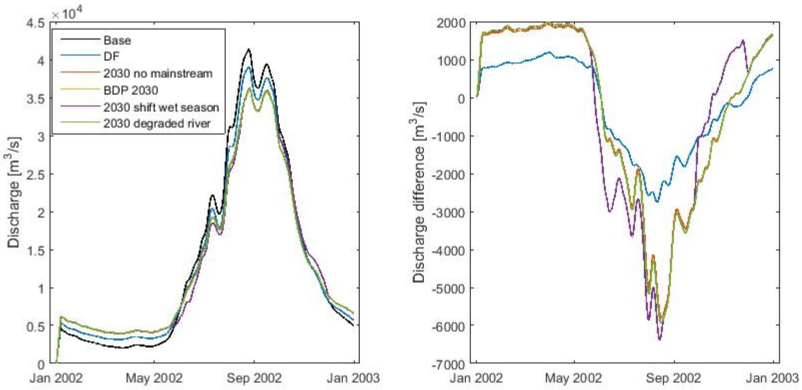
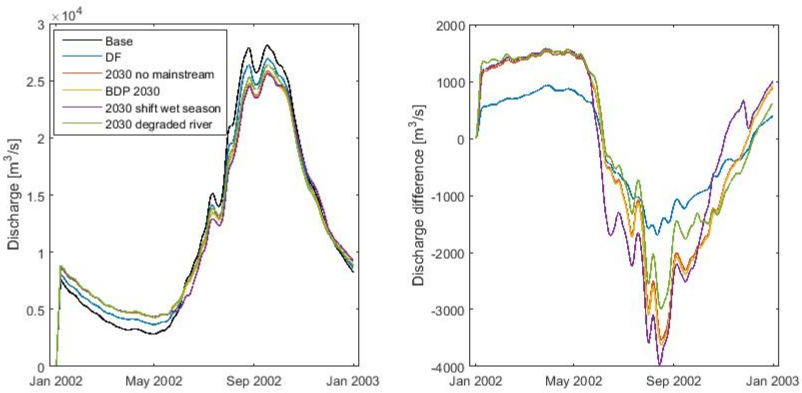


Figure F.5: Measurement locations

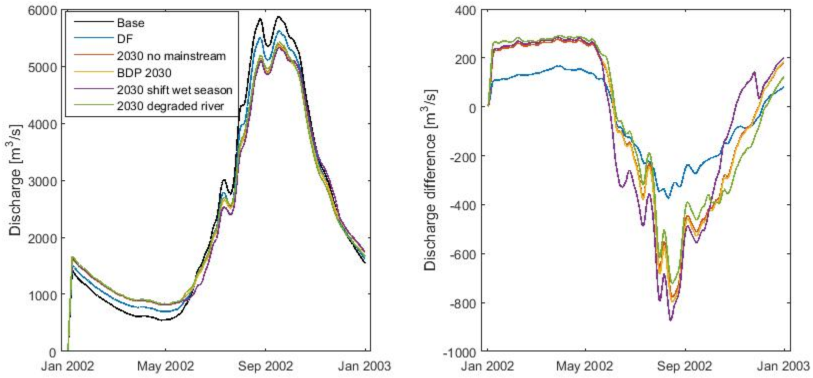


(a) Phnom Penh

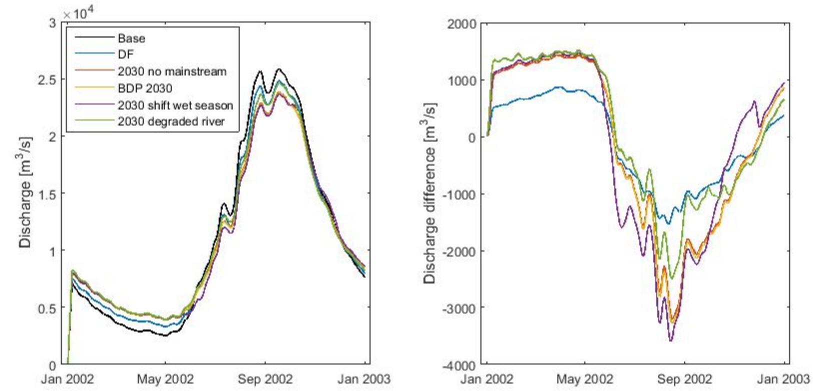


(b) Neak Luong

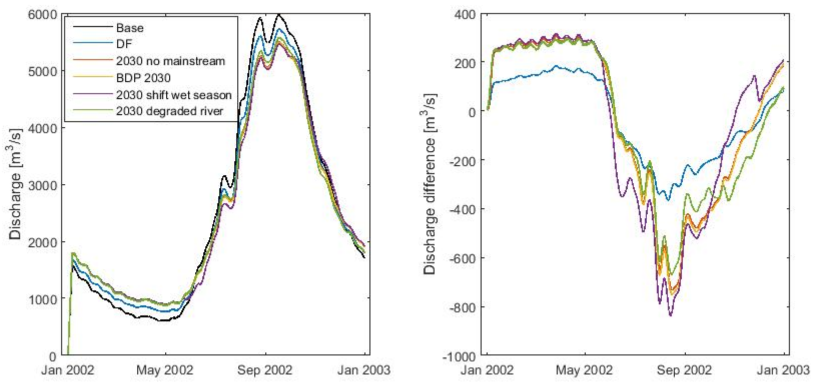
Figure F.6: Discharge and difference from base for different scenarios at measurement locations (1)



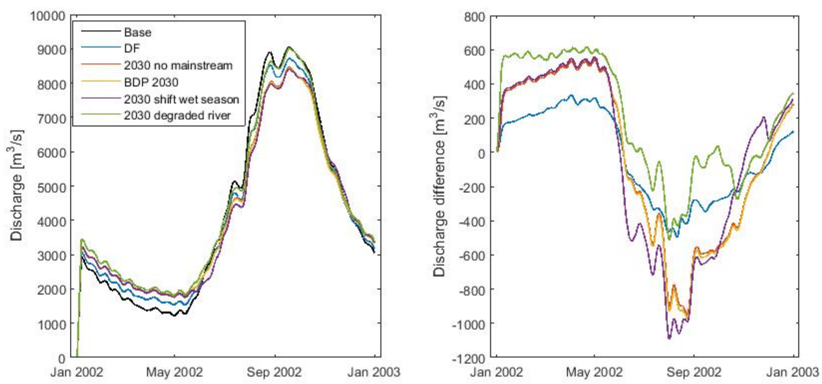
(a) Chaktomouk



(b) Tan Chau

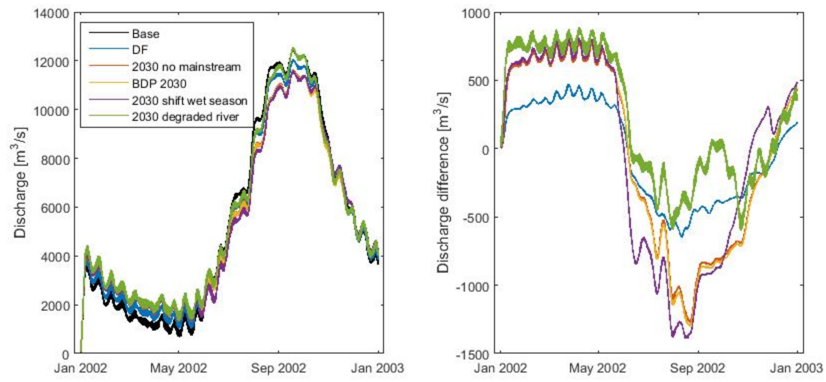


(c) Chau Doc

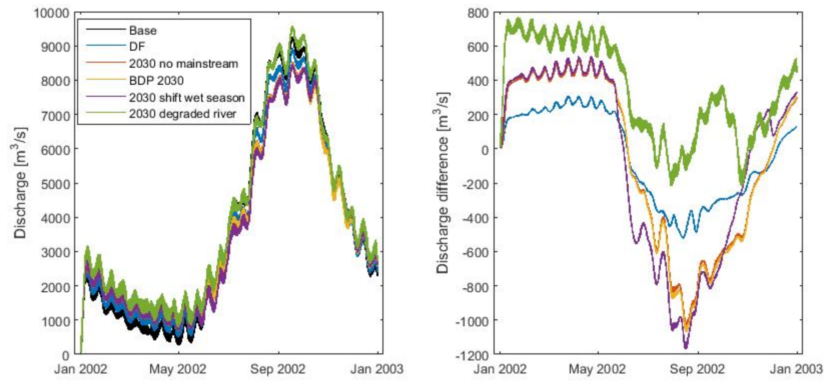


(d) Vam Nao

Figure F.7: Discharge and difference from base for different scenarios at measurement locations (2)



