Tha Chin River Project

A solution for salt intrusion in the Tha Chin River mouth

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by

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Preface

This is the final report of the Tha Chin River project, a multidisciplinary Civil Engineering project undertaken by Inge Arends, Willem Cijsouw, Han de Jong en Lieke Lokin. We are four Dutch Master students in Civil Engineering from TU Delft, specializing in Hydraulic and Structural Engineering. In the fall of 2016, we spent two months working at King Monkut's University of Technology Thonburi, Bangkok, on a solution for salt intrusion in the Tha Chin River in central Thailand.

The multidisciplinary project is an elective in the master of Civil Engineering at the Delft University of Technology. The goal of the project is to combine the knowledge different specializations in order to come to an integral solution for a problem. In our case the Royal Irrigation Department in Thailand provided us with the assignment, which gave us also the opportunity to work in Thailand.

During the project we not only learned more about the processes and impacts of salt intrusion, but also a lot about the Thai culture and habits. Adjusting to and dealing with obstacles we encountered during these two months made this learning experience even more valuable for our future as Civil Engineers.

Our time in Thailand will remain a valuable memory, not only because we got to see different sides of the country and talk to a lot of different people. But also because of the sad historical time we stayed there. During our time we saw the country turn black after the decease of His Majesty King Bhumibol Adulyadey, who was the countries leader for 70 years. The mourning of the Thai over their King made a great impression on us all. We learned that next to a leader who was present throughout many turbulent years the late King was also an engineer who did a lot on water resources. We wish the Thai people strength in their mourning and the start of a new era.

This project would not have been possible without the help of some people that have helped us throughout the process. First we would like to thank Dr Somkiat Apipattanavis, from the RID, for providing us the case and for the good mutual cooperation during the project. We also want to thank Dr. Chaiwat Ekkawatpanitand and Dr. Aphinat Ashakul from the KMUTT. They helped us with all practical matters, resources and valuable information. Last we will also never forget our great fellow student friends at KMUTT, who helped us a lot with all kinds of matters and with whom we have shared some great moments. Last but not least we would like to thank our sponsors who made the project possible.

We thank the Royal Irrigation Department for their confidence and hope our report will be to the Department's satisfaction. We hope this project will further contribute to our countries good mutual relationship, which was already established when His Majesty King Chulalongkorn graciously founded the RID's predecessor in 1902 and appointed the Dutchman Mr. van der Heide to undertake irrigation project planning in Thailand, and which will hopefully continue for a long time.

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Bangkok, October 2016

Executive summary

The Tha Chin River is a river in central Thailand, which starts in Chainat province as a branch of the Chao Phraya River and flows into the Gulf of Thailand at about 35 km southwest of Bangkok. The Tha Chin is one of Thailand's most important rivers and it plays a vital role for the lives of over two million people living in this basin. Near the river mouth, it serves as a traffic route for about 4000 ships, mostly used for fishing, located in the area. More upstream, the river is used for both shrimp farms and fisheries, as well as fruit and flower farming and paddy fields. Al these fields are irrigated using a vast and complex network of increasingly smaller irrigation channels, controlled by water gates. The use of river water is however not limited to irrigation only. Besides the agricultural users, the industrial and domestic users are two other major consumers of water from the Tha Chin.

Currently the river basin is experiencing serious problems regarding water quality. One of these problems is the high amount of pollution in the river. Multiple factors (e.g. waste water dump from several sources, oil spillage and water hyacinths) contribute to lower dissolved oxygen levels, higher levels of chemicals and algae blooms. Resulting in considerable damage to the ecosystem in the last decades.

Another major water problem is salt intrusion. The tide in the Gulf of Thailand brings saline water into the river. Currently this water is pushed back by increasing the river discharge, which is controlled by the Pho Praya water gate in the Suphanburi Province. However, during the dry season the river discharge is often too low to effectively push back salt water and therefore salinity in the Tha Chin becomes too high. The salt water threatens the agricultural production, it decreases the amount of yearly grown crops or even destroys them complete, causing major economic damage. Additionally, it decreases the river capacity with respect to its function to provide fresh water.

One of the major institutions involved in managing and controlling the Tha Chin River is the Royal Irrigation Department (RID). This is a department of the Thai Ministry of Natural Resources & Environment. The RID is responsible for the development and maintenance of the main irrigation systems. As such, it controls the irrigation network in the Tha Chin Basin. Part of their mission is developing water resources and in their search for solving the salt intrusion problem in the Tha Chin, they asked the TU Delft project team to find with a solution.

Two solutions are proposed. The first solution is building a barrier in the river at 12 km upstream from the river mouth. This solution is the only one that can solve the salt intrusions problem, however due to negative experiences in other rivers this solution is likely to encounter much opposition. The second solution is the construction of Balance Islands in front of the river mouth. The principal of this solution is to alter the tidal flow such that saline water flows less into the river while the river discharge is not obstructed. In order to implement this solution further research is needed. Also this solution is not able to solve the salt intrusion problem entirely, but will make the problem less severe.

Contents

1 Introduction

The Tha Chin is a distributary of the Chao Praya river, the largest and most important river in Thailand.The Choa Phraya river flows thourgh Bangkok. The Tha Chin River is locatated west of Bangkok and is approximately 300 km long.

The Tha Chin River basin suffers from low water quality. Two causes can be linked to this problem. The first one is the pollution which exceeds the current standards, due to point and non-point pollution. Secondly, the salinity in the lower part of the basin is too high. During the wet season and the beginning of the dry season, the upstream fresh water supply is enough to counterbalance salt water intruding from the Gulf of Thailand. In the end of the dry season, especially around April and May, insufficient water is available so the salinity rises to undesirable levels. The second cause is in this research the most important one.

The fresh water in the Tha Chin River basin is mainly used by farmers, households and industry. When the demands of those users is not met, a few problems occur. The first one is the quality of life of the people that live in the basin area, which will go down if they do not have enough fresh water. The next problem that arises is that yield of the farmers and the productivity of the industry will decrease.

In order to prevent those problems the RID asked the project team to come up with a solution that deals or mitigates the saline water.

This report deals with the steps and considerations of the project team in order to give an advise on the salt intrusion problem. The next chapter, the analysis, contains the environmental and stakeholder analysis which are conducted in order to obtain a clear view on the project. Chapter 3 gives the problem statement with the boundaries and requirements of the project. Then in the fourth chapter different solutions are proposed, which are evaluated in chapter 5. The last chapter, the conclusion and recommendations, will given an advise on a final solution.

In the appendices more information can be found on specific parts of the project, references to these appendices are given in the text.

2 Analysis

In order to get hold of the problem and the general aspects of the Tha Chin an analysis is done, of which the results are given in this chapter.

This chapter is divided into three main sections. The first section, the environmental analysis, elaborates on the river basin. This includes geographical information about the land use and the course of the river and side channels as well as hydraulic and hydrological conditions. The second section elaborates on the stakeholders in the river basin and their interests and influence. The last section elaborates on reference projects and lessons that could be learned from these projects.

2.1. Environmental analysis

The environmental analysis is divided in different subsections. First the most relevant aspects of the Chao Phraya River basin will be elaborated. Second the Tha Chin River basin will be discussed in more detail. The geology, water demands, climate, flow properties and water quality of the Tha Chin River basin will be elaborated.

2.1.1. The Chao Phraya River basin

The Tha Chin river is part of the Chao Phraya river basin, which is the largest basin in Thailand. The Chao Phraya is most important river basin in Thailand. The total basin covers 160,000 km^2, in which the Tha Chin River basin covers 18,105 km^2. Several projects have been conducted to improve the irrigation system of the Chao Phraya River basin. Since 1950, the government has constructed approximately 3,000 dams to store monsoon flows for the dry season (WWAP, 2003).

As can be seen in figure 2.1, the upper basin consist of four large rivers; the Ping, Wang, Yam and Nan River. These four rivers are the source of the Chao Phraya River. The Tha Chin River, which is a branch of the Chao Phraya River, is displayed in figure 2.1 as the Nakhon and the Chai Si River. Both the Chao Phraya and Tha Chin river mouths are located in the most northern part of the Gulf of Thailand, the Bay of Bangkok.

To control the water supply in the Chao Phraya River basin, numerous control structures are located in the basin. The most important structures are:

- Bhumiphol dam, Ping River
- Chao Phraya gate, Chao Phraya River
- Sirikit dam, Nan River
- Polthep gate, upstream in Tha Chin River
- Pho Phraya gate, Tha Chin River

The first two dams are located in the upper Chao Phraya basin. The two reservoirs created by these dams control 22 % of the total discharge (WWAP, 2003). Besides water storage these dams have additional purposes such as electricity generation, irrigation and regulation of domestic and industrial water use.

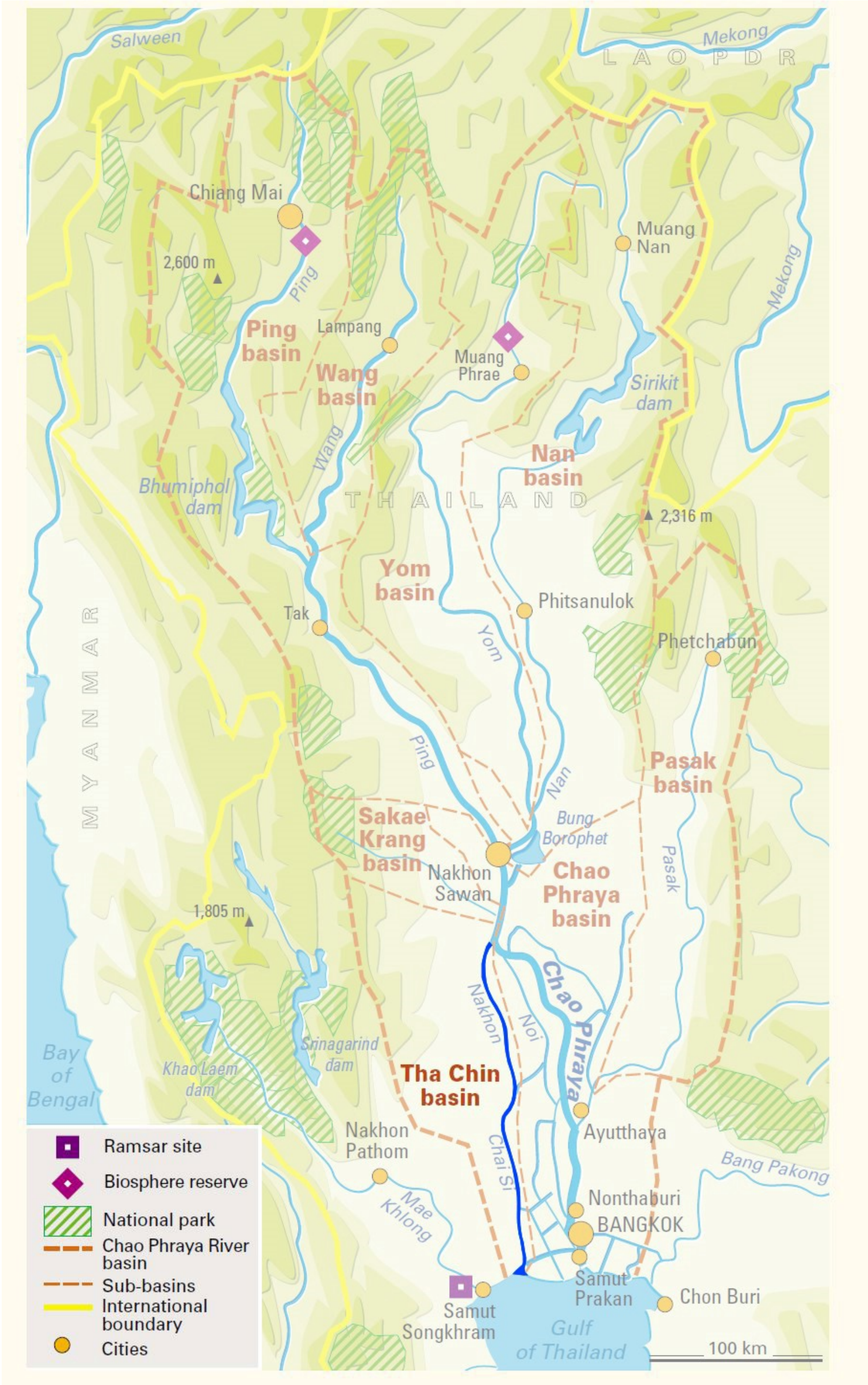


Figure 2.1: Rivers in Thailand, both the Chao Praya and Tha Chin basins are indicated with the dashed lines. The Tha Chin river is highlighted in dark blue. source: WWAP (2003)

2.1.2. Tha Chin River basin

The Tha Chin River is a branch of the Chao Phraya river and starts at the Pholthep gate (approximately 300 km from the river mouth), which together with the Chao Phraya gate regulates the discharge distribution between the Chao Phraya River and the Tha Chin River. The Pho Phraya water gate (located approximately halfway the Tha Chin River) is the gate that regulates the discharge downstream of the gate. For a more detailed overview of the river see appendix A.

Upstream of this gate there is a tributary, the Krasiao River, which has the Krasiao reservoir far upstream. A gate, called the Sam Chuck gate, regulates the inflow of this tributary. The most important tributaries of the lower Tha Chin basin are the Song Phi Nong River (which connects to the U Thong water supply) and the Bang Len, Bang Pla and Bang Phra canals (which connect to the Maeklong river). The Tha Chin is favored in water supply over the Maeklong River in the west, while at the same time it has lower priority in water supply than the Chao Phraya River in the east (which runs through Bangkok). The Chao Chet River and Phraya Banlue canal are the most important channels through which water is diversed from the Tha Chin to the Chao Phraya River.

All these channels connected to the Tha Chin River have water gates at their respective connections with the Tha Chin. These gates are used to manage water allocation from and to the Tha Chin. Additionally, an extensive system of irrigation canals, mostly with local regulation gates, is connected to the Tha Chin River. Through these canals the whole basin is provided with fresh water for irrigation purposes and domestic and industrial use.

2.1.3. Geology

In this section geological data of the basin will be elaborated. It will start with the Land use in the river basin, followed by the soil properties. thirdly the mangroves the sediment in the river basin will be discussed. Finally the bathymetry will be discussed.

Land use

The Tha Chin River basin covers 18,105 km^2 and consist of 12 provinces, 48 districts, 329 Tambons (municipalities) and 2,775 villages. In 2009 the basin had a population of 2,418,727 people (RID, 2011).

Figure 2.2 shows the land use in different areas. The left overview is from 2002 and the right one from 2009. As can be seen in this figure most of the land is used for paddy fields, but the total area used for paddy fields has been decreased in these seven years. In the lower basin area the decrease of paddy fields is the most significant. The paddy fields have been replaced by other kinds of agriculture (especially fruit trees) and urban areas (buildings). The change in land use has its source in the urbanization of the lower part, the expansion of Samut Sakhon.

Urbanization has led to a relatively large change in agricultural area. The replacement of paddy fields by other agriculture has also occurred in the upper basin area. Besides the change in land use over the last years, it can concluded that there is a clear division between the lower and the upper part of the basin. The lower part is mainly used as living area and associated agriculture. On the other hand, the upper part is mainly used for paddy fields and crops. Other agricultural activities, in this context, are livestock, aquatic plants and integrated agriculture.