(a) My Thuan

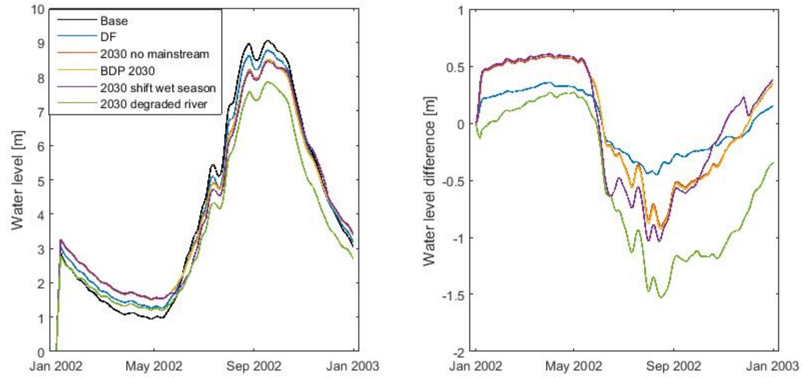


(b) Can Tho

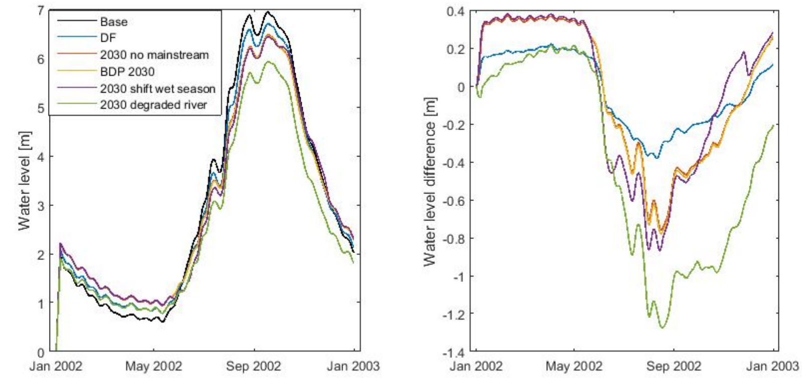
Figure F.8: Discharge and difference from base for different scenarios at measurement locations (3)

Max. discharge Location	Baseline	Definite Future	BDP 2030 without main-stream dams	BDP 2030	BDP 2030 with degraded branches	Shift to start wet season
Phnom Penh	41,300	38,980 *-5.5%*	36,200 *-12.3%*	36,070 *-12.6%*	36,070 *-12.6%*	36,070 *-12.7%*
Chaktomouk	5,870	5,620 *-4.3%*	5,370 *-8.5%*	5,350 *-8.8%*	5,420 *-7.7%*	5,326 *-9.9%*
Neak Luong	28,090	26,930 *-4.2%*	25,820 *-8.1%*	25,750 *-8.3%*	26,370 *-6.1%*	26,560 *-5.4%*
Chau Doc	5,970	5,730 *-4.1%*	5,500 *-7.9%*	5,480 *-8.1%*	5,570 *-6.6%*	5,460 *-8.5%*
Tan Chau	25,860	24,840 *-4.0%*	23,840 *-7.8%*	23,780 *-8.1%*	24,620 *-4.8%*	23,660 *-8.5%*
Vam Nao	9,040	8,720 *-3.6%*	8,460 *-6.4%*	8,440 *-6.6%*	9,010 *-0.3%*	8,410 *-7.0%*
Can Tho	9,270	8,940 *-3.6%*	8,540 *-7.9%*	8,510 *-8.2%*	9,600 *+3.5%*	8,480 *-9.3%*
My Thuan	12,510	12,080 *-3.4%*	11,670 *-6.7%*	11,650 *-6.9%*	12,580 *+0.5%*	11,607 *-7.2%*
Min. discharge Location	**Baseline**	**Definite Future**	**BDP 2030 without main-stream dams**	**BDP 2030**	**BDP 2030 with degraded branches**	**Shift to start wet season**
Phnom Penh	2,050	3,150 *+53%*	3,880 *+89%*	3,940 *+92%*	3,940 *+92%*	3,940 *+92%*
Chaktomouk	545	700 *+28%*	810 *+49%*	820 *+50%*	830 *+52%*	820 *+50%*
Neak Luong	2,800	3,650 *+31%*	4,280 *+53%*	4,320 *+54%*	4,270 *+53%*	4,320 *+55%*
Chau Doc	600	760 *+26 %*	870 *+46%*	880 *+48%*	860 *+45%*	880 *+48%*
Tan Chau	2,460	3,260 *+33%*	3,850 *+57%*	3,890 *+58%*	3,870 *+57%*	3,890 *+58%*
Vam Nao	1,210	1,510 *+25%*	1,740 *+44%*	1,750 *+45%*	1,790 *+48%*	1,750 *+45%*
Can Tho	250	500 *+95%*	680 *+160%*	690 *+170%*	800 *+210%*	690 *+270%*
My Thuan	680	1,040 *+53%*	1,320 *+95%*	1,340 *+97%*	1,370 *+101%*	1,340 *+97%*

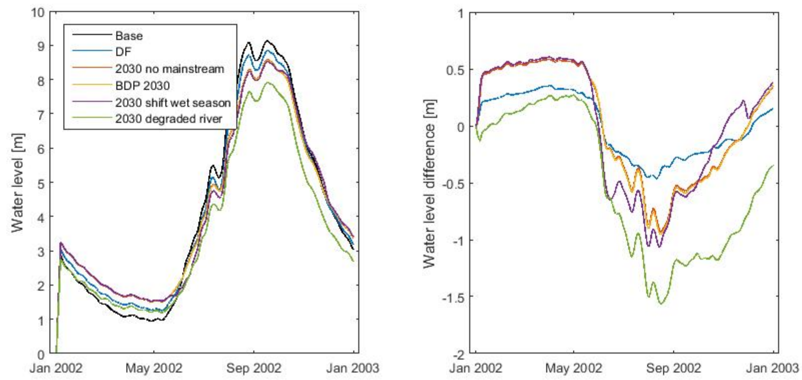
Table F.1: Maximum and minimum 5-day averaged discharge, including change in percentage from the base scenario