Soil properties

The whole the Tha Chin River flows through the lower delta regions. Because of this, the soil around the river is composed of different sorts of clay, which depositions of upstream material e.g. lime stone and volcanic rock. In some areas this clay is mixed with silt and sand (loam soil) and/or organic materials. Due to the continuous deposition of materials by the river, the soil is very layered. In the lower Changwat Nakhon Pathom area west of the river a significant amount of land is created by dredged material from the river. Therefore, this soil contains above average amounts of organic material (RID, 2011).

Mangroves and sediment

Thailand has lost 84 percent of its mangrove forests. This is the largest loss of mangrove of any country in the world (AMNH, 2004). The mangrove area around the lower part of the Tha Chin River basin has declined as well. A mangrove forest needs a mildly saline environment, when there is too much or too little salt they will not survive. However, in time, a mangrove forest is capable of adapting to new environments (Faridah-Hanum et al., 2014). More information about mangroves can be found in appendix C.

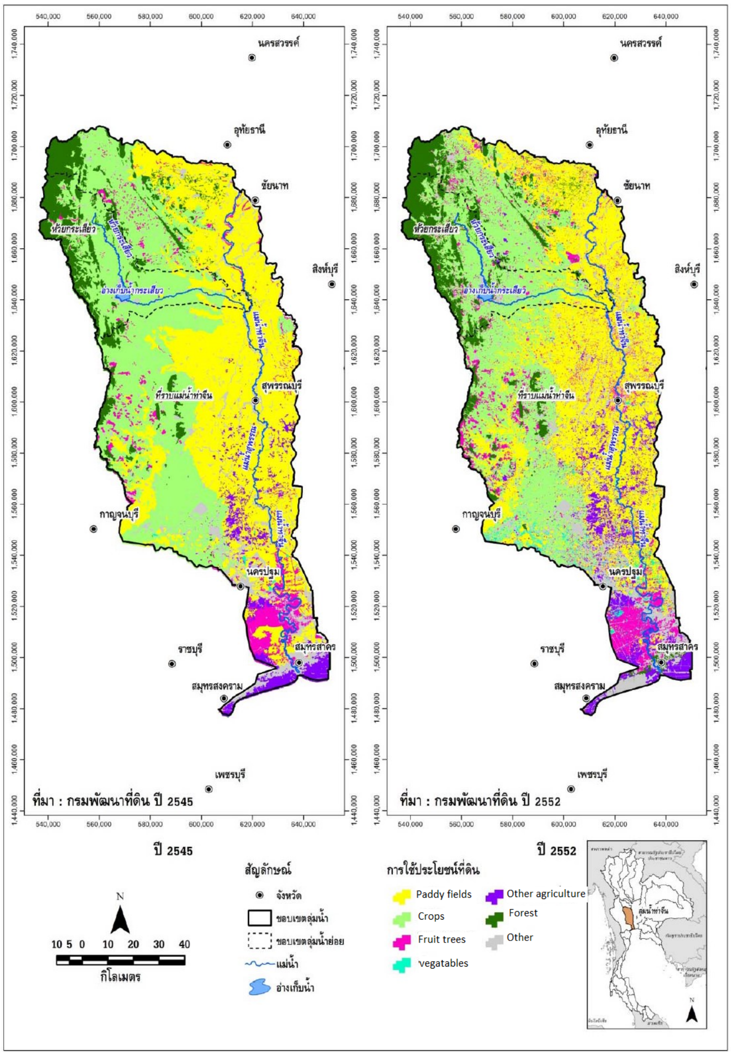


Figure 2.2: Land use in the Tha Chin River basin in 2002 (left) and in 2009 (right). Source: RID (2011)

The sediment found in the river is mostly fine sediment (mud). This mud contains a lot of water. The strength is obtained through cohesion between clay particles. However, this is quite small. The beds are soft and can erode and liquefy easily. The large water content causes a small bearing capacity and the small permeability causes a higher risk of liquefaction. Also sandy solutions do not work on muddy beds (Winterwerp, 2016).

Bathymetry
The Tha Chin Estuary has an almost no bed slope. Due to the many bends in the lower area, the river depth varies a lot. The mouth is very shallow with large floodplains (with mangroves). A shipping channel is maintained in the middle of these floodplains extending to a deeper part. The estuary ends at approximately 80 km upstream from the mouth. From this point on, the bed slope increases. The channel width converges quickly at the mouth. After 80 km the convergence length increases. Specific details (charts, figures and tables) about the bathymetry can be found in appendix D.

2.1.4. Water demands

The water in The Chin Basin is used by multiple users, all with their own need for fresh water. The total amount of water needed is 8,075 MCM/year ($256 m^3/s$) (RID, 2011). The data is collected during the years 2000 through 2009, for more detailed information see appendix E.1. Water that is used for the 'Ecosystem' means water that is used to maintain the quality of the ecosystem downstream in the Basin is meant. Note that there multiple water demands researches have been performed and all had different conclusions. However the order of magnitude of the total water demand in these researches is equal. In the left pie chart in figure 2.3 it can be seen that the agriculture sector uses most of the water, around 84 % of the total water use. A more detailed overview of the other 16 % can be found in the right pie chart. More information can be found in appendix E.1.

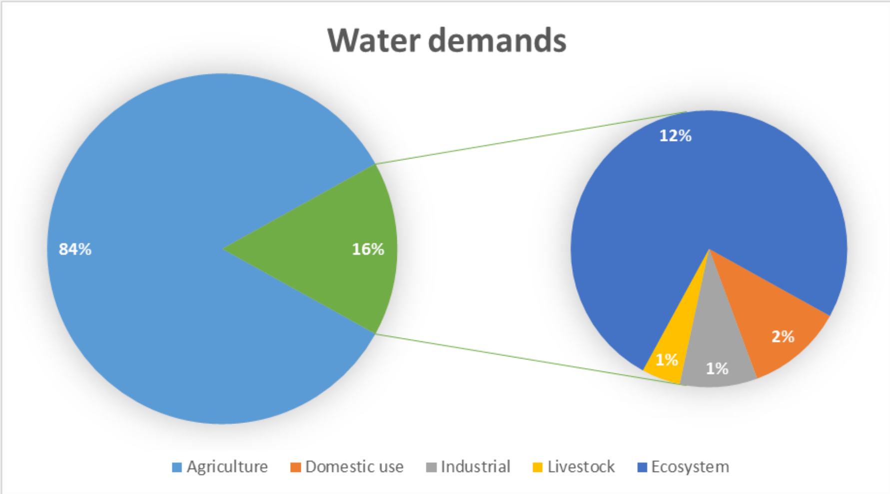


Figure 2.3: Water demands in the Tha Chin River basin. Source of the data: RID (2011)

In the wet season fulfilling the demands of the users does not cause any problems, but in the dry season this might be different.

During the dry season the water supply to the Tha Chin River is mainly restricted to the release of the Bhumibol and Sirikit Dam. These dams also provide a large part of the country with energy. Both the energy demand and the downstream water demand have to be met during the dry season. During droughts this may cause conflicts, as the consistency of the energy supply has the highest priority.

During droughts the allocation of water to the different users is regulated by priority. Users with the highest priority are the last ones to get cut-off of water supply. The priority is as follows (RID, 2011):

1. Domestic use: water consumption of people living in the basin as well as of industry
2. Low water demand agriculture, farmers will be encouraged to use less water
3. The control of the salinity levels in the river mouth
4. Second harvest crops
5. Navigability of the river

The allocation of water within the agricultural sector is regulated by importance of the branch and the damage caused by a cut-off. The priority is as follows:

1. Aquaculture, fish ponds
2. Vegetables and fruits
3. Crops (Rice, Mais, Wheat etc.)
4. Second harvest crops

An important influence decreasing the water supply is the large amount of water hyacinths in the Tha Chin River. These plants lose large amounts of water through transpiration: the combination of evaporation of water and transpiration through the leaves. In a water bed filled with water hyacinths, up to four times the amount of water is lost through transpiration compared to direct evaporation.

2.1.5. Climate

The part of Thailand in which the Tha Chin River basin is located has, as most of Thailand, three seasons.

1. a wet season (mid-May to mid-October)
2. a cooler dry season (mid-October to mid-February)
3. a warm dry season (mid-February to mid-May

In the warm dry season, a high-temperature climate dominates, with maximum temperatures up to 40°C or more. . The average monthly temperatures in the Tha Chin basin range from 24.7°C to 30.1°C, the highest temperatures are reached in April, at 36.4 degrees.

The onset of the southwest monsoon leads to intensive rainfall from mid-August until early October, often accompanied by thunderstorms. The average annual rainfall is 1113 mm. The peak of rainfall is in September. Humidity reaches its peak during the rainy season, especially in October, with a measured peak of 94.5%. The average annual humidity is 75.9%. Monthly averages differ from 71.5 to 81.5 percent. (RID (2011), TMD (2016))

There is a large variability in the annual rainfall in Thailand, which can cause years of severe floods, as well as years of severe drought and water shortages. The last large flood occurred in 2011 with an estimated economic loss exceeding USD 45 billion.

The Bhumibol and Sirikit reservoirs are the two main basins that provide the Tha Chin with fresh water. Appendix F gives an overview of the water storage levels in the reservoirs. These are the two main basins that provide the Tha Chin with fresh water and can give an impression of the rainfall in the last few decades. Especially after the 2011 flood, the basin has experienced extreme drought which lead to the currently low storage levels in the reservoirs. A similar period of extreme drought occurred in the first years of the 1990's, after which a period of abundant rainfall followed. This pattern of alternating periods of extremes is seen especially in the last 20 years.

Storms occur in the Gulf of Thailand. There were six severe storms (typhoons) that previously crossed over the Gulf of Thailand between 1962 and 1998 (Phaksopa and Sojisuporn, 2003). These storms often occur in the wet season and not in the dry season.

2.1.6. Flow properties

In this section the Flow properties of the Tha Chin are elaborated. First the discharges are discussed followed by water levels in the river. The last part elaborates on the water levels in the mouth, which includes the tide propagating into the river

Discharges

The discharges during the years 2009 to the start of 2016 are provided by the RID. The data is collected from measurement stations at the Pho Praya gate and the Song Phi Nong canal. For the exact location see figure schematic overview in appendix A. Since there are more canals between these two points the exact discharge may be different, however data from all canals was not available.

A clear division can be made between high and low discharges in the wet and dry season respectively. In the dry season the discharge is between 20 to 50 m^3/s and in the wet season it is around 100 m^3/s, but it can reach up to 330 m^3/s.

Water levels in the river

Water levels of three measurement stations have been provided by the RID; T14 at 58 km T1 at 88 km and T13 at 145 km upstream from the mouth. The data and more information can be found in appendix G. Notice that the tide propagates quite far upstream and that its influence during the dry period is still present at T13. On the other hand, the high discharges are still visible at the lowest station, but the peaks in water level are lower than more upstream. Furthermore, the annual water level difference is approximately 3 meter with the lowest water level during the dry season.

Water levels in the Mouth

At the mouth the water level changes due to tide, storm surges and sea level rise. The tide in the mouth has a mixed character, with a form factor $\left(F = \frac{K1+O1}{M2+S2}\right)$ of the tide of 1.26. The number of days that the diurnal component is dominant and that the semi-diurnal component is dominant is almost equal. For information see appendix G.

The highest tidal elevation measured is MSL + 1.71 m in the past six years. The theoretical water level computed with the tidal constituents is MSL + 1.78 m. The storm surge level is approximately MSL + 2.7 m for a 100 year return period (WorldBank, 2009). Storm surge levels from different models indicate a rise of 0.6 m to 1.0 m (Phaksopa and Sojisuporn, 2003) which confirms the storm surge level of MSL + 2.7 m.

2.1.7. Water quality

The water quality of the river is split into two components: salt intrusion and pollution. Salt intrusion is a problem in the most downstream part of the river. During the dry period, especially during periods of drought, the problems with salt intrusion will occur higher upstream. To properly understand the salt intrusion problems the first part will deal with the theory of salt intrusion in estuaries. Pollution is a year round problem but it is most severe during the dry periods. Pollution itself is mostly caused by human action in the river basin.

Salt intrusion process

In estuaries there is an interaction between tide in the sea, where the water is saline, and the fresh water provided by the river. During flood the salt sea water flows into the estuary and during ebb it will flow out. The interaction between tide, discharge and the local bathymetry determines to what extend the salt water will penetrate into the estuary. Two dimensionless numbers are related to this interaction, the Canter-Cremers number and the Estuarine Richardson number.

The relative volume of the fresh water discharge (Q_f) in a tidal period (T) over the tidal prism (P_t) is represented in the Canter-Cremers Number (equation 2.1). A higher Canter-Cremers number indicates that there is more fresh water available to push the saline water, flowing into the river due to the tide, downstream.

$$N = \frac{Q_f T}{P_t} \tag{2.1}$$

The Estuarine Richardson number (equation 2.2), which is the ratio of the potential energy provided by the fresh water discharge as buoyancy and the kinetic energy provided by the tide. This number can give an indication what kind of mixing is present in an estuary.

$$N_R = \frac{\Delta\rho}{\rho_0} \frac{gh}{v^2} \frac{Q_f T}{P_t} \tag{2.2}$$

Where ρ_0 is the fresh water density, $\Delta\rho$ is the density difference between fresh water density and the density at the river mouth, g the gravitation constant, h mean water depth and v the amplitude of the tidal velocity.

While both of these numbers are small an estuary is of the well mixed type and while both these numbers are large the estuary will be stratified. Salt intrusion in general will be more severe in well mixed estuaries (with a low Q_f and high P_t) (Savenije, 2012).

Since there is a gradient in salinity over the longitudinal axis of the mixing in the estuary is not only advective but also dispersive. When averaged over the tidal period the distance traveled by one particle is equal to the average fresh water velocity, but the tidal motion and smaller fluctuations are averaged out. These flows also contribute to the advective transport. This is solved with adding dispersion. The main drivers for dispersion (and mixing) are the tidal motion, gravitational circulation as result of the density gradients over the estuary and wind. This gives the main components that influence the dispersion in the Tha Chin: the tidal period, the tidal excursion, the density gradient. Next to these parameters bathymetry is also important, first because it influences the tide and second because it creates complex flow patterns.

The relation between the bathymetry and estuary shape on the salt intrusion can be seen in the shape of the salt intrusion curve. As the Tha Chin river mouth can be classified as an alluvial estuary the the discharge and tide form the estuary while they are also influenced by the lay out of the estuary.

Savenije (2012) has developed a method to analytically derive salt intrusion curves. This method will be explained further in appendix T. The most important conclusion from this model is when the fresh water discharge is low the the salt intrusion becomes more severe. Prolonged periods with low discharges may lead to salt intrusion lengths of 100 km or more.

Salt intrusion

As given in section 2.1.6 the discharges in the Tha Chin River during the dry season are quite low, while the tidal amplitude is in the order of 1.5 m. This results in a well mixed system where little fresh water is available to push the salt water downstream..