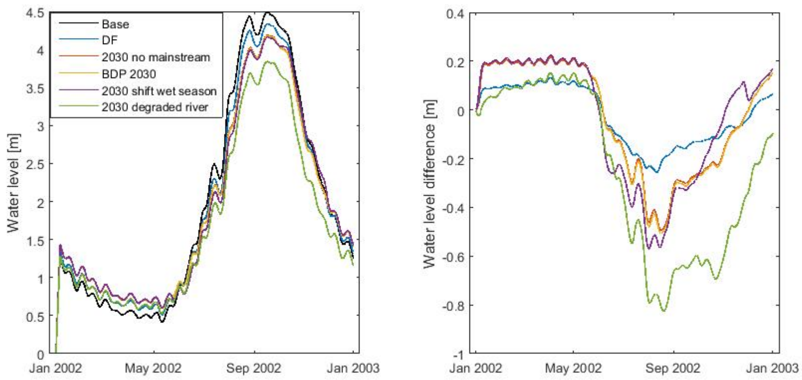
(a) Phnom Penh



(b) Neak Luong

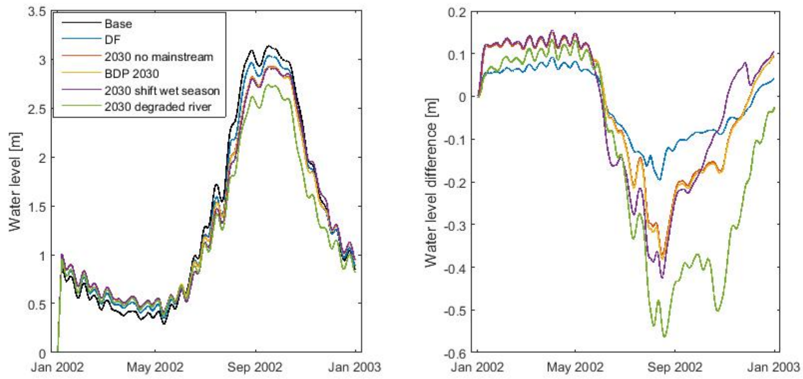


(c) Chaktomouk

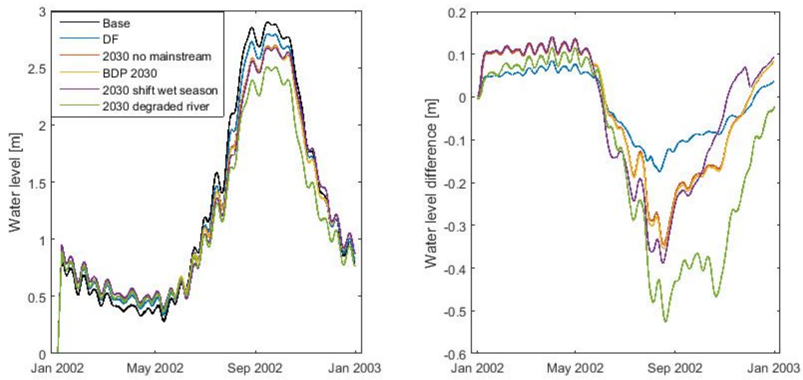


(d) Tan Chau

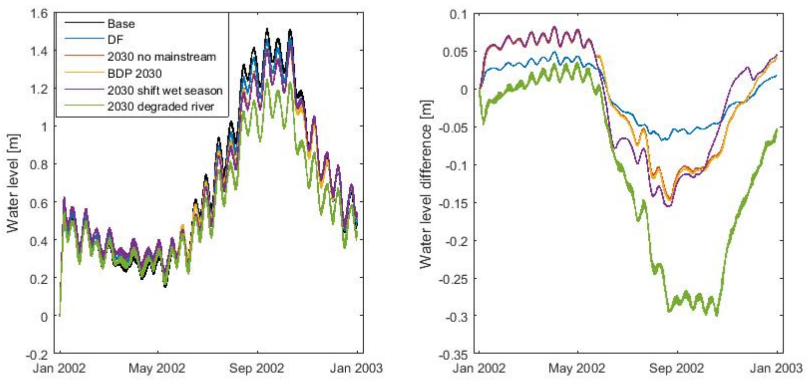
Figure F.9: Water level and difference from base for different scenarios at measurement locations (1)



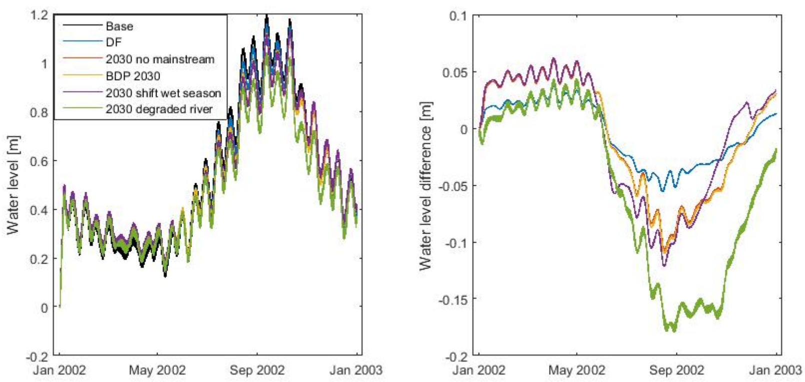
(a) Chau Doc



(b) Vam Nao



(c) My Thuan



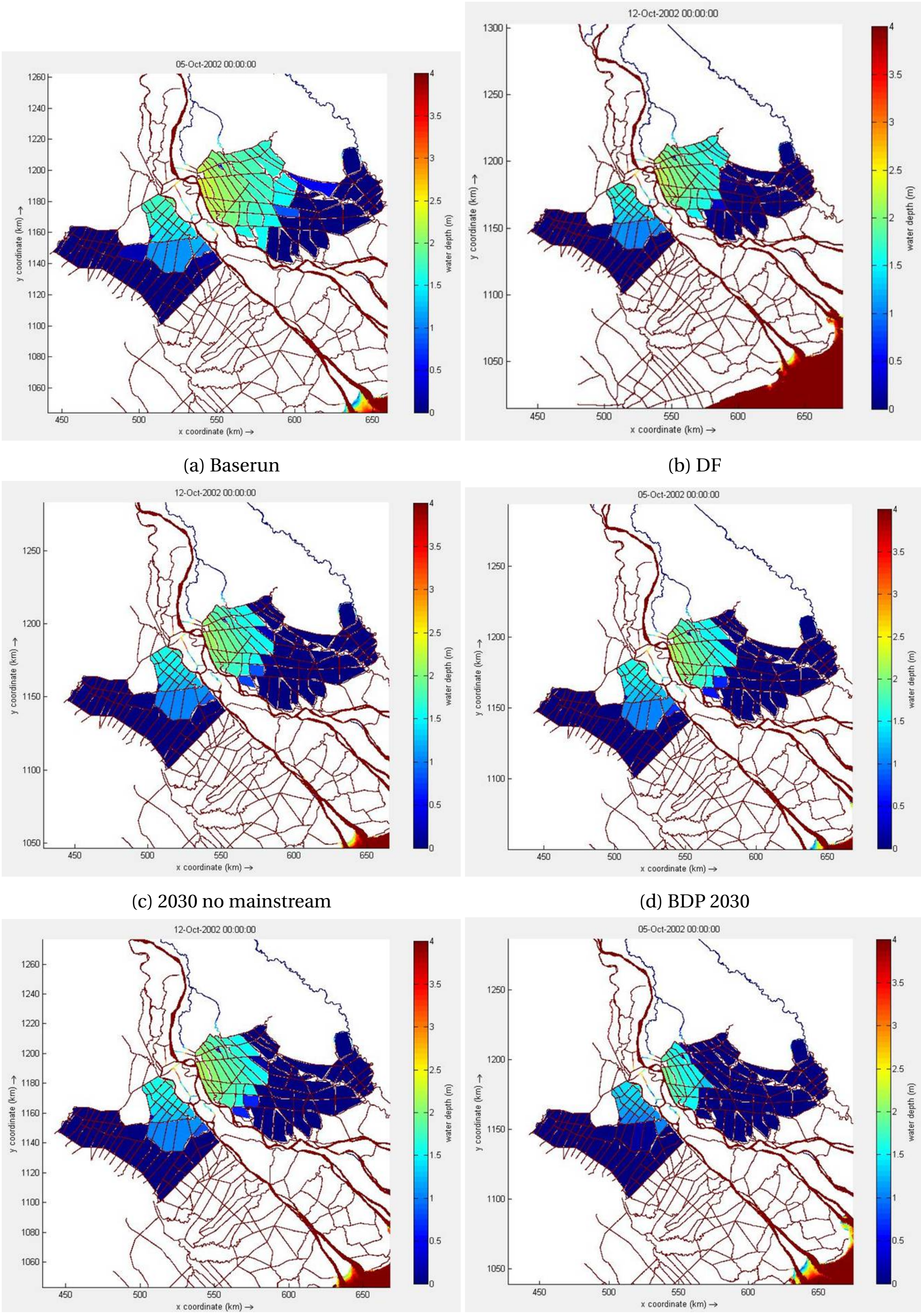
(d) Can Tho

Figure F.10: Water level and difference from base for different scenarios at measurement locations (2)

Max. water level Location	Baseline	Definite Future	BDP 2030 without main-stream dams	BDP 2030	BDP 2030 with degraded branches	Shift to start wet season
Phnom Penh	9.05	8.77 *-0.28 m*	8.50 *-0.55 m*	8.48 *-0.87 m*	7.85 *-1.20 m*	8.45 *-0.47 m*
Chaktomouk	9.13	8.85 *-0.28 m*	8.57 *-0..56 m*	8.55 *-0.58 m*	7.91 *-1.22 m*	8.52 *-0.48 m*
Neak Luong	6.94	6.70 *-0.23 m*	6.48 *-0.43 m*	6.46 *-0.48 m*	5.93 *-1.0 m*	6.43 *-0.39 m*
Chau Doc	3.13	3.03 *-0.10 m*	2.92 *-0.21 m*	2.92 *-0.21 m*	2.73 *-0.40 m*	2.91 *-0.18 m*
Tan Chau	4.49	4.34 *-0.15 m*	4.19 *-0.30 m*	4.19 *-0.31 m*	4.84 *-0.65 m*	4.16 *-0.26 m*
Vam Nao	2.90	2.80 *-0.10 m*	2.70 *-0.20 m*	2.69 *-0.21 m*	2.51 *-0.39 m*	2.67 *-0.18 m*
Can Tho	1.20	1.16 *-0.04 m*	1.12 *-0.08 m*	1.12 *-0.08 m*	1.04 *-0.16 m*	1.13 *-0.07 m*
My Thuan	1.52	1.46 *-0.05 m*	1.42 *-0.10 m*	1.41 *-0.10 m*	1.25 *-0.27 m*	1.43 *-0.09 m*
Min. water level Location	**Baseline**	**Definite Future**	**BDP 2030 without main-stream dams**	**BDP 2030**	**BDP 2030 with degraded branches**	**Shift to start wet season**
Phnom Penh	0.94	1.27 *+0.32 m*	1.51 *+0.57 m*	1.53 *+0.59 m*	1.20 *+0.25 m*	1.53 *+0.59 m*
Chaktomouk	0.94	1.26 *+0.32 m*	1.51 *+0.56 m*	1.53 *+0.58 m*	1.20 *+0.25 m*	1.53 *+0.58 m*
Neak Luong	0.60	0.78 *+0.17 m*	0.94 *+0.34 m*	0.95 *+0.35 m*	0.78 *+0.18 m*	0.95 *0.35 m*
Chau Doc	0.29	0.35 *+0.06 m*	0.41 *+0.12 m*	0.41 *+0.12 m*	0.38 *+0.09 m*	0.41 *+0.12 m*
Tan Chau	0.41	0.51 *+0.10 m*	0.60 *+0.19 m*	0.60 *+0.19 m*	0.52 *+0.11 m*	0.60 *+0.19 m*
Vam Nao	0.28	0.33 *+0.06 m*	0.38 *+0.11 m*	0.39 *+0.11 m*	0.36 *+0.08 m*	0.39 *+0.11 m*
Can Tho	0.12	0.14 *+0.02 m*	0.16 *+ 0.04 m*	0.16 *+0.04 m*	0.14 *+0.02 m*	0.16 *+0.04 m*
My Thuan	0.15	0.18 *+0.03 m*	0.20 *+0.06 m*	0.20 *+0.06 m*	0.16 *+0.015 m*	0.20 *+0.06 m*

Table F.2: Maximum and minimum 5-day averaged water level, including absolute change from the baseline

F.4. Effects on floodplain inundation



(a) Baserun

(b) DF

(c) 2030 no mainstream

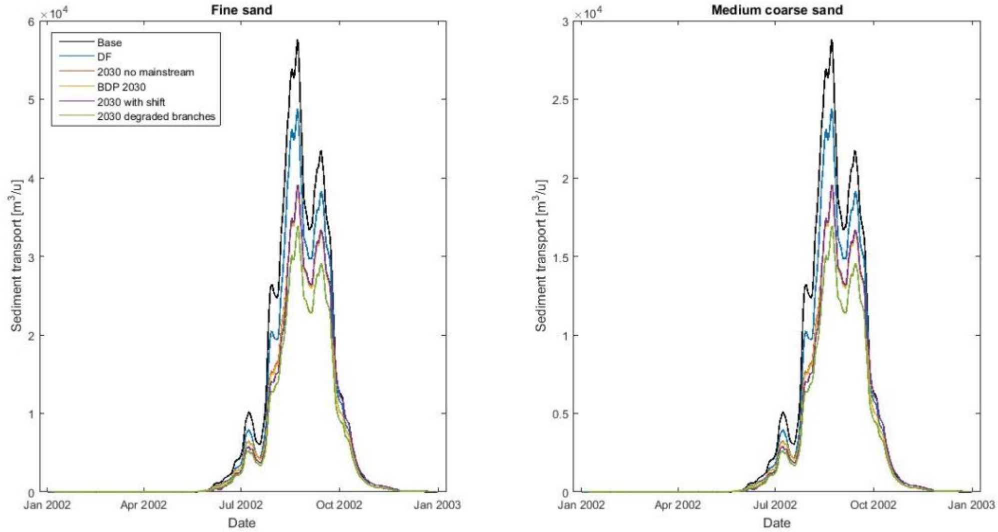
(d) BDP 2030

(e) 2030 shift wet season

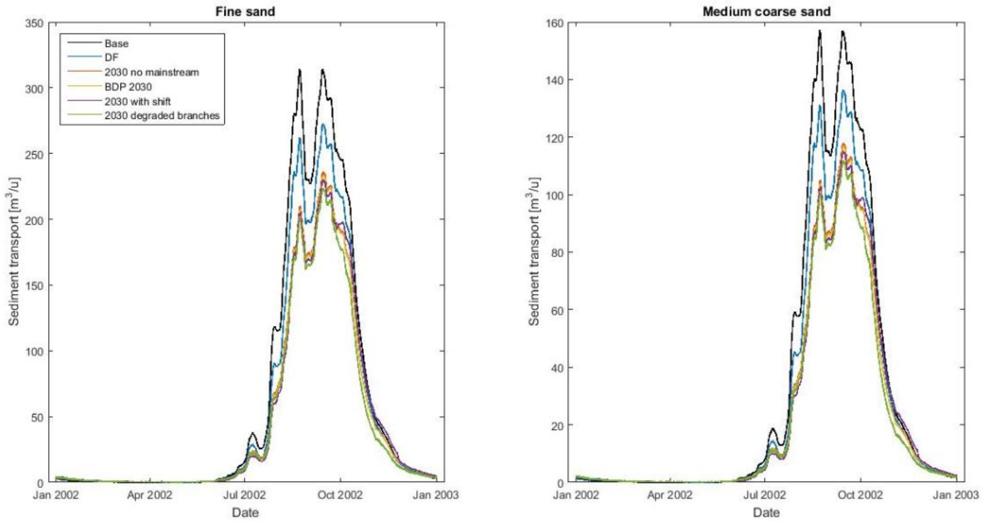
(f) 2030 degraded river

Figure F.11: Maximum extent and waterdepth in the Floodplains for different hydropower scenarios