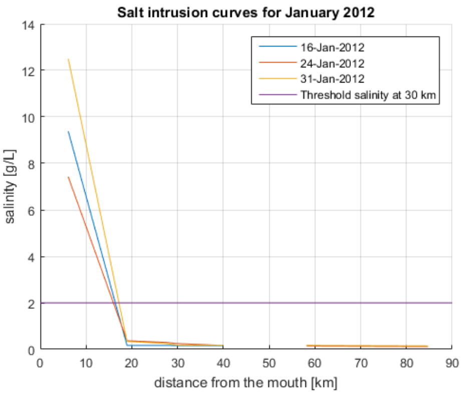


Figure 2.4: Measured salinity curves in January 2012

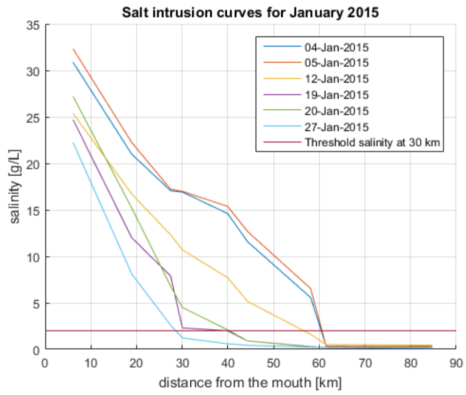


Figure 2.5: Measured salinity curves in January 2015

The current salinity management is done by releasing more water from the Pho Praya dam in order to push the water back. The threshold for releasing more water is when the salinity in at 30 km upstream of the river mouth is higher than 2 g/l. In the dry seasons of 2015 and 2016, which are known to be dry and follow consecutive years of (severe) drought, this threshold value has been exceeded often. Because the Tha Chin has a lower priority than the main branch of the Chao Praya River, it will be cut of water supply at the bifurcation during droughts in favor of the Chao Praya River. The consequence is that not enough water is available to increase the discharge at the Pho Praya dam.

Data provided by the RID shows that the most severe salt intrusion has been up to 60 km during the dry season in 2015. However, the salinity was not measured on daily basis and it is not known at what time the measurements were taken. Figure 2.5 shows the measured salinity curves in January 2015, which was a very dry month. Figure 2.4 shows the salinity curves in January 2012 which was in the dry season following the wettest wet season in the data set.

Other factors that can increase the salinity in the river have been elaborated by Mr. Pipat Ruang Nam[1]. He mentioned four other factors that can influence the salinity of the river negatively. The first is salt intrusion in the permeable ground layers that are connected to the river. Secondly he mentioned short-cut channels that were created during the 2011 floods which give short cuts for the incoming tide while the outgoing tide still has to follow the river. The third factor is the reduction of the retention areas which used to discharge fresh water to the river mouth in the dry season, due to changes in this area this water has also become saline. The last factor is the construction of bridges in the past years. The pillars are not in line with the water flow, obstructing the outflow (of salt water).

Pollution

Next to salt intrusion, pollution is a major issue in the Tha Chin basin. The sources of the pollution are not only located within the river itself, a large part of the water pollution is caused by users in the upper Chao Praya basin. The water quality in the lower Tha Chin (lowest 82 km) are in class 5 of the standard level set for surface water quality. Class 1 means clean water and 5 means heavily polluted and which can only be used for navigation. Class 5 is only used for sources which can not be classified in the four other classes. The ambition is to clean the water to class 4, which gives a lower limit for dissolved oxygen (DO) of 2 gm/l.

In data provided by the RID (in appendix H) can be found that during the dry season this requirement is never met. Pollutants found in the river are e.g.: heavy metals, chemical waste and fertilizers (RID (2011), chapter 1.2.7).

In the Tha Chin basin the main pollution sources are agriculture, industries and domestic use. Farmers use fertilizers for their crops. These fertilizers end up in the river with the runoff, causing algae blooms which lead to reduced DO concentrations and less light penetration affecting the entire ecosystem. Industries release their waste water directly into the river, during the dry season pollution can be measured more easily. During the first weeks of the rainy season peaks in pollution are measured, resulting high pollution discharges in this period (personal conversation with Mr. Pipat Ruang-Nam). Also domestic waste water is often not treated before discharged into the river.

[1] Mr. Pipat Ruang-Nam is the director of the Crisis Centre at the Department of Water Resources (DWR) in Thailand. The notes on the interview with Mr. Pipat Ruang Nam can be found in appendix V.4

These polluters are also present in the upper basin of the Chao Phraya. An extra pollution source is deforestation in the Nan province. During the deforestation process different chemicals are used up to speed up the process. These chemicals are brought to the river by runoff and end up downstream. In August 2016 almost all fish in the Song Phi Nong canal (Suphanburi province) have died of chemical intoxication. (personal conversation, Pipat Ruang-Nam DWR).

The river mouth has pollution problems related to ships. These ships discharges oil in the water which causes oil spills. These accumulate at places where flow velocities at the surface are low.

Water hyacinths prevent the transfer of oxygen from the air to the water surface and prevent other plants or algae form producing oxygen by blocking their access to sunlight. This makes DO levels in the river drop under the required level. Also debris from dead hyacinths accumulates on the river bed and causes a release of phosphorus. This can increase the amount of blooms which in their turn further lowers the DO levels.

Solutions dealing with the salt intrusion may not influence the pollution of the river negatively.

2.2. Stakeholder analysis

The framework for water management on an institutional level in Thailand is extensive; 31 departments under 10 ministries are involved. Along with the ministerial departments, six national committees have been appointed to advise in the water management sector.

In the management of the Tha Chin basin 8 ministries and 19 departments are involved. Also, different institutions, NGOs and users are involved in decisions regarding the basin. In 2002, the Thai government introduced a river basin committiee (RBC) for each river basin in Thailand. The RBCs were set up to strengthen governance and reach a more integrated approach in water management. For a further analysis of the stakeholders in this project, please refer to appendix I.

2.2.1. Government

Many government parties have a stake in this project. Here, only three parties are discussed. For a further elaboration of these and other government parties, please refer to appendix I. The main governmental department that controls the water is the Royal Irrigation Department (RID). The RID is the client of the project. Their interest is in water that can be used for irrigation and for this they have built a vast amount of structures to control and divert water.

Water resources are managed by the Department of Water Resources (DWR). Since a larger part of the water of the Tha Chin River is used for irrigation, the RID is in charge of the water management. However, the DWR is also involved in policy making up to the national level. The DWR makes policy and develops plans for every other agency involved in water.

The Marine Department (MD) controls transport over the river. Since the Tha Chin is also used for (transport) traffic, the MD will play a role in the design of a solution, especially when it would be built in or near the river mouth.

The large number of government departments indicates the fragmentation of the government. This causes practical problems: data is gathered and stored at different departments, which causes gaps and inconsistencies in information. Partly because of the fragmentation, an integral approach to tackle problems is sometimes lacking (Feld et al., 2003, Molle et al., 2009). Different departments sometimes have conflicting priorities. This priorities cause competition between the institutions because their areas of interest overlap.

2.2.2. Users

Water in the Tha Chin basin is used for farming, fish or shrimp farming, industrial and domestic use and some freight traffic. Farmers are in close contact with local RID offices and contact the RID when salinity levels are too high. Domestic water users will likely experience problems with salinity, as saline water is hard to treat. The river is polluted by several sources, with sea traffic and industries among them. (Appendix V.4 and V.3). All users, except for traffic and industry, are affected by water pollution. The local communities in the Tha Chin basin are tight-knit and have bad experiences with failing government water projects. They will not be persuaded easily when an intervention in the river system would be proposed.

2.2.3. NGOs

Non-Government Organizations and local communities have been dealing with the processes of development and globalization. Support from NGOs has improved public awareness and participation in development projects in Thailand.

A large acting NGO in the Tha Chin River Basin is We Love Tha Chin River Society (WLTS). The Members of WLTS are local residents along the Tha Chin River. WLTSs activities mainly focus on organizing public participation in river water management (Khonthet, 2007).

The 1997 Thai Constitutional Law guarantees communities the right to participate in the process of conducting an Environmental Impact Assessment (EIA). NGOs help local communities use this power by providing them with knowledge, media coverage and organizational help. In the case of the Tha Chin River, WLTS published two documents about negative consequences these dams would have on the environment. The presentation of these reports to the government together with a public meeting held in May 2002, made We Love Tha Chin successful in blocking the construction of the proposed dams. Thus, in the case of the Tha Chin River project, the impact of an adjustment of the river system will have to be thoroughly assessed. Explanation of the project to and clear communication with local communities will be key for successful implementation of the project.

2.2.4. Tha Chin River Basin Committee

River Basin Committees were introduced to lead an strengthen an integrated approach to water management. However, the are often *'poorly authorized and generally ineffective in maintaining consistent standards of river basin planning'* (NLDEmbassy, 2016). In the Tha Chin RBC all parties involved in the use, management and regulation of the Tha Chin are represented. The committee meets two or three times per year to discuss the current state of the river and projects in the area.

2.2.5. Conclusions

The RID is the client of the project. With an extensive network of local offices, it is the party with the largest influence in (daily) management of the river basin. The parties with a stake in the Tha Chin River are numerous and their interrelations, individual responsibilities and influences are diverse and complex. The government is very fragmented, which creates lack of a single authority and a long-term integrated master plan in water management for the whole basin. As a result, policy often lacks overview, much problems are addressed locally only and cooperation between different parties is limited. The project will have to propose a solution that is feasible and durable under these circumstances.

2.3. Reference projects

The Tha Chin River is not the only river in Thailand experiencing salt intrusion problems. Over the years, multiple water engineering projects, including salt intrusion projects, have been executed by the Thai government. One case similar to the Tha Chin River is the construction of a water gate in the Bang Pakong River in 2000 (figure 2.6). To block salt intrusion in the river, a large water gate was built at approximately 76 km of the river mouth. However, shortly after the dam came into operation, critical environmental problems forced the RID to cease operation. Downstream of the dam the tidal amplitude increase, this caused flooding during high tide and bank erosion, due to landslides, during low tide. Pollution accumulated upstream of the dam which destroyed the local ecosystem.

All the gates in the dam were opened again and up to today, it is still kept fully open (and thus unused). Approval of the public is necessary before further actions are implemented. For more info about this project is presented in appendix J.

Influence of the public can also be seen in other projects. For example, in 2002 the NGO "We Love Tha Chin River Society" mobilized the public to effectively blocked construction of two dams which were designed to block salt intrusion in the Tha Chin River. Other examples are Kon Chi Mun water diversion mega-project in North East Thailand, of which a big part has been blocked because of public protests; and the Flood Control Project, which has been delayed after environmentalists brought it to the Thai court in 2013 (Manowong and Ogunlana, 2004, Terashima, 2011). In each of these examples, the public used an EIA to investigate the impact of the project and subsequently block the project when the EIA proved that negative effects would outweigh positive consequences. For more information on these reference projects can be found in appendix J.

In investigating the causes of problems with projects in Thailand, multiple studies named flaws in organization as one of the causes. Feld et al. (2003) concluded that a lack of appropriate information for basin-wide planning was a significant underlying problem in managing the river basin. Molle et al. (2009) notes that requests made by the sub-districts are made without a general view of water management in the Province or in the basin. There is a lack of overview in river basin management and overlaps and conflicts in administrative jurisdiction occur between different government agencies on different levels.

For the Tha Chin River project to become a success, avoiding the problems of the Bang Pakong dam is imperative. Another key factor is involving the public, since it has a big influence on infrastructural projects. Limiting negative impact of the project is the key to keep local protests at a minimum. In proposing a solution, it is vital to also evaluate effects on other parts of the basin, as well as feasibility in organization and implementation, as cooperation between different (government) parties will be needed.

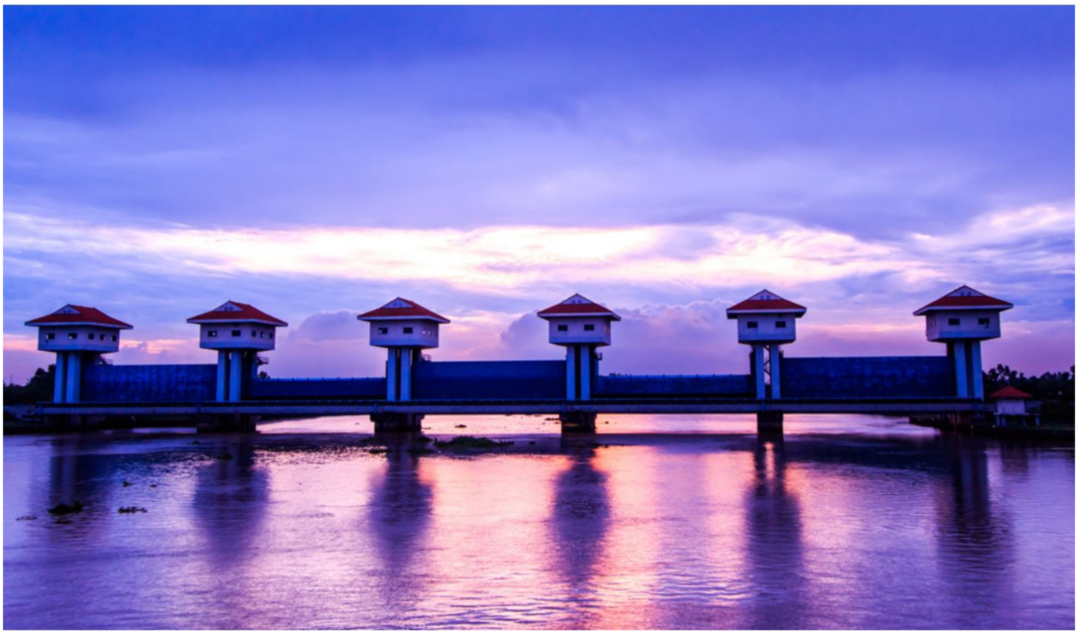


Figure 2.6: The Bang Pakong gate. Source: NLDEmbassy (2016)

3
Problem statement

After the analysis, the current situation of and problems in the Tha Chin river basin are clear. This chapter describes the exact problem statement and project objective. This comes with a list of criteria which the proposed solution should fulfill.

3.1. The ideal situation

The Tha Chin River basin is used for multiple purposes e.g. domestic water use, agricultural and industrial use and fish farms. The water in the basin should be fresh water, which means that the salinity and pollution levels should not exceed a critical level. The exact level depends on the location and the kind of the pollution. Beside the water quality, the water quantity is also an important aspect. This should be high enough fulfill the demands of the users, while no compromise is made on ecology.

3.2. The problem

The Tha Chin River basin suffers from low water quality. Two causes can be linked to this problem. The first one is the pollution which exceeds the current standards, due to point and non-point pollution. Secondly, the salinity in the lower part of the basin is too high. During the wet season and the beginning of the dry season, the upstream fresh water supply is enough to counterbalance salt water intruding from the Gulf of Thailand. In the end of the dry season, especially around April and May, insufficient water is available so the salinity rises to undesirable levels.

3.3. Effect of the problem

The fresh water in the Tha Chin River basin is mainly used by farmers, households and industry. When the demands of those users is not met, a few problems occur. The first one is the quality of life of the people that live in the basin area, which will go down if they do not have enough fresh water. The next problem that arises is that yield of the farmers and the productivity industry will decrease.