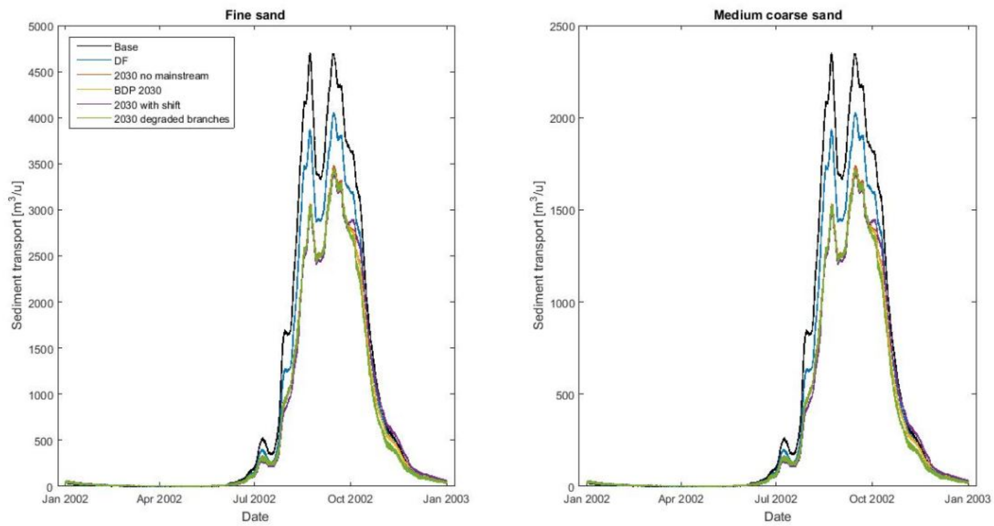
F.5. Effects on transport capacity



(a) Phnom Penh

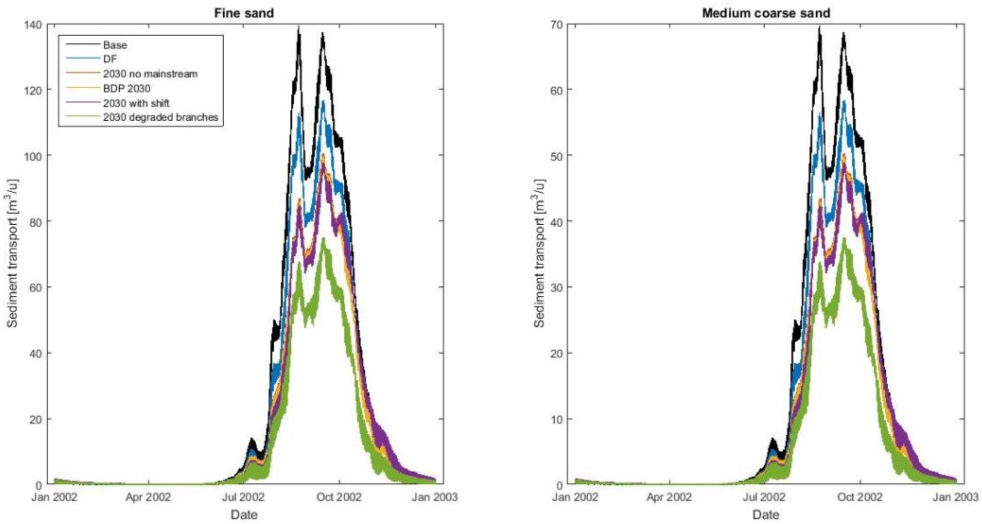


(b) Chaktomouk

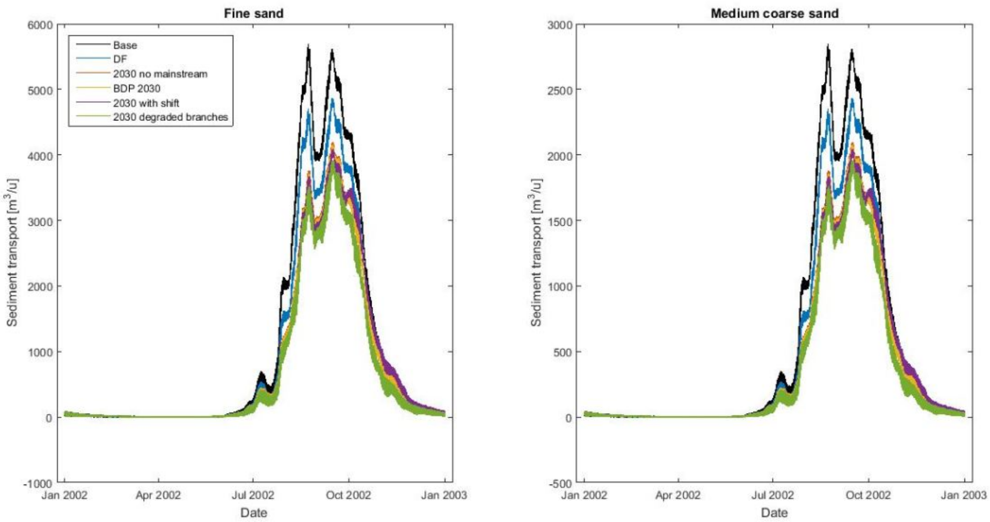


(c) Neak Luong

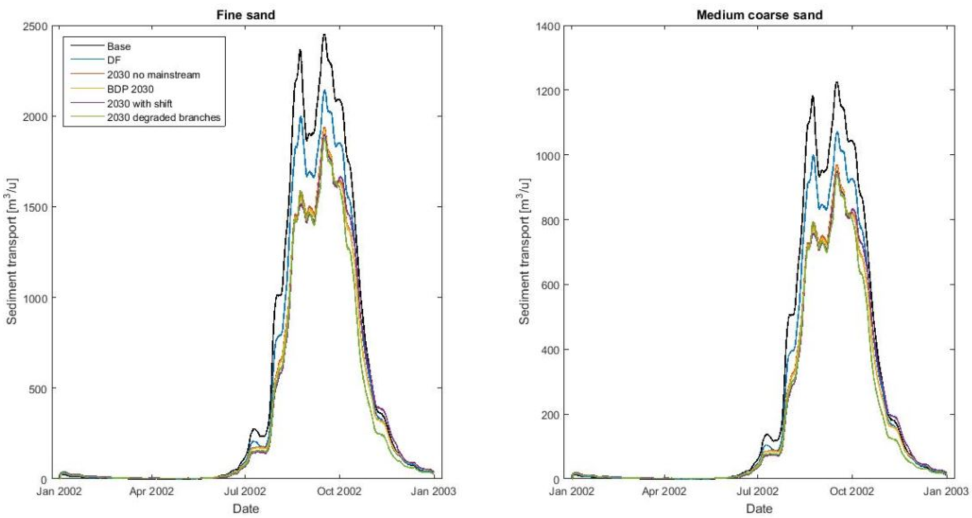
Figure F.12: Transport capacity for different scenarios of fine sand and medium coarse sand per location



(a) Chau Doc

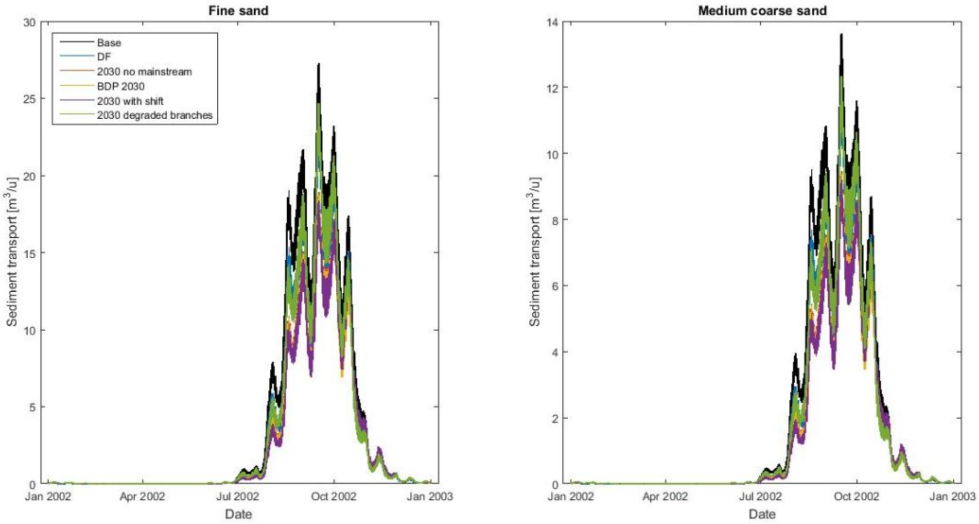


(b) Tan Chau

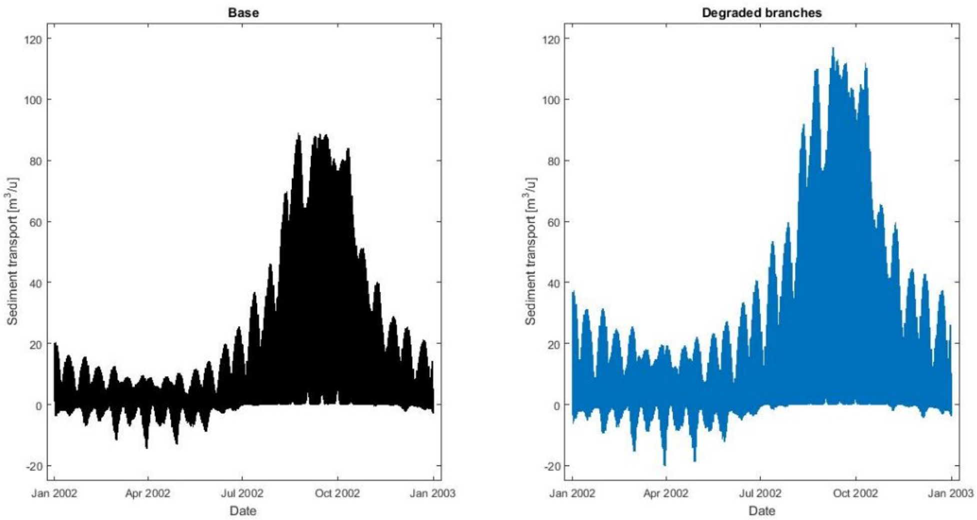


(c) Vam Nao

Figure F.13: Transport capacity for different scenarios of fine sand and medium coarse sand per location

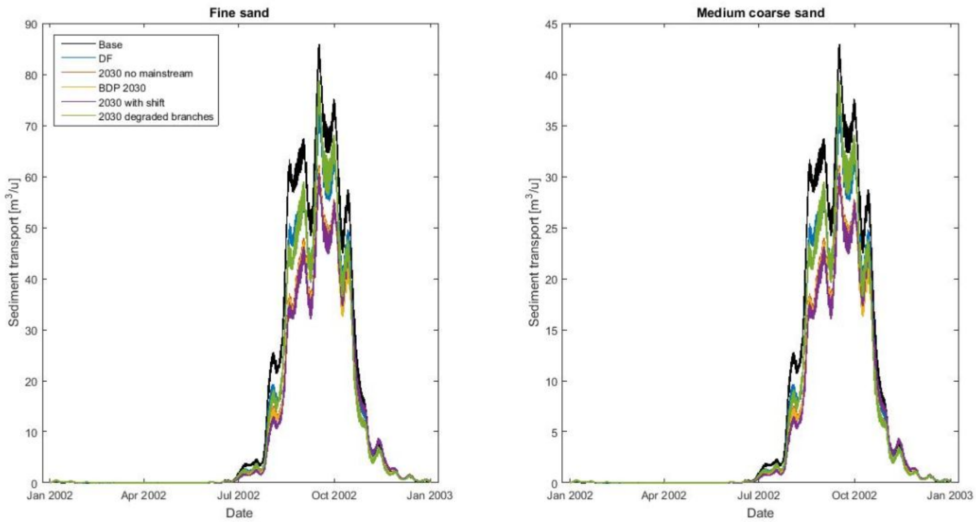


(a) Hydropower scenarios daily averaged

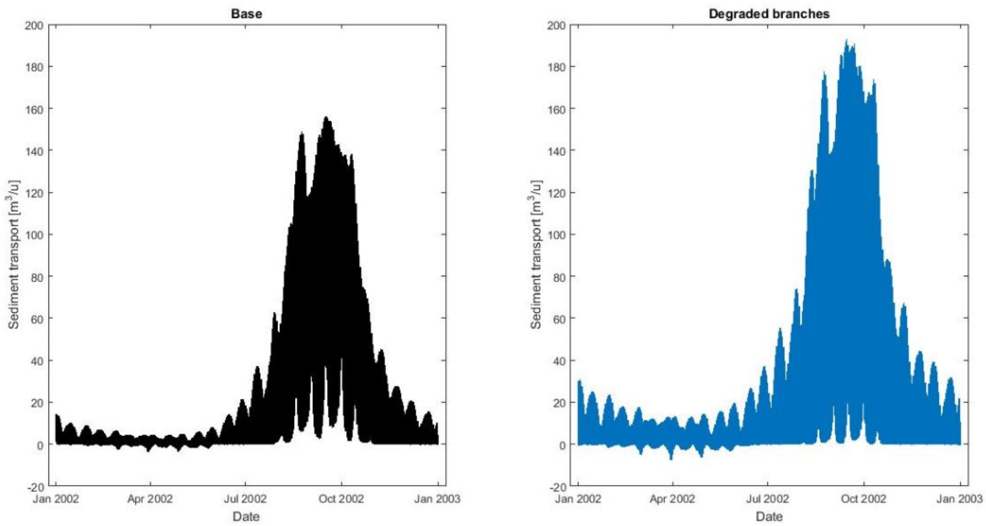


(b) Tidal influence Base scenario and degraded branches

Figure F.14: Transport capacity at Can Tho



(a) Hydropower scenarios daily averaged



(b) Tidal influence Base scenario and degraded branches

Figure F.15: Transport capacity at My Thuan

F.6. Effects salt intrusion

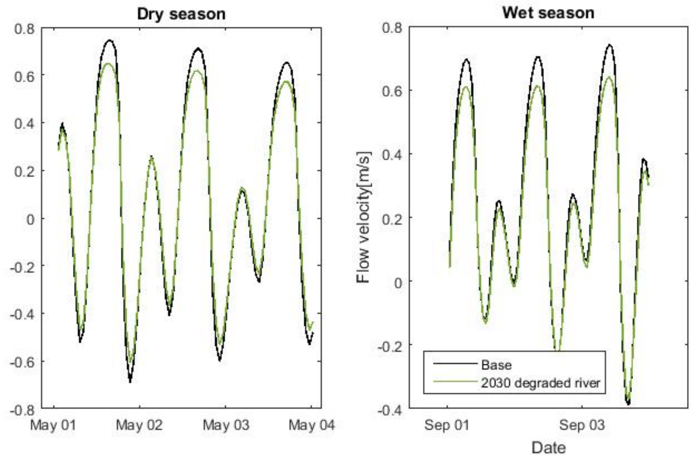


Figure F.16: Flow velocity in mouth of Bassac for a short period in the wet and dry season

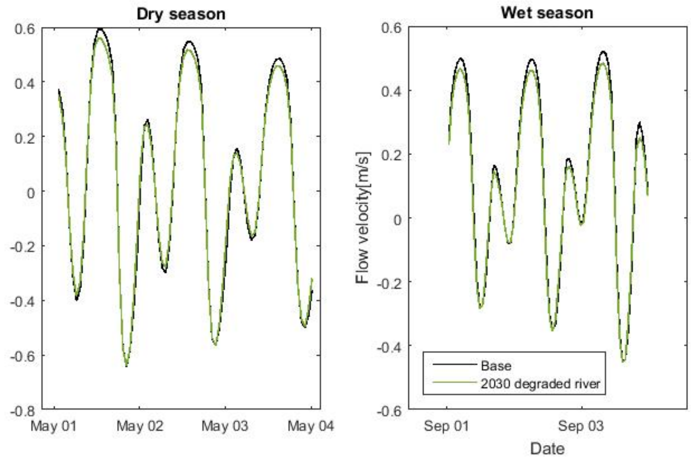
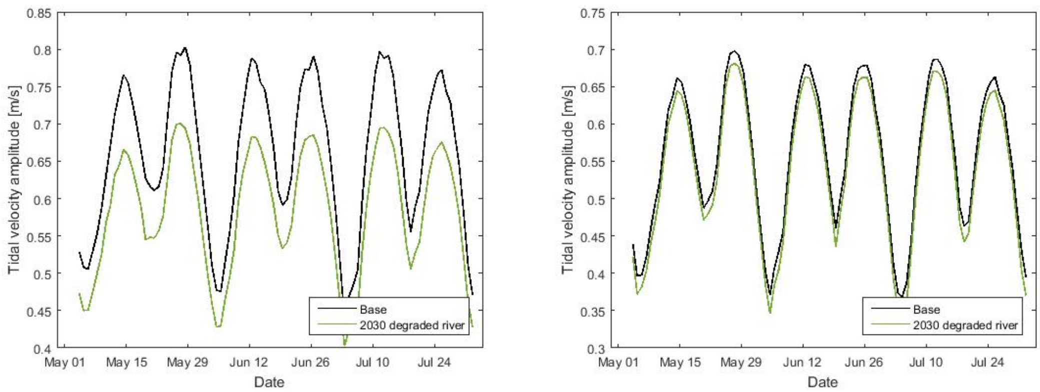


Figure F.17: Flow velocity in mouth of Mekong for a short period in the wet and dry season



(a) Bassac

(b) Mekong

Figure F.18: Tidal velocity amplitude in the mouth base scenario and degraded branches in both branches

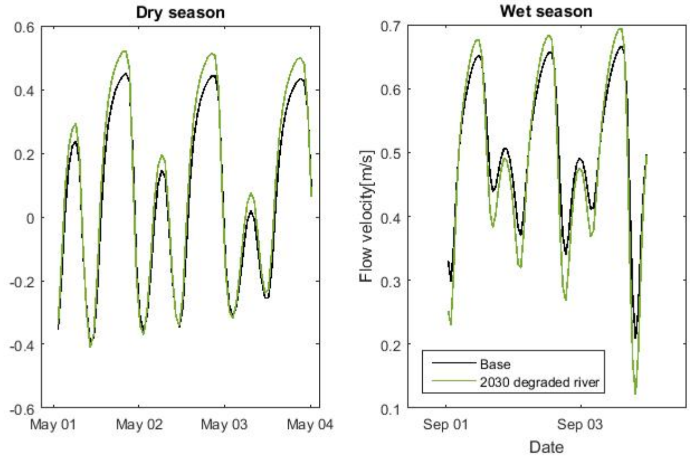


Figure F.19: Flow velocity in Bassac (Can Tho) for a short period in the wet and dry season

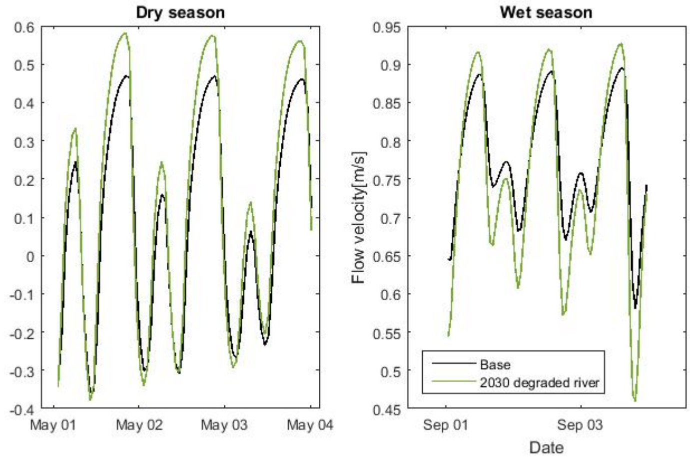
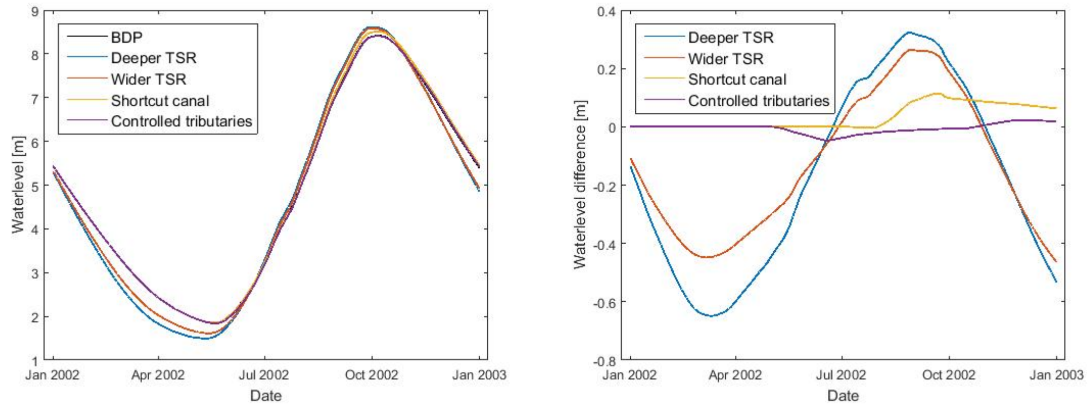


Figure F.20: Flow velocity in Mekong (MyThuan) for a short period in the wet and dry season