3.4. Project objective

In this project the main focus lies on the salinity problem. The goal is to find a solution for the salinity problem in the Tha Chin River. Pollution falls out of the project scope and objective,as it is a different problem than the salinity and therefore requires a different approach. However, since pollution is a serious threat to water quality as well, an estimate of the effects on pollution will be elaborated as much as possible.

3.5. Criteria for the solutions

A list of requirements and wishes which the eventual solution has to satisfy has been composed. This list can be found in appendix K. From this list, a number of criteria has been made. The solution has to meet this criteria as much as possible. These criteria are displayed below.

Salt intrusion The solution has to provide enough usable fresh water available during the year, especially in the dry season. At 30 km upstream from the mouth the salinity should be lower than the threshold value of 2 g/L.

Feasibility The solution has to be feasible in Thailand, which consists of three parts. First, the solution has to be technically feasible; it should not be too complex to build, use materials or (building or operation) processes that do not exist in Thailand. Second, it should be organizationally feasible; implementation has to be possible, even with the large amount of different government and non-government parties involved in a project of this scale. Third, it has to be socially feasible; negative consequences need to be limited in order to keep (local) community protests at a minimum.

Environmental impact Increase of water pollution levels (DO, pesticides, etc.) in the river has to be avoided. Negative impact on the ecosystem should be limited, so current flora and fauna will not disappear. Furthermore, negative consequences for the current infrastructure on land, such as forced resettlement, should be avoided.

River transport capacity The current capacity of the river to accommodate traffic has to stay intact. Ships should not be bothered by a solution. Water depths in the river should not become smaller, because ships may get stuck on the river bed. Also water levels cannot increase too much upstream because this would make it impossible for ships to pass low bridges.

Durability The solution has to be durable, both in management (both maintenance and operation should be assured) as well as technically (it should resist natural influences without breaking down). It has to function for a long period (for example 100 years) and it has to do this sustainable.

Costs Of course the solution needs to be financed and thus has to be low in costs. Potential revenues from the solution are taken into account as well.

4 Solutions

This chapter presents the solutions for the salt intrusion problem that have been developed during the course of the project. Developing a recommendation for solving the salinity problem was done in a pyramid model

4.1. Preliminary research

First, a brainstorm session was held to come up with as many ways to solve the problem as possible. In this session, all ideas were welcome, as it served as a means to be creative, not as a means to already investigate feasibility. The outcomes of the session are presented in appendix W. This created a list of 14 preliminary solutions, which were each further investigated. The first 14 preliminary solution possibilities are:

- Using a bubble screen to block salt intrusion
- Using a desalination plant to desalinate the seawater penetrating the river
- Increasing the river area at the river mouth, so salt water could be stored there
- Implementing the ‘Balance Islands’-concept in front of the river mouth
- Constructing a partly barrier in the Gulf of Thailand to decrease the tidal excursion
- Constructing a salt basin in the river mouth to store sea water
- Building a ‘salt-stair’ on the river bed in the river mouth
- Building a barrier in the Gulf of Thailand to shut off the river from the sea
- Constructing one or multiple upstream freshwater reservoirs to increase water storage capacity
- Constructing a water gate in the river which can be opened and closed, to block salt water intruding
- Increasing friction, so the tidal excursion will be decreased
- Using a small-scale, local desalination irrigation system, so all river water can be desalinated and used locally by users themselves
- Change the shape of the river mouth and making its convergence angle steeper, thereby influencing the tidal excursion
- Creating sand banks more upstream the river, which can be used as a natural salt intrusion barrier

Research on each solution was done to investigate its functioning and to have a first indication of its feasibility. The preliminary research report of each solution can be found in appendix L. Subsequently a first evaluation was done in order to rule out the solutions that were not feasible. This evaluation can be found in appendix M. This left 5 solutions to be further investigated.

4.2. Final solutions

In this section the five solutions with the highest potential will be discussed. More information on each solution can be found in appendices N to R.

4.2.1. Changing the convergence length

The mouth of an estuary has a significant influence on the salt intrusion length. Therefore, adjusting the river mouth will affect salt intrusion. The main parameter influencing salt intrusion is the convergence length of the mouth: the characteristic length scale of the decrease in width and flow area in an estuary. Changing this length will change the tidal prism and tidal amplitude, which influences the salt intrusion. When the tidal amplitude decreases the salt intrusion length will be smaller. The Tha Chin river mouth has a trumpet shape, the downstream part has a small convergence length with respect to the upstream part, the place where the convergence length changes is called the inflection point (Savenije, 2012). Because of the current shape, only the most downstream part has to be altered. see figure N.1.

Two different options are possible. The first option is placing the inflection point closer to the mouth, this decreases the convergence length in the most downstream part and the part where the longer convergence length starts will be closer to the mouth. In this case the original cross-sectional area of the river mouth will not change. The second option is to keep the inflection point at its current position and decrease the cross-sectional area in the mouth, creating a larger convergence length in the mouth.

To create the new convergence length, the banks of the river mouth could be made of the current sediment present in the coastal area. To protect the banks, bamboo piles can be placed to mimic the function of mangroves, the newly created banks can serve as area for mangrove restoration area. In this way, this solution could reduce salinity levels by building with nature, without having a large impact on the current area and its ecosystem.

Changing the bathymetry of an estuary influences the tidal prism and other flow conditions, therefore the exact design should be tested and optimized on erosion and sedimentation. Continuous maintenance of the new banks will very likely be needed.

The results from the analytical salt intrusion model show that a reduction of the salt intrusion length of at most 5% might be possible (appendix T). In the Tha Chin river this would not be enough to solve the salt intrusion problem. Therefore additional measures are needed.

4.2.2. Balance Islands

Balance Islands is a concept in which sand banks are constructed in front of the river mouth which alter water flows (4.2). Because of the altered water flows a brackish area will be formed in front of the river mouth. This implies as smaller salinity gradient between the river and the area in front of the mouth. In general, the amount of salt intrusion is proportional to the salinity gradient. Therefore, the salt intrusion length will be smaller (van Rooij et al., 2012).

The islands will act as a U-shaped funnel, deflecting the tidal flow but letting river water flow out easily. Further research with more complex models is needed to determine the final shape and location. As most

Figure 4.1: Changing the convergence length.

costs will are linked to dredging the needed material, the final design will determine the costs. A study for Balance Islands in a similar situation in the Mekong Delta, Vietnam, estimated costs varying from 200 to 500 million US dollars (Raadgever et al., 2016).

The core of the islands will probably be made of clay, since this is widely available in the surrounding area. The newly gained area could be forested with mangrove trees, to increase the stability of the island as well as to strengthen the local ecosystem. The salinity reduction can only be achieved when the islands are placed at the correct location. A wrong placement, for example too close to the mouth, could even increase the salinity (de Kort and van Rooij, 2013). When the islands work correctly, this solution could lower the salinity.

A first estimation with SOBEK-RE showed a reduction of the salt intrusion length up to 20% in the wet season and in a relatively wet dry season. During the driest dry seasons (2015) this reduction is lower, around 15 % (appendix U). The threshold value of 2 g/l at 30 km, however, is sometimes exceeded but less frequent and shorter than in the current situation.

SOBEK-RE is a one dimensional model, this solution requires complex 3D models so further research is needed to give the exact salinity reduction due the balance islands. For more information on this solution, see appendix O.

Figure 4.2: Balance Islands. This is an impression of what the islands could look like, for the exact place and design of the island further research should be done.

4.2.3. Salt barrier in the river

The principle is based on a barrier that lets through the same river discharge without losing any river capacity during floods, but can be closed to block salt water when salinity levels become too high. Choosing the right location is crucial. Not only because of the possible hydrologic and pollution consequences, but also because of the local, spatial and societal consequences of a structure in the river.

In the past, similar barriers in Thailand have shown to cause an increase in tidal amplitude with negative consequences, such as enhance erosion of river banks. Therefore the location of the barrier has to be chosen such that there is no significant increase in tidal amplitude downstream. Also, the location and effect on water levels is of major importance for transport over the river (shipping). Even when these problems are addressed, (local) protests against this solution are very likely if this solution would be implemented. Clear communication and taking enough time to explain the effects of the barrier to the stakeholders are key aspects. However, the relative simple technology raises the feasibility of this option.

The proposed location for the barrier is 12 km upstream from the river mouth, directly upstream of the

Rama II Bridge. This location is close enough to the river mouth that the raise in tidal amplitude is limited, while still far enough from the mouth to limit impact on transport and the surrounding area. This would require a barrier with a widht of approximately 250 m. In the middle, the barrier would have mitre gates instead of standard gates, to let ships pass through when the barrier is open. During the dry season, when the barrier is closed for a longer period, the water level upstream of the barrier will rise. Then the gate will be partly opened, acting as a weir, to let fresh water flow through. This will reduce the impact on pollution levels and the environment.

Several barrier management options have been tested to obtain an overview of the actual salinity reduction and the effectiveness of every scheme. The best management scheme is to control the closing of the barrier when the discharge far upstream (240 km from the mouth) is lower than 30 m^3/s. This results in an effective reduction in salinity that fulfills the requirement stated by the RID. With the chosen scheme, the barrier will be closed on average 35 % of the time. In this closing period, fresh water is still released by partly opening the gates to maintain a certain required water level upstream of the barrier. This can be set greater or equal to the downstream water level to even further minimize environmental consequences.

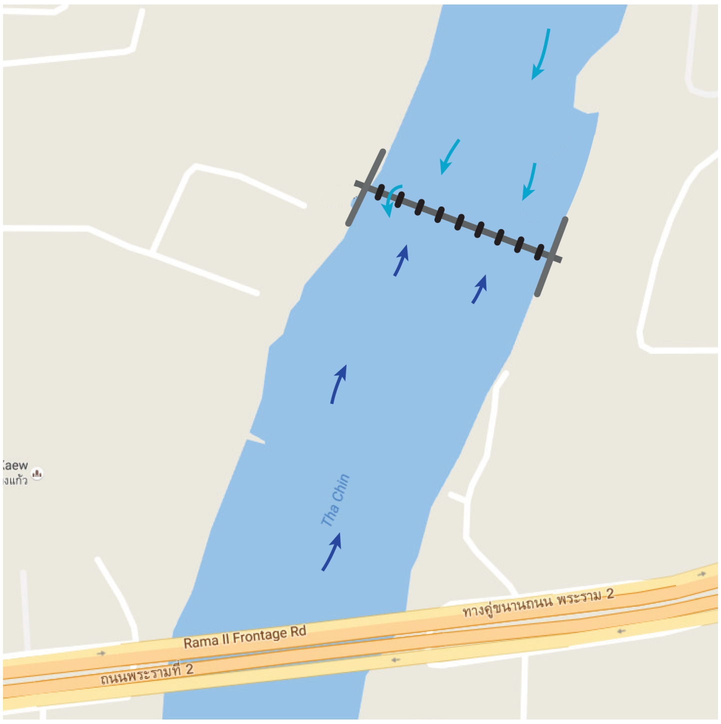


Figure 4.3: The salt barrier in the River

To be able to function as a weir and optimize the management scheme even further, the gate should be able to partly open and regulate the size of the cross section for flows in both ways. The total cross section when the gates are open, is kept equal to the current maximum flow area of the river. The barriers principle and location can be seen in figure 4.3

The barrier will have large environmental consequences for the river. These are minimized by reducing the closing period. Because the high flows that maintain the equilibrium shape of the river are still present. Also sediment accumulated behind the barrier after a longer closing period are likely to erode. When the gates are partly opened polluted water is able to flow out decreasing the effect of pollution. An environmental impact assessment is still to be done when further researching the barrier. A more elaborate analysis of the salinity barrier can be found in appendix P.

4.2.4. Partly dam in the Bay of Bangkok

This solution is based on the construction of a dam in sea that will partly close a part of the Gulf of Thailand, the Bay of Bangkok, in which the mouth of the Tha Chin is located (figure L.11). The inner bay will not be completely closed, so the tide is still able to flow in and out and the water in the whole Gulf will stay saline and a slightly brackish basin will be created behind the dam. The goal of the dam is decreasing the tidal amplitude in this basin, therefore decreasing the salt intrusion length. A positive side effect is that the salinity in the bay decreases. At the same time, the change in ecosystem would be limited because water would remain salt and tide is still present.

This solution requires complex and detailed models in order to determine the technical layout, as the exact location and size are crucial to its functioning. A wrong location could even increase the tidal amplitude. The dam could be made of a combination of clay (abundant in the Gulf), rock and concrete.

Water flows through the openings will be accelerated, which will cause erosion of the seabed. Therefore the openings need special attention in the design, so this acceleration may be kept as low as possible. Bed protection will be needed, however. A project of this scale would have impact on a very large amount of land and people. Construction costs will be very high, probably running into billions of US dollars. These are two factors reducing the feasibility of this solution.

The conclusion from SOBEK-RE is very promising but only gives a rough estimation. This solution requires complex 3D models. Nonetheless, to see whether the solution is suitable for salt intrusion and to obtain order estimates of the reduction SOBEK-RE can be used. A reduction of 40 % of the 2 g/lsalinity intrusion is achieved in the SOBEK-RE model. If this solution is chosen more research should be done on the exact layout and reduction. For further elaboration on this solution, go to appendix R.

Figure 4.4: Partly dam in the bay of Bangkok.

4.2.5. Dam in the Bay of Bangkok

This solution proposes building a permanent dam (e.g. a breakwater or a dyke) in the Bay of Bangkok, see 4.5. Depending on the location and size, the dam would shut off the river mouths of some or all of the biggest rivers of Thailand. Which creates a freshwater basin in front of the coast of Thailand and salt water from the Gulf of Thailand will be completely blocked. River water would thus become permanently fresh. The new water basin could also be used as a retention area in case of floods. In that case, excess fresh water could be pumped out into sea, keeping the basin artificially low, allowing new river flood water to enter. Finally, the barrier could serve as a storm barrier, protecting the Thai shore and Bangkok from high sea water levels. This solutions would thus not only solve salt intrusion in the Tha chin, but multiple other large-scale water problems in (different parts of) Thailand as well.

This is a solution with both high impact. The length and layout of the barrier therefore partly depends on which amount of (both positive and negative) impact is preferred. The function of the barrier could also influence its layout, because the barrier could (partly) be constructed as new islands, thus creating new area. The newly won land could be commercially developed as living and leisure areas. The barrier would have to include gates (for example sluices) to still provide access to sea traffic. When determining the location of the barrier it is very important to account for the tidal amplitude. A wrongly chosen location could cause a rise in tide near the barrier, which could potentially destroy the barrier.

This option would create a large, closed-off fresh water basin in the Bay of Bangkok, in which the major rivers discharge. Because the water here would become fresh and water flows will almost be non-existing, the local ecosystem would get a big blow. Also, waste water treatment is absolutely necessary as the rivers flowing into the basin are heavily polluted. Fishing ships and other parties near the shore depending on salt water will have to relocate. On the other hand, the freshwater basin gives new opportunities for commercial development, for example in the leisure field. Also, the basin could be used for freshwater production and thus solve the freshwater problems, especially in Bangkok. Costs of the barrier would run in the billions of US dollars (NCICD, 2014). Benefits from land development and freshwater production could run in the hundreds of millions too. However, the direct benefits will probably not outweigh the direct costs. For further elaboration on this solution, please refer to appendixQ.

Figure 4.5: Barrier in the bay of Bangkok.