G

Mitigation measures

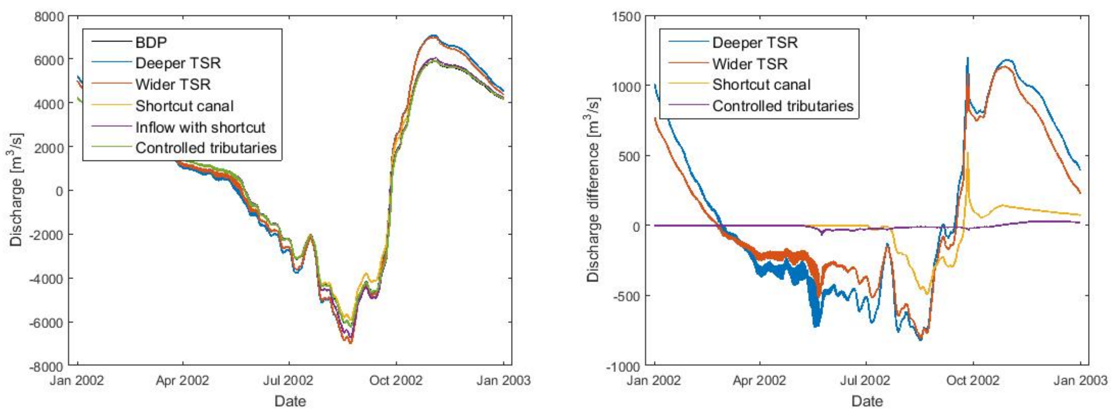
G.1. Mitigation Tonle Sap lake



(a) Water level Tonle Sap lake

(b) Water level difference from BDP 2030

Figure G.1: Water level and difference from BDP 2030 in Tonle Sap lake for different mitigation measures

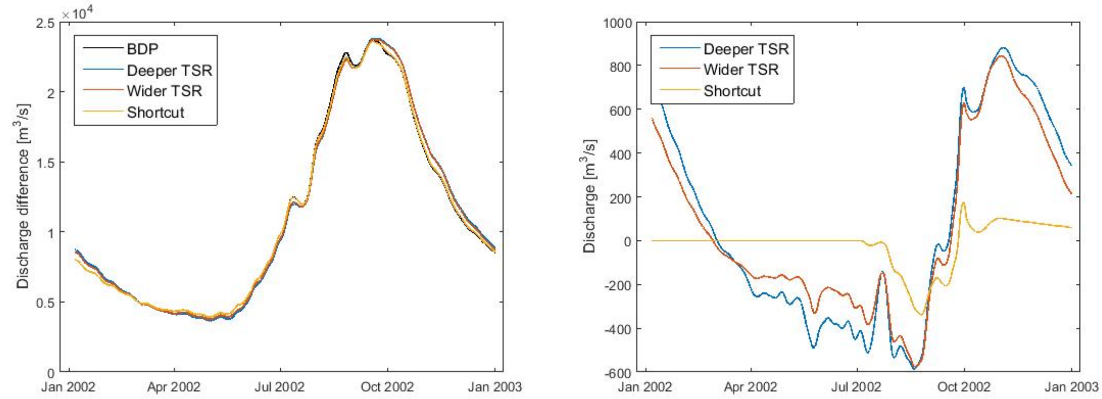


(a) Discharge

(b) Discharge difference from BDP 2030

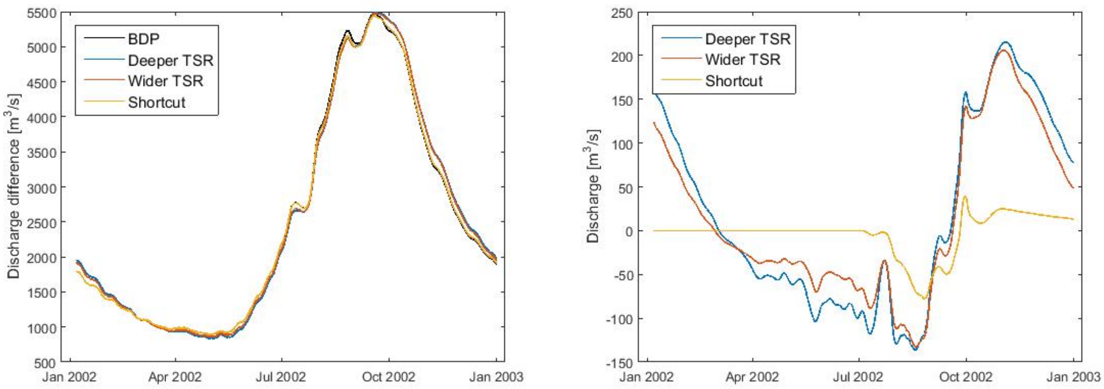
Figure G.2: Discharge and discharge difference to and from the lake (TSR) for different mitigation measures

G.1.1. Effects on the delta



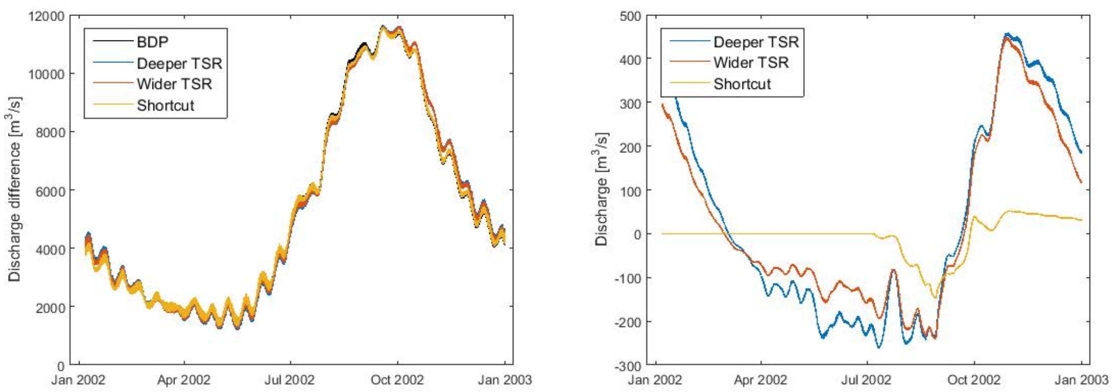
(a) Discharge (b) Discharge difference from BDP 2030

Figure G.3: Discharge and discharge difference at Tan Chau for different mitigation measures of Tonle Sap lake



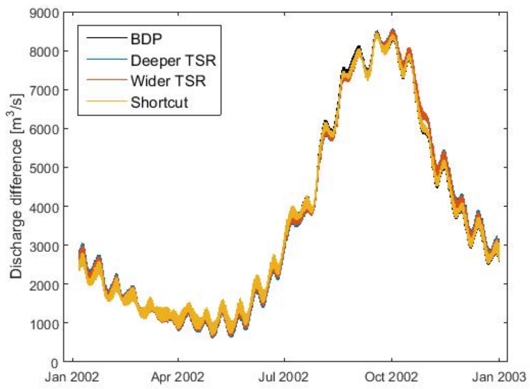
(a) Discharge (b) Discharge difference from BDP 2030

Figure G.4: Discharge and discharge difference at Chau Doc for different mitigation measures of Tonle Sap lake

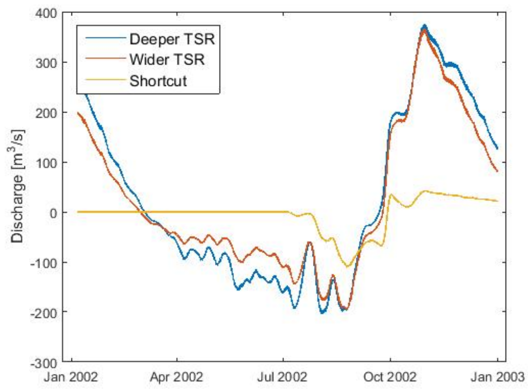


(a) Discharge (b) Discharge difference from BDP 2030

Figure G.5: Discharge and discharge difference at My Thuan for different mitigation measures of Tonle Sap lake

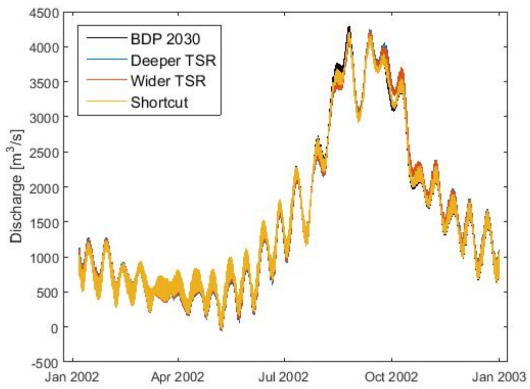


(a) Discharge

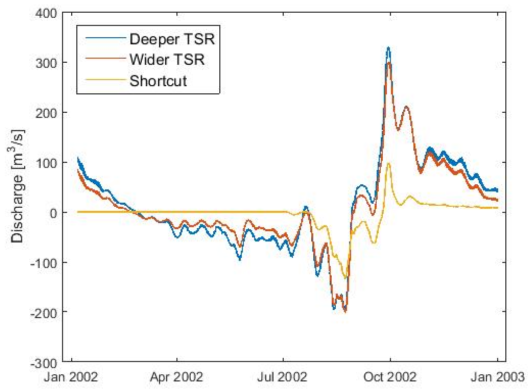


(b) Discharge difference from BDP 2030

Figure G.6: Discharge and discharge difference at Can Tho for different mitigation measures of Tonle Sap lake