5

Evaluation

The last part of the project is the evaluation, in which the possible solutions are evaluated and a recommendation on which solution is best-suited for the problem is made. In order to make well-founded recommendation, a multi-criteria analysis (MCA) is conducted. In this analysis, each criterion for the solution will be assigned a weighting factor. After that, each solution is ranked on performance for each criterion. This will produce a score for each option and a ranking to what extend solutions fit the problem.

5.1. Criteria for the solution

A broad list of the criteria is already given in section 3.5. The criteria on which each solution are tested are briefly presented again below.

A Salt intrusion

B Feasibility

C Environmental impact

D River transport capacity

E Durability

F Costs

5.2. Multi Criteria Analysis (MCA)

Some criteria have a higher priority than others. Therefore, all criteria are ordered and compared against each other, using a score. If one criterion outweighs another criterion, it will get a score of 1. If a criterion does not outweigh another, it will score 0. If they have the same priority, they both will score 1. The first column of table 5.1 displays criteria that, towards the right, are compared to the other criteria.

These priorities have been set by the TU Delft project team and are based on the outcomes and experiences from the analysis (see also chapter 2). As the priorities are based on this analysis only, it is possible that other parties in the same situation would have set different priorities. However, these priorities are based on the conclusions from the analysis and are therefore found to be adequate.

After the scores have been determined, weighting factors can be assigned. When one criterion scores 0, it will be given a score of 1 and the scores of the other criteria will be doubled to make assigning factors possible. After that, each value of each criterion is weighted against the sum of all values. The eventual weighting factors are displayed in table 5.2

Now, each solution can be tested to what extend it fulfills each criterion, this results in a score between 1 and 10. This score is multiplied by the weighting factor, the final score for each solution sum of the weighted scores. The higher the score, the better a solution fulfills the criteria. All the scores of each possible solution are displayed in table 5.3.

The extend to which each solution fulfills each criterion, have been set by the TU Delft project team. Even though these scores are educated guesses, they are based on the conclusions from the analysis, the

Table 5.1: The calculation of the weighting factor for each criterion

Criteria	A	B	C	D	E	F
Salt intrusion (A)		1	1	1	1	1
Feasibility (B)	1		1	1	1	1
Environmental impact (C)	0	0		1	1	1
River transport capacity (D)	0	0	0		0	0
Durability (E)	0	0	0	1		0
Costs (F)	0	0	0	1	1	

Table 5.2: The weighting factors for all criteria

Criterion	Score	Weighting factor
Salt intrusion	10	0.303
Feasibility	10	0.303
Environmental impact	6	0.182
River transport capacity	1	0.03
Durability	2	0.061
Costs	4	0.121
Sum	33	1

results simulation and on engineering knowledge gained at TU Delft. Furthermore, since these scores are the consensus of four people, they are found to be adequate.

Table 5.3: Scores of each solution. The letters in the criteria list correspond to the criteria as mentioned in section 5.1. The total score is the sum of the scores after the weighting factor was applied.

Solutions vs. criteria	A	B	C	D	E	F	Total score
Salinity barrier	9	6	5	3	7	7	6.8
Balance Island	7	7	9	6	4	3	6.7
Full barrier in the Gulf	10	1	1	2	9	1	4.2
Partly barrier in the Gulf	8	2	3	5	8	2	4.5
Change convergence angle	4	6	9	9	4	7	6

5.3. Conclusion

Based on the MCA, building a salinity barrier in the river and implementing the Balance Islands concept are found to be most adequate to solve the salinity problem. The other possible solutions clearly fulfill the criteria less.

6
Conclusion and Recommendations

The multi-criteria analysis has been conducted and the results are used to give a final conclusion of the objectives stated in chapter 5. In the first section the general conclusions about the whole project are discussed. In the second section recommendations are done for the project in general and for the two best solutions from the MCA.

6.1. Conclusion

Salt intrusion is currently controlled by the fresh water release from the Pho Phraya, which pushes salt water back to the the sea. Problems occur when insufficient water can be released to effectively push back salt water. The objective was to find a solution to this salinity problem. The MCA resulted in two best solutions. The first one is the salt barrier in the river and the second one is the Balance Islands. Those two will be elaborated in the next sections.

6.1.1. Salt barrier in the river

The salinity barrier, as shown in figure 6.1, is the only solution that is able to block the saline water completely and therefore it has a large certainty that it will work effectively. The proposed location for the barrier is 12 km upstream from the river mouth, right after the Rama II Bridge. This location is close enough to the river mouth that the amplification of the tide is limited, while still far enough from the mouth to limit the impact on transportation and the surrounding area.

The best management scheme is to control the closing of the barrier when the discharge far upstream (240 km from the mouth) is lower than 30 $m^{3/s}$. This results in an effective reduction in salinity that fulfills the requirement stated by the RID. With the chosen scheme, the barrier will be closed on average 35% of the time. In this closing period, fresh water is still released by partly opening the gates to maintain a certain required water level upstream of the barrier. In the middle, the barrier could be fitted with mitre gates instead of lifting gates, to let ships pass through unhindered when the barrier is open.

The drawback on this solution is that implementation will probably face public protest as seen with proposed gates in the past.

6.1.2. Balance Islands

The Balance Islands, shown in figure 6.2, is a solution that only reduces the salt intrusion length to a certain amount. A first estimation showed a reduction in salt intrusion length of 20% in an average dry season and in an extreme dry season (2015) a reduction of 15 %. This is quite promising, but during the dry period the requirement of less than 2 g/l at 30 km is not always met. During a drought, like 2014 and 2015, the threshold of 2 g/l at 30 km is exceeded, but the period in which it exceeds is much shorter. The Balance Islands are very environmental friendly and probably will cause less protest than the salinity barrier.

Drawbacks on this solution are the amount of research still to be done and the costs, which will exceed those of the barrier.

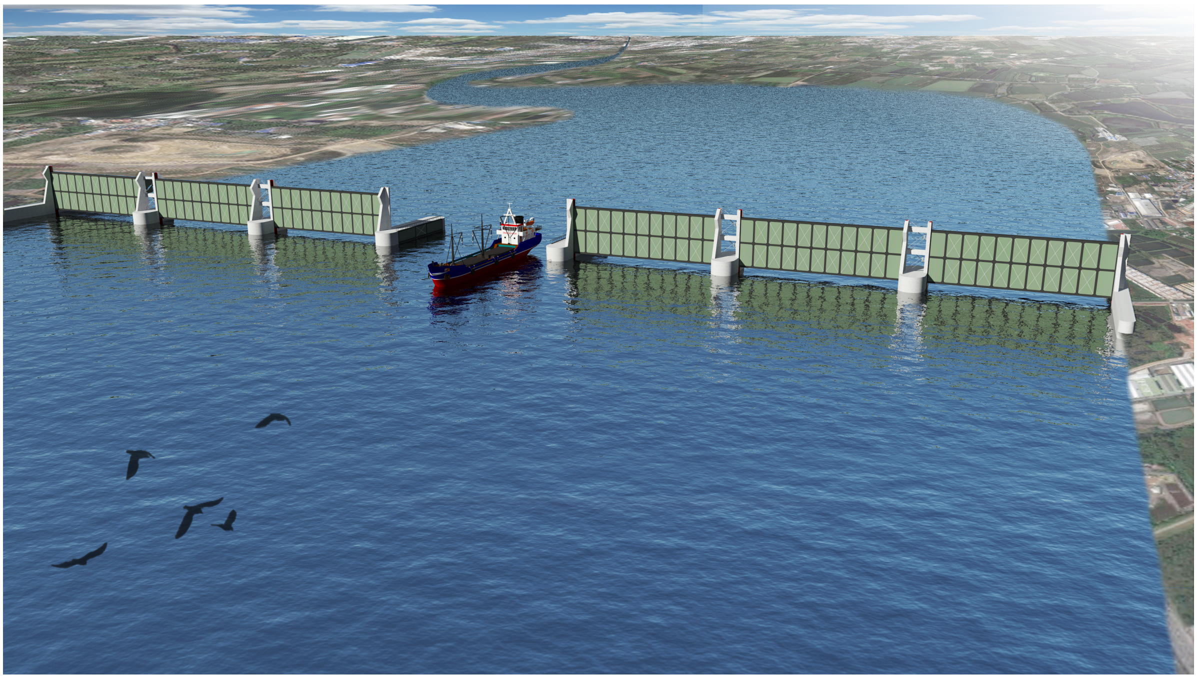


Figure 6.1: Artist impression of the salt barrier in the river

Figure 6.2: Artist impression of the Balance Islands

6.2. Recommendation

In this section first some recommendations on the two best solution will be given. Followed by some general recommendations which hold for every solution that will be implemented. They give an advice on pollution, water consumption, feasibility and data collecting.

6.2.1. Salinity barrier the river

The recommended management scheme to control the barrier can be further optimized to minimize closing time. Furthermore, the banks of the river up to 12 km have to be checked if they can handle the tidal amplitude increase computed by the models. If both are optimized, an environmental impact assessment can be done to assess pollution levels. A positive outcome can help convince the local communities, since the salinity barrier has been strongly and successfully opposed by them in the past.

Further focus should be on implementation at the chosen location, involving every stakeholder to satisfy them as much as possible. Technical details (technical design, bed protection etc) should be spared to the last phase. Lastly, The models used (analytical and numerical) give approximations. They do not represent the exact river behaviour. For a more detailed analysis of the amplification of the tide and effective salinity reduction, higher dimension numerical models are recommended.

6.2.2. Balance Islands

The first thing that is important to say is that the conclusion is based on a SOBEK-RE model which is calibrated and validate on only a few data sets. This causes the model to be not very accurate and the reduction was only a very rough estimate. However, it shows that the balance islands will most likely work under the circumstances that are present in the Tha Chin River basin. To obtain the exact reduction and layout much more computations with more complex 3D models should be performed. From this it the amount of maintenance needed should also become clear. In order to build such a model more detailed information about the incoming tide, current bathymetry and discharge from more downstream are needed. Lastly, further research can be done on how to exploit the newly acquired land and to asses a possible increased probability of flooding since the river mouth is partly blocked.

The Balance Islands have been investigated with data of the past 6 years, which means climate change is not included. In this data set of the past 6 years a dry and a wet year was included, but it is also important to know how often a dry year will occur in the future. This is because in a dry year the solution is less efficient, so when it is likely to happen that dry years will occur more often the Balance Islands might not be a very efficient solution.

6.2.3. Pollution

Currently pollution problems, such as waste water and oil dumping, occur in the Tha Chin River. Blocking salt intrusion always means affecting the river system, with possible negative consequences for pollution, as flows and water levels will change. The solutions for salt intrusion presented in this report do not address pollution problems in depth. However, the need to solve pollution problems is evident. It is therefore proposed that, together with the solution for the salt problems, additional measures for the river are taken. Further research on the environmental impact should be performed for whatever solution is chosen. For now, the project team proposes the following measures to be taken additionally to implementing the project:

- More monitoring of chemical pollution by industries along the river. As at the moment industries dump (chemical) waste water in the river at times when pollution is not monitored, for example at night, it is hard to indicate individual polluters. Implementing permanent pollution monitoring systems and making more inspections may help reducing waste water pollution and indicating individual polluters.

- More monitoring of waste water dumping by (fish) farmers along the river. Again, implementing more inspections and permanent monitoring may help to force polluters to start managing waste water in a responsible way. Individual polluters could be given fines, the revenues of which could be used to further address pollution problems.

- Setting up a plan to reduce water hyacinths in the river and implement measures for hyacinth removal. As the plants multiply very fast (Ndimele et al. (2011), UNEP (2013)), removing hyacinths will be most effective when it is done as far upstream as possible. Less hyacinths will then have the opportunity to multiply on their way downstream. Reducing the amount of water hyacinths in the river will increase water flows and reduce the amount sedimentation of organic matter. Both results will have a positive effect on water quality levels.

6.2.4. Water consumption

The next advice is on the water consumption. Implementing a solution will make more fresh water available for use and therefore it is very likely that also more water will be used (Feld et al., 2003). If water consumption increases proportional to the additional available fresh water, two things are likely to happen. The first one is an increase in agricultural productivity, as more plants can be grown and even increasing crop rotation might become possible. Together with a possible increase in industrial production, this will cause a growth in economy.

The second consequence will be a possible return of the salt intrusion problems. As again more water will be extracted from the river, the discharge can become too low to effectively push back salt water.

This would mean that, even though productivity has risen, the salt intrusion problem would still not be solved. The TU Delft project team therefore advises the RID to regulate water use in order to keep salinity at an appropriate level while maximizing the use of the river water. It is very reasonable to make economic growth the main goal of this project. However, the main goal is a durable solution to the salinity problem, so it is proposed that water consumption of all users is monitored more in the future. For example, this can be done by allocate all water use. This will lead to a sufficient fresh water supply to keep the salinity in the river below the threshold value.

6.2.5. Project feasibility

The third recommendation is about the project feasibility. This project will have a large impact on the Tha Chin River basin and the people living there. Eventhough the project will have many positive outcomes (less saline water, higher crop yields, etc.), it is inevitable that some people will experience negative consequences due to changes in their environment. It is likely that the project will face protests from locals, even when more positive outcomes than negative outcomes are gained. It is advised that, when positive outcomes clearly outweigh negative outcomes, the RID tries to continue the implementation of the project by working together with the local communities. This can be done by involving all relevant stakeholders and show them the advantages of the solution. Besides that, it is advised to also discuss the disadvantages and show them a way to mitigate or deal with the negative effects.

The large number of government parties involved in the Tha Chin means there could be a risk of uncertainty in information and responsibilities. In order to smooth cooperation, it may help to appoint one party as chief agency, so there is a central point for information, data and policy. This party could arrange communication, collaboration and data exchange between all the parties involved in the project.

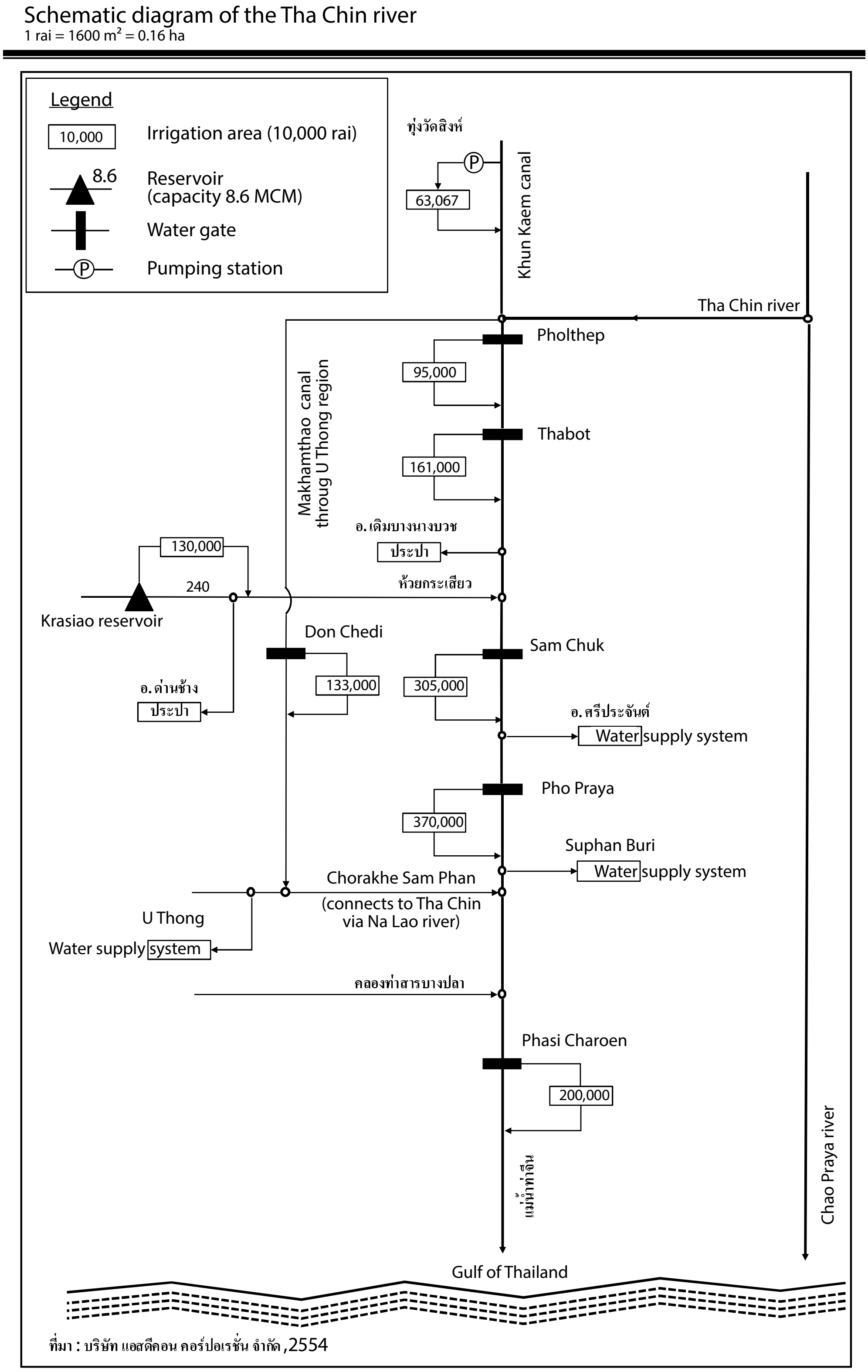
6.2.6. Data collection and sharing

In general, each project needs and uses data in order to make well-funded design decisions. Engineering needs high-quality and reliable information, this also holds for the Tha Chin River project. During the project time this was not available for our project group. In order to make further research possible more (reliable) data should be collected. To profit even more from data available, it may be wise to collect all data about the Tha Chin River at a central point or at one agency

A

Overview Tha Chin River basin

This appendix contains two overviews of the Tha Chin river, the first one is an overview of the irrigation channels and the area they feed (figure A.1), the second is a map of the area with the most important places and objects in the area (figure A.2). The figures can be found on the next page.



รูปที่ 1.14 ระบบลุ่มน้ำท่าจีน (Schematic Diagram)

Figure A.1: Schematic overview of the Tha Chin River

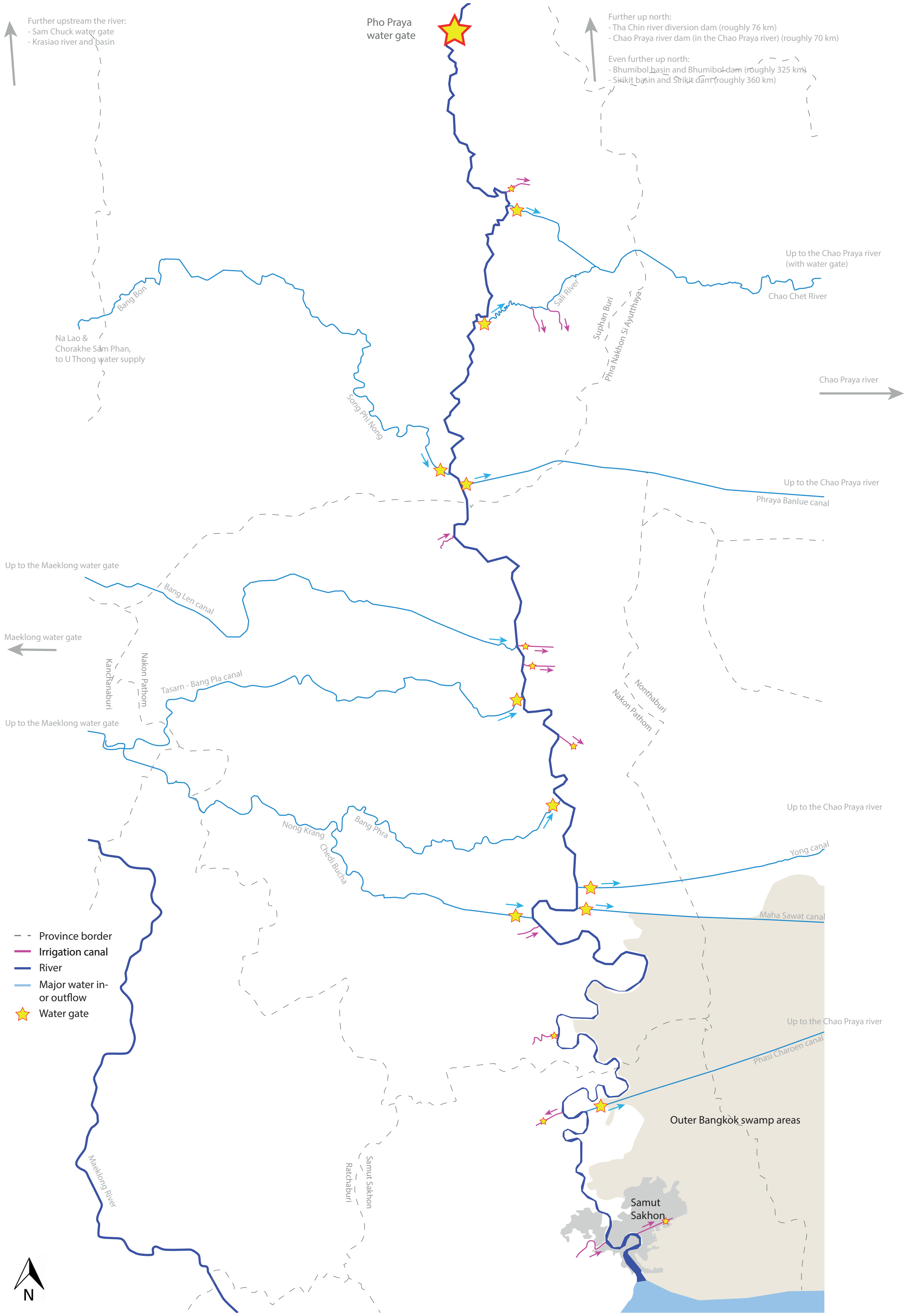


Figure A.2: Map of the Tha Chin River with the most important Channels

B

Measurements stations

In the figures below the measurement stations are shown.

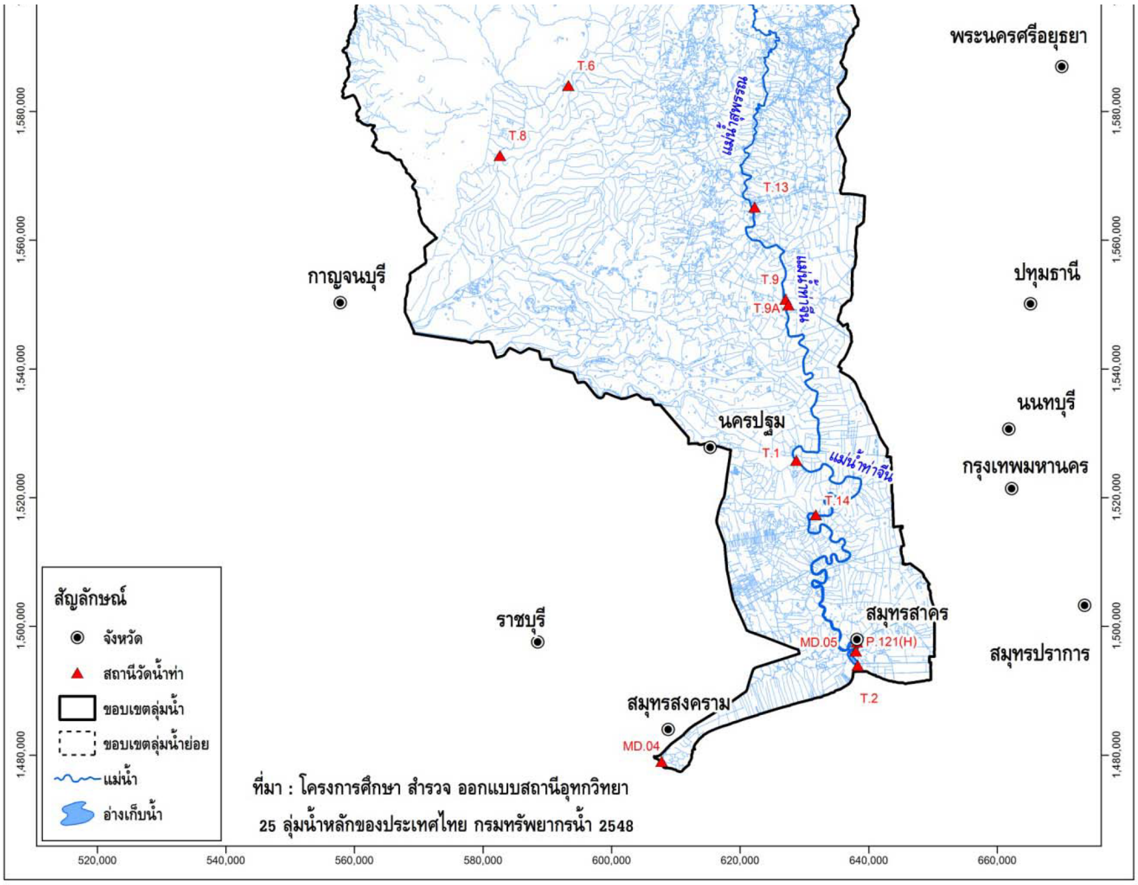


Figure B.1: Water level measurement stations: T1, T13, T14. Source: RID (2011)

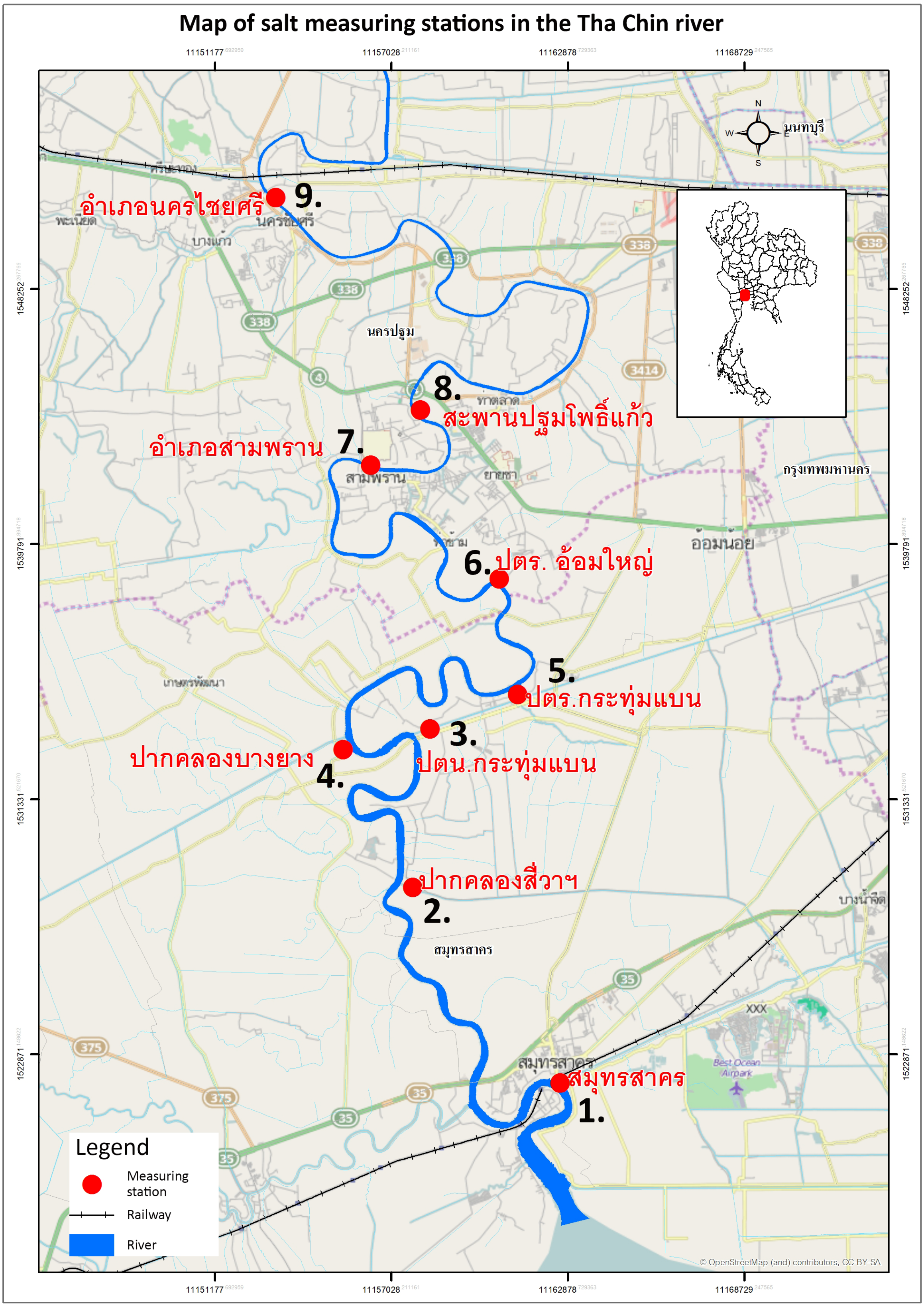


Figure B.2: Salinity and DO Measurements stations. Source: RID (2016)

C Mangroves

A mangrove forest is a very vulnerable habitat that is one of the most endangered in the world. Mangrove forests are lost all over the world. Thailand has lost 84 percent of its mangroves. This is the largest loss of mangrove of any country in the world (AMNH, 2004). In 2015 the IUCN and the Department of Marine and Coastal Resources (DMCR) in Thailand presented a new management act regarding Marine and Coastal Resources (IUCN, 2015). This new law ensures the participation of local governments, communities and other groups that have an interest in restoration and conservation of mangroves. From that point, the DMCR has designated mangrove conservation areas to protect these areas from further deforestation (Nguyen, 2015).

The initial dramatic decrease of mangrove forest in Thailand was caused by over-exploitation for charcoal. Then, shrimp farming became the main factor. Other causes were urban expansion, industrial expansion and agriculture. The mangrove area around the lower part of the Tha Chin river basin declined as well. Also, the sediment contains a lot of heavy metals. However these concentrations do not create a problem for the mangroves, but they do for fauna in these areas (Faridah-Hanum et al., 2014).