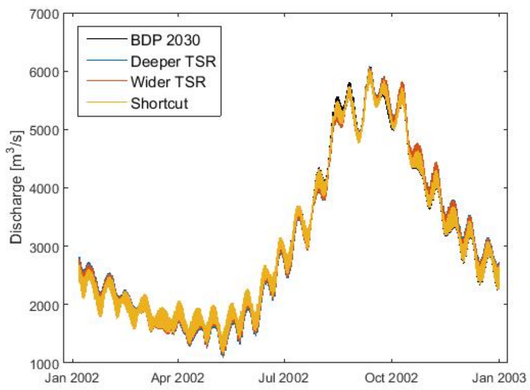


(a) Discharge

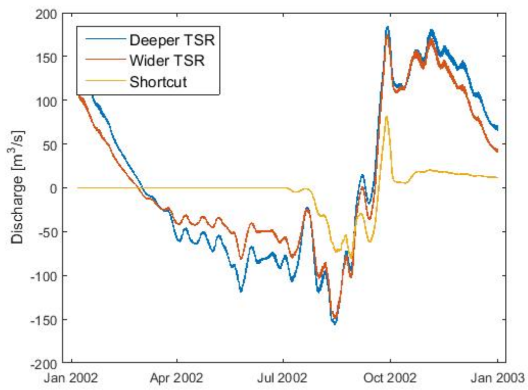


(b) Discharge difference from BDP 2030

Figure G.7: Discharge and discharge difference to the Plain of Reeds for different mitigation measures of Tonle Sap lake



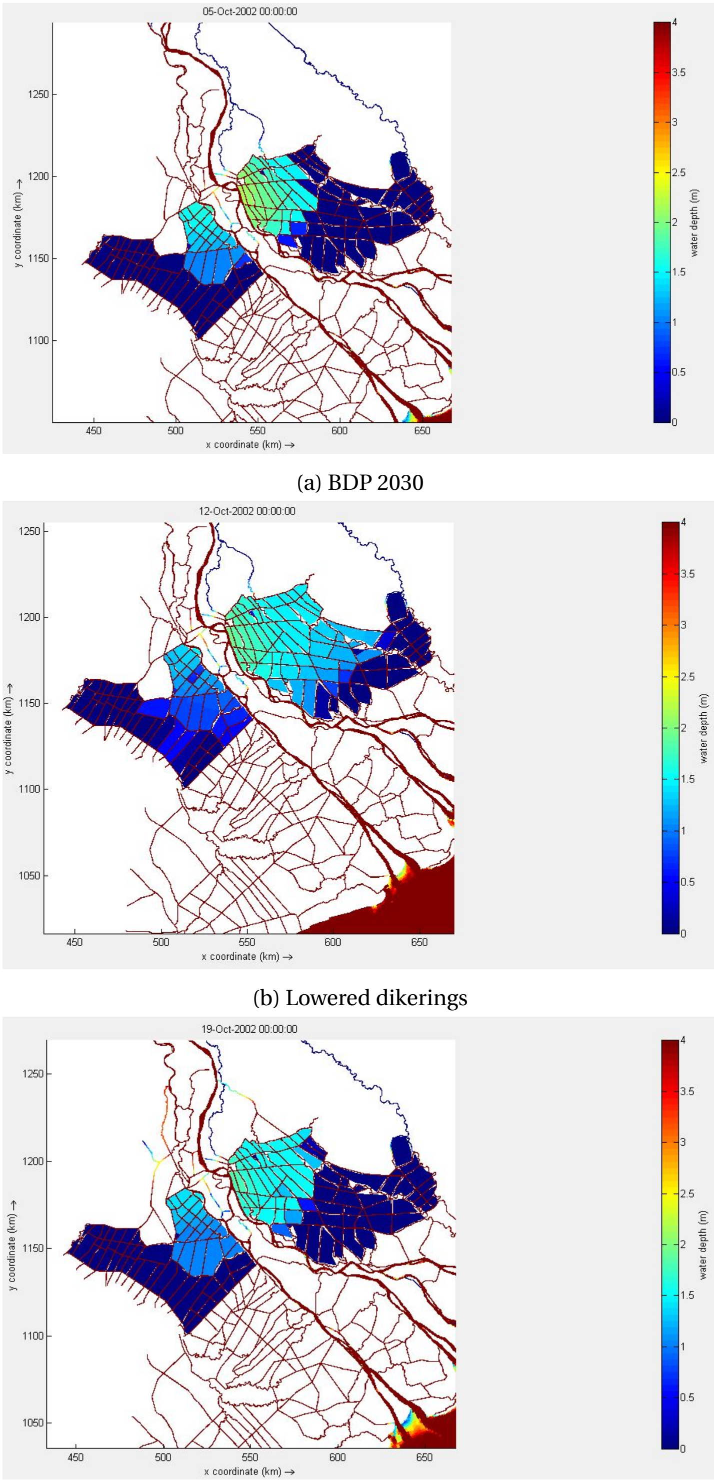
(a) Discharge



(b) Discharge difference from BDP 2030

Figure G.8: Discharge and discharge difference to the Long Xuyen Quadrangle for different mitigation measures of Tonle Sap lake

G.2. Mitigation Vietnamese canal-floodplain system

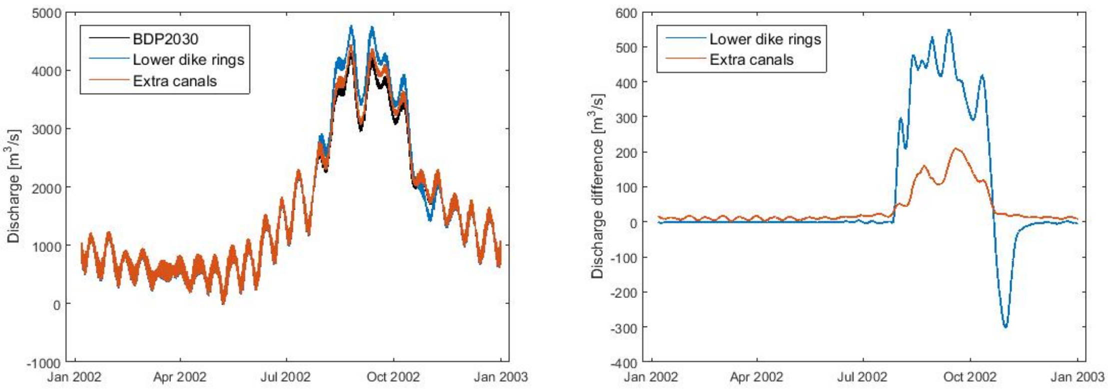


(a) BDP 2030

(b) Lowered dikerings

(c) Extra canal to floodplains

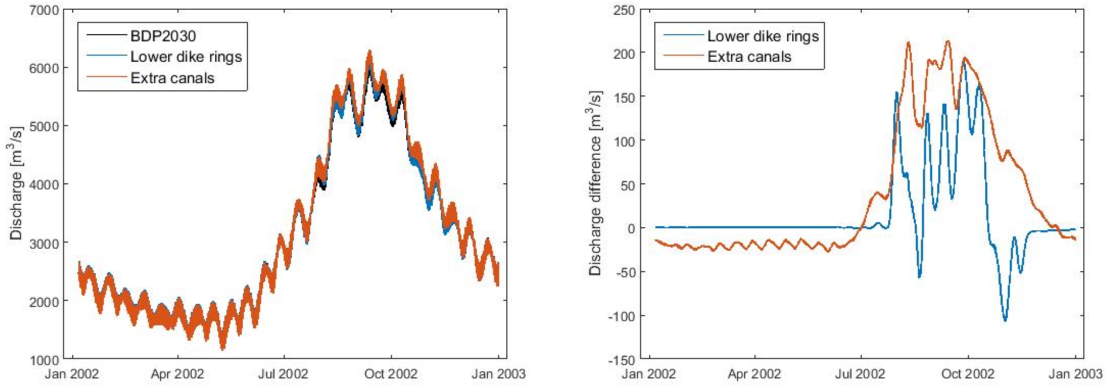
Figure G.9: Maximum extent and water depth in floodplains for different scenarios



(a) Discharge

(b) Discharge difference from BDP 2030

Figure G.10: Discharge and discharge difference to the Plain of Reeds for different mitigation measures of the floodplain area



(a) Discharge

(b) Discharge difference from BDP 2030

Figure G.11: Discharge and discharge difference to the Long Xuyen Quadrangle for different mitigation measures of the floodplain area