The functions of the mangroves in Thailand are:

- Natural sea defense
- Habitat and nursery for many species
- Fishing area
- Filter of seawater and nutrients and contaminants

The waves in the Gulf of Thailand are eroding sediment at the coast of the Tha Chin. The tide brings this sediment back to the coast. If the tide changes, the sediment supply will change and the floodplains of the mouth can get a concave upward shape, which minimizes the area where mangroves can grow. Furthermore, a mangrove forest needs a mildly saline environment. Too much or too little salt and they will not survive. However, in time, a mangrove forest is capable of adapting to new environments (Faridah-Hanum et al., 2014).

D

Bathymetry

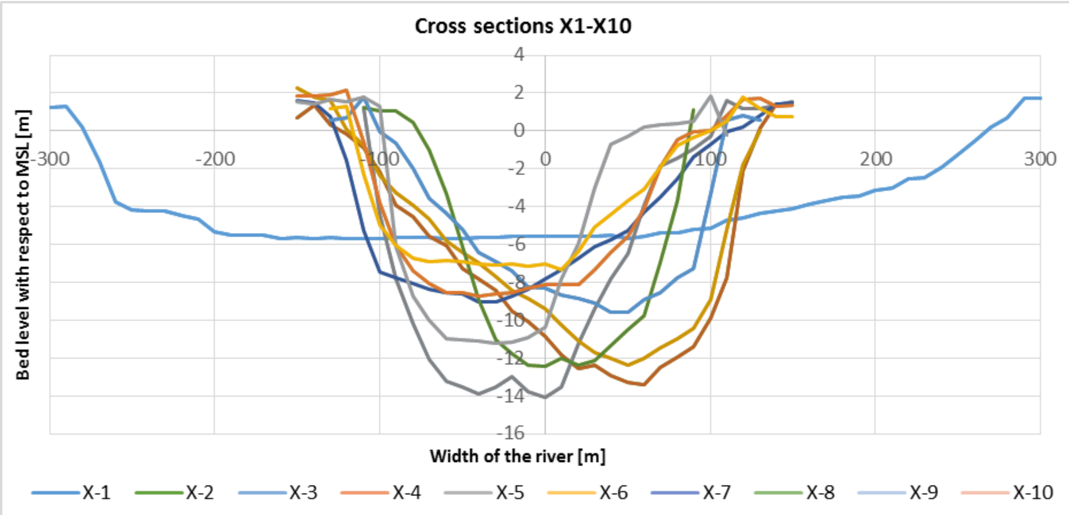


Figure D.1: Bathymetry X1 to X10. Based on values provided by RID

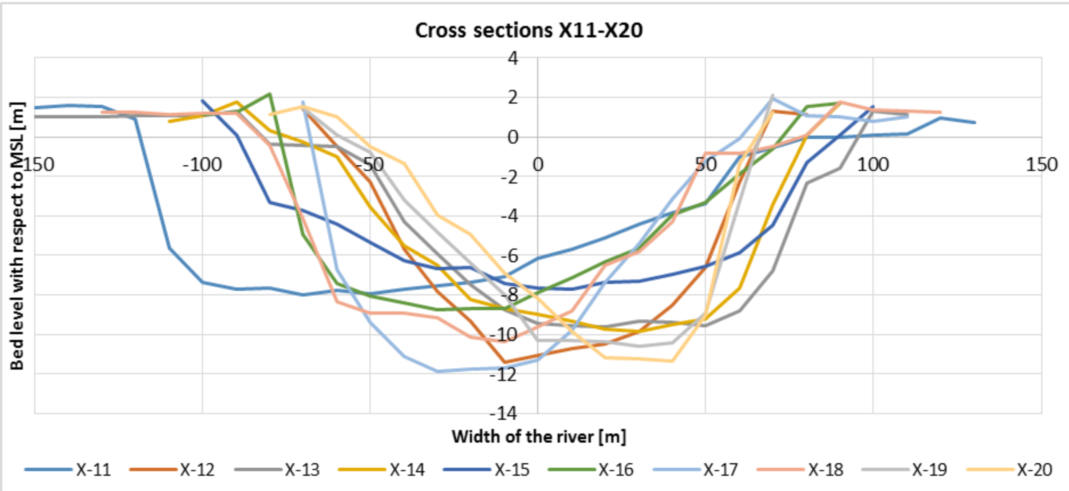


Figure D.2: Bathymetry X11 to X20. Based on values provided by RID

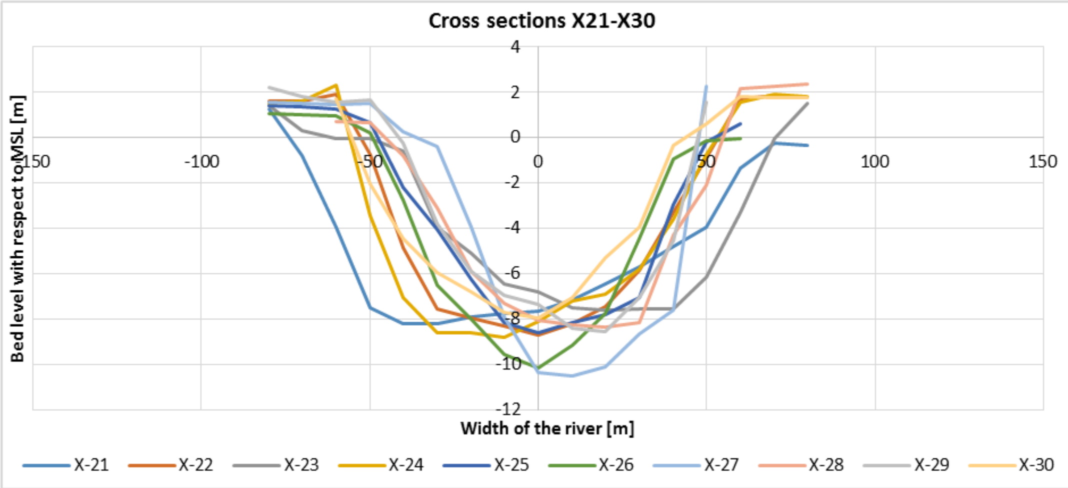


Figure D.3: Bathymetry X21 to X30. Based on values provided by RID

Figure D.4: Bathymetry X31 to X40. Based on values provided by RID

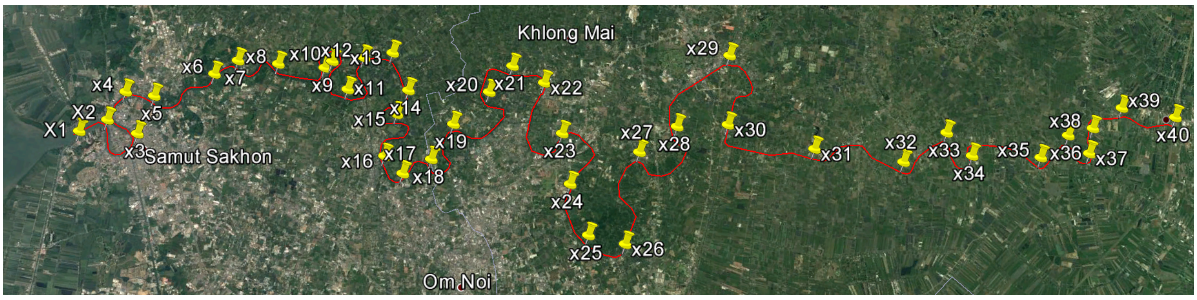


Figure D.5: Locations measured profiles. Based on values provided by RID.

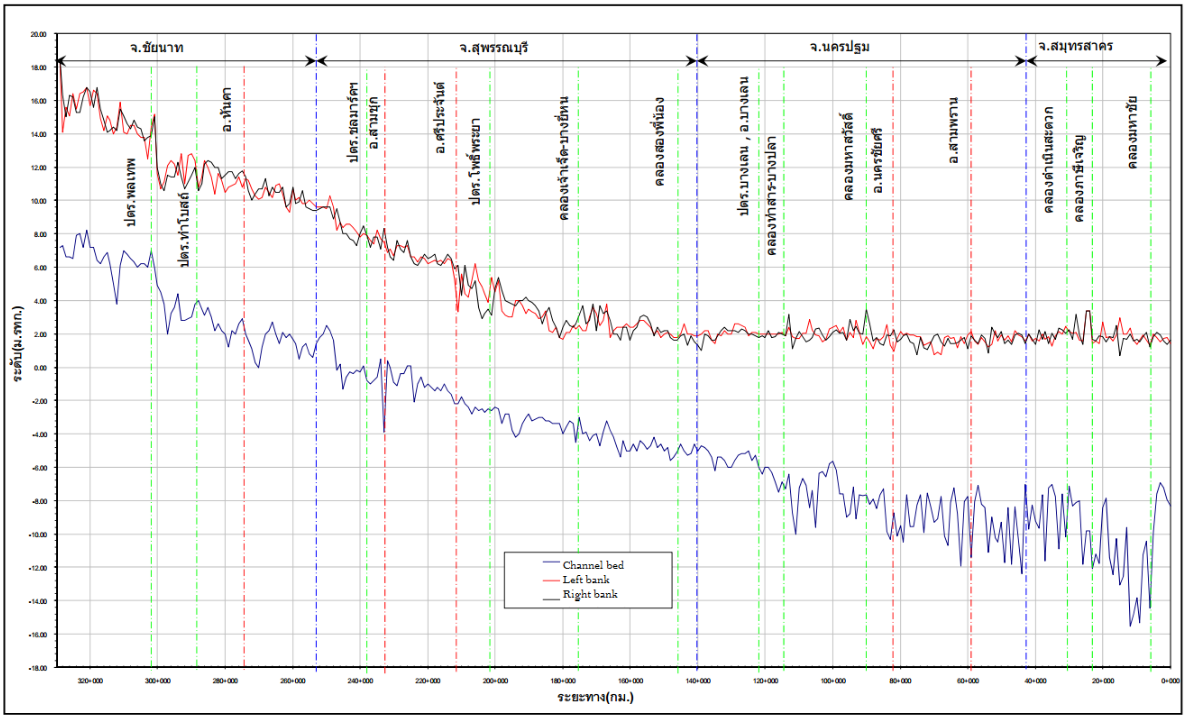


Figure D.6: Bed level and depth profile along the channel axis (RID, 2011)

Table D.1: Locations measured bathymetry. Based on values provided by RID and google earth.

Point	Distance [m]	Point	Distance [m]	Point	Distance[m]	Point	Distance [m]
X1	2857	X11	27931	X21	55542	X31	98096
X2	4879	X12	30743	X22	58149	X32	103319
X3	7413	X13	32565	X23	62917	X33	106291
X4	10385	X14	34865	X24	68065	X34	108355
X5	12248	X15	37467	X25	70910	X35	113240
X6	15712	X16	41184	X26	72844	X36	115205
X7	17512	X17	42478	X27	78330	X37	116694
X8	20309	X18	44679	X28	82805	X38	118104
X9	22608	X19	47829	X29	88188	X39	120559
X10	26059	X20	52513	X30	93200	X40	123488

E

Water demands

The exact data as gathered from the (RID, 2011) can be found table E.1, the time during which the data origins can be found in table E.2.

Table E.1: Water demands for each sector

Water used for	Demands	
	MCM/ year	m^3/s
Consumption and tourism	146.84	4.66
Agriculture	6773.30	214.78
Industrial	118.08	3.74
Livestock	58.85	1.87
Sum	7097	225.04
Ecosystem	977.70	31.00
Total	**8074.77**	**256.05**

Table E.2: The years in which the data is collected

Data of	From	To
Consumption and tourism	2008	2009
Agriculture (result)	2003	
Land development	2009	
Rainfall	1971	2000
Soil of the land	2000	
Industrial	2004	
Livestock	2009	
Ecosystem	2003	

F
Climate

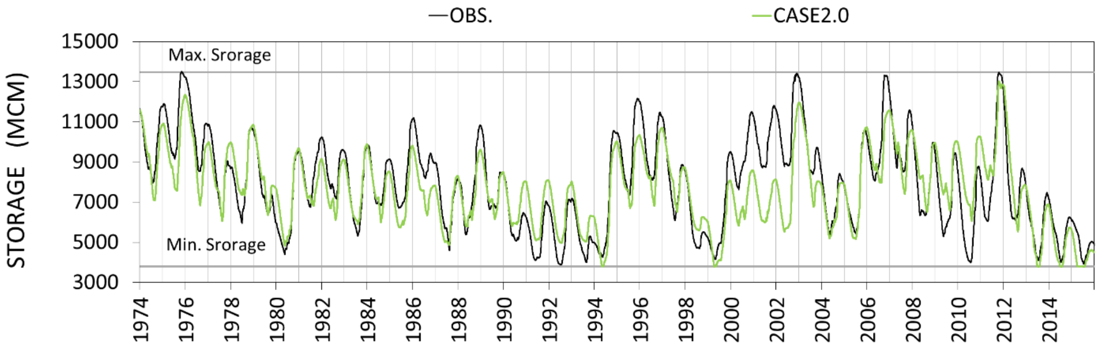


Figure F.1: Water storage in the Bhumibol dam, source: Tebakari (2016)

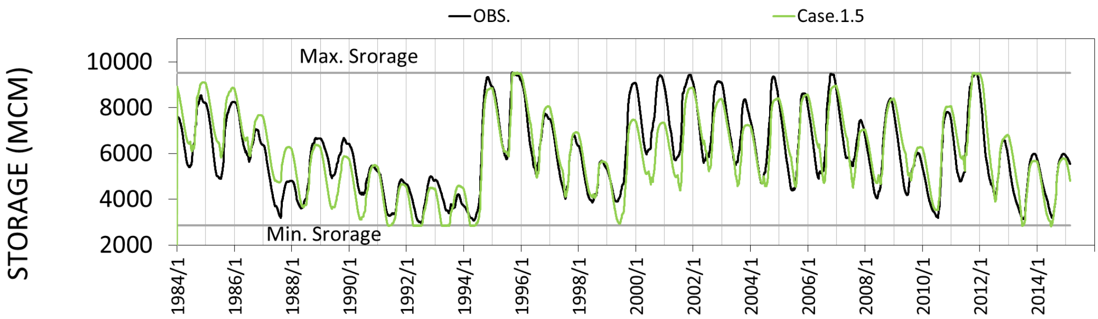


Figure F.2: Water storage in the Sirikit dam, source: Tebakari (2016)

G

Flow properties

G.1. Discharges

The daily discharges of 2009 until the beginning of 2016 from measurements stations at the Pho Phraya gate and the Song Phi Nong canal (with a gate) are provided by the RID, for the exact location see the schematic overview of the Tha Chin River in appendix A. See figure G.1 for the discharges. In figure G.2 it can be seen that there are some data point missing which makes the date less reliable.

The measurements stations are located quite upstream (around 300 km) and it is not completely sure that between that point and the area of interest no other in-or outflows occur along the river branch. But from google earth it became clear that the Pho Phraya and the Song Phi Nong are at least two of the biggest gates. For this project a summation of the discharge of the two gates is uses, see figure G.1.

G.2. Water level

The hourly data from the three measurement stations can be found in figures G.3, G.4 and G.5. A note must be made that it was not completely clear what the used reference point was. So only the changes in water level will be used to check our models.

From figures G.3, G.4 and G.5 G.1 it can be seen that water levels and the discharge correlate really well. At times of low discharges there is also a low water level which makes the data more reliable. Figure G.5 shows that during the dry season (starting around January) the tides propagates much deeper into the river than during the wet season.

The wet year of 2011 is quite well visible in figure G.5. The water level at the end of 2011 remains constant although the discharge varies, which implies a flood during that period. This matched what is know from reality, see F.

G.3. Tide

Tidal elevation data from 2009 till 2014, provided by dr Chaiwat, have been analysed. See figure G.6 The mean water level is + 0.53 m. By subtracting this number, the measurements results in the tidal water elevation around mean sea level (MSL). The highest recorded elevation in these six years is MSL + 1.71 m. Data from this station gives the instantaneous water level and includes other sources of water level variation throughout the year, such as setup of the sea water by wind and changing river discharges.

G.3.1. Tidal constituents

Also, the theoretical tidal constituents have been analysed in the Tha Chin River (Anongponyoskun, 2007). The results of this study are presented in table G.1.These constituents add up to a total tidal amplitude of MSL + 2.70 m. However, this amplitude is not likely occur because these constituents will have to coincide. By plotting the constituents with their phase differences, the theoretical tidal elevation is found. The results are displayed in figure G.13. A maximum theoretical tidal elevation of MSL + 2.00 m once every 1000 years was found by increasing the time period of the computation.

It can be seen that the major contributors are Sa, O1, P1, K1, M2, S2 and K2. The annual tide and both the semi-diurnal and diurnal parts of the principal lunar, principal solar and lunar solar declinational con-

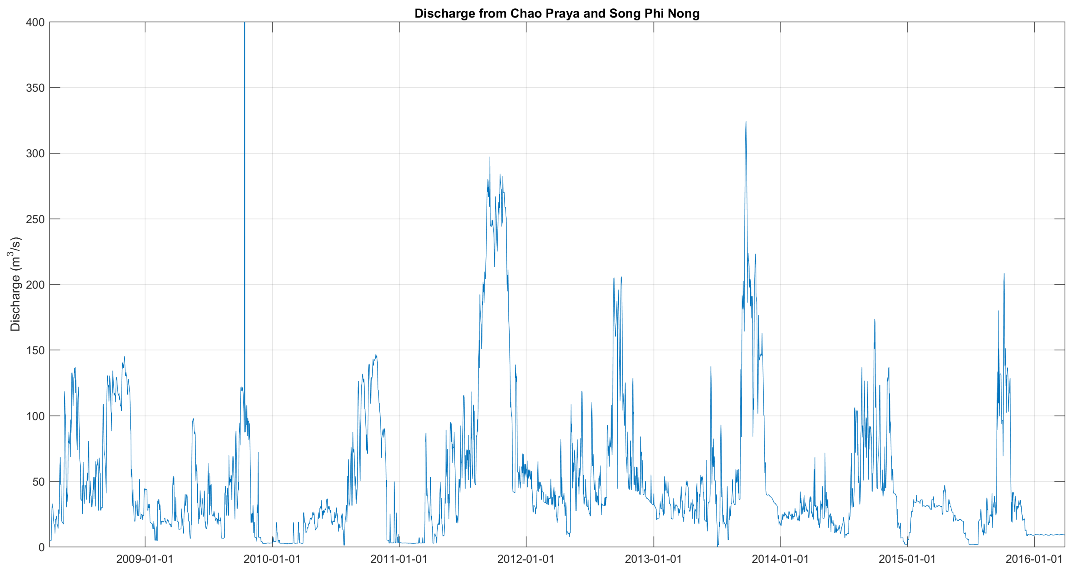


Figure G.1: Total discharges 2009 until 2016. Based on data provided by the RID

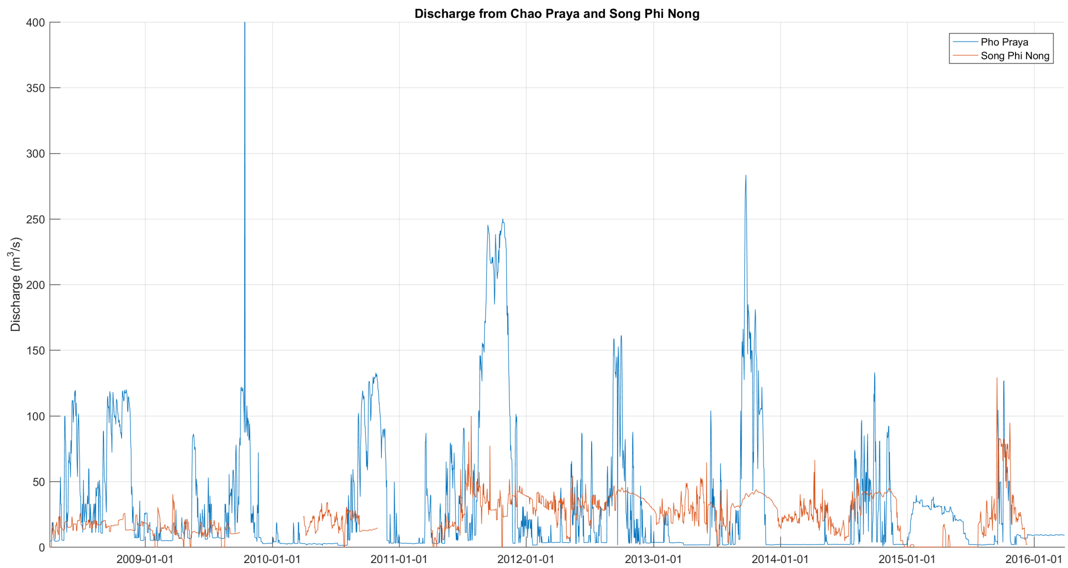


Figure G.2: Separate discharges 2009 until 2016. Based on data provided by the RID

stituents. The form factor, $F = \frac{K1+O1}{M2+S2}$, has a value of 1.26 which is in the middle of the mixed tidal regime, both the semi-diurnal and diurnal components are present in the tide. This can also be seen in the figures of the tide per year, figure G.7 to G.12.

G.3.2. Sea level rise

According to different reports with measurements of absolute sea level rise, this does not play a role in the upper gulf (Sojisuporn et al., 2013). Therefore absolute sea level rise will not be further included in the report. However, there are still other factors present that result in a relative sea level rise, mainly subsidence.

Table G.1: All the tidal constituents present in the mouth of the Tha Chin with their amplitude, phase and frequency. Source: Anongponyoskun (2007)

Symbol	Amplitude [cm]	ω_0 [rad/s]	Phi [rad]	T [hr]	Importance
Sa	15	1.99113E-07	5.096361416	8765.522279	Important
Ssa	1	3.98226E-07	0.191986218	4382.76114	Not large contributor
Mm	3	2.63918E-06	1.588249619	661.3149145	Not large contributor
Msf	3	4.92522E-06	1.710422667	354.3655872	Not large contributor
Mf	3	5.3234E-06	2.775073511	327.8598945	Not large contributor
Q1	7	6.49585E-05	1.762782545	26.86835848	Not large contributor
O1	39	6.75978E-05	2.07694181	25.81933352	Important
M1	0.7	7.02819E-05	3.822271062	24.83325504	Not large contributor
P1	17	7.25229E-05	2.844886681	24.06589241	Important
S1	1	7.27221E-05	1.570796327	24	Not large contributor
K1	62	7.29212E-05	2.879793266	23.93446743	Important
OO1	3	7.82446E-05	3.420845334	22.30607655	Not large contributor
2N2	1	0.000135241	4.380776423	12.90537208	Not large contributor
M2	2	0.000135594	3.508111797	12.8717569	Not large contributor
N2	8	0.00013788	2.111848395	12.65834802	Not large contributor
N2	1	0.000138233	2.583087293	12.62600578	Not large contributor
M2	54	0.000140519	2.548180708	12.42060302	Important
Λ2	2	0.000142805	2.792526803	12.2217722	Not large contributor
L2	6	0.000143158	2.809980096	12.19161975	Not large contributor
T2	1	0.000145245	2.059488517	12.01645052	Not large contributor
S2	26	0.000145444	3.665191429	12	Important
K2	12	0.000145842	3.228859116	11.96723371	Important
M3	0.7	0.000210778	4.468042885	8.280400109	Not large contributor
M4	2	0.000281038	3.717551307	6.210300439	Not large contributor
M6	0.3	0.000421557	3.543018382	4.140200054	Not large contributor

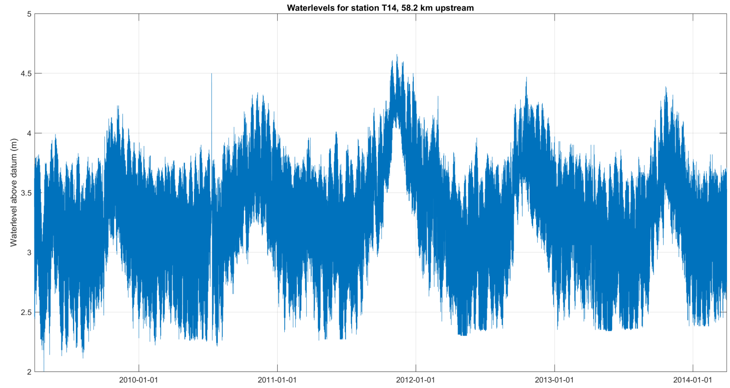


Figure G.3: Water level at station T14. Based on data provided by the RID

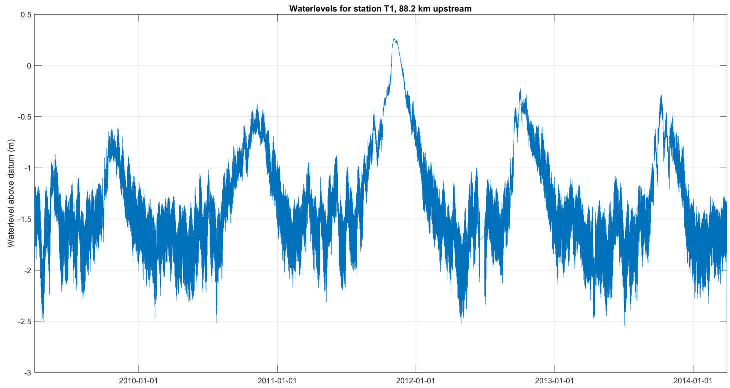


Figure G.4: Water level at station T1. Based on data provided by the RID

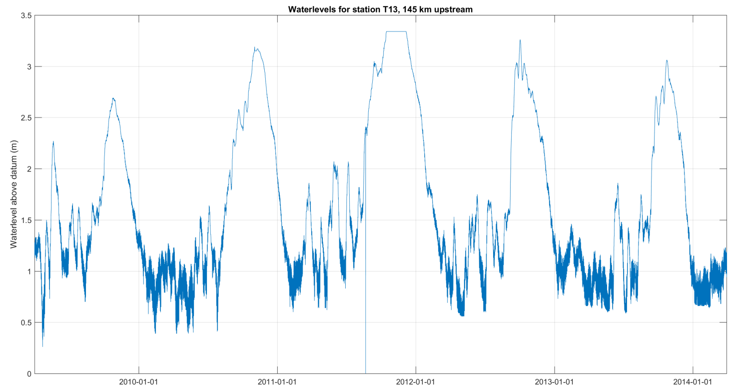


Figure G.5: Water level at station T13. Based on data provided by the RID

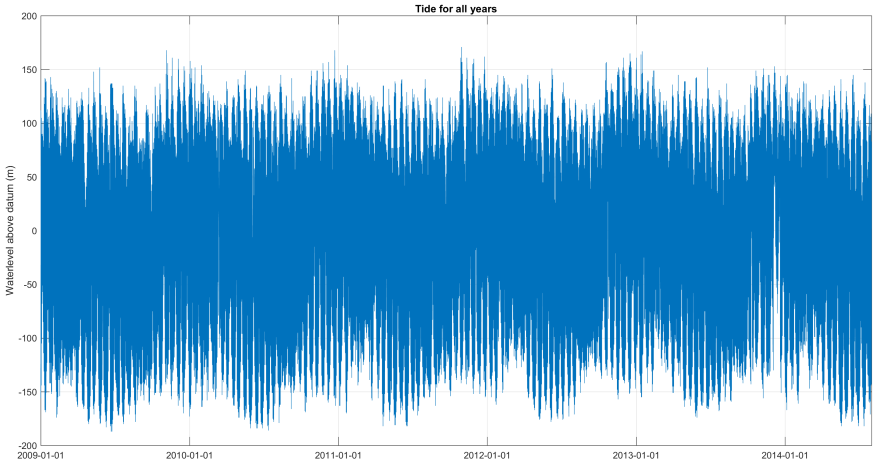


Figure G.6: Measured tide in the river mouth over the years 2009 till 2014. Based on data provided by the RID

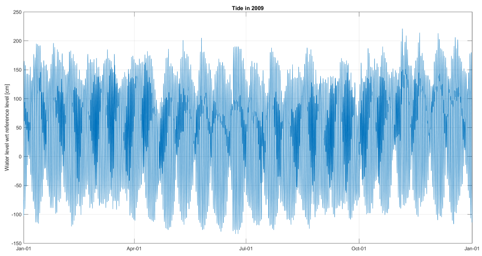


Figure G.7: Tide 2009. Based on data provided by the RID

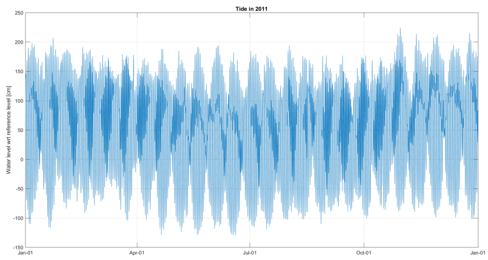


Figure G.8: Tide 2010. Based on data provided by the RID

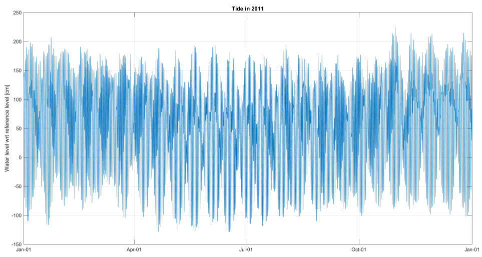


Figure G.9: Tide 2011. Based on data provided by the RID

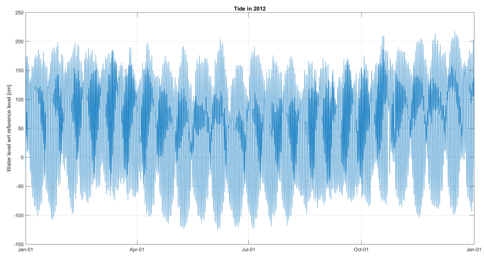


Figure G.10: Tide 2012. Based on data provided by the RID

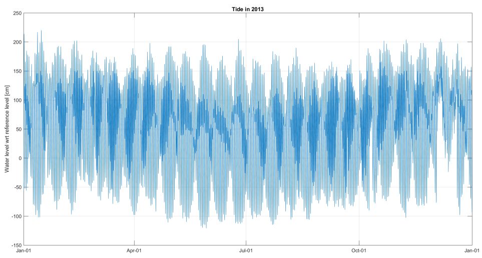


Figure G.11: Tide 2013. Based on data provided by the RID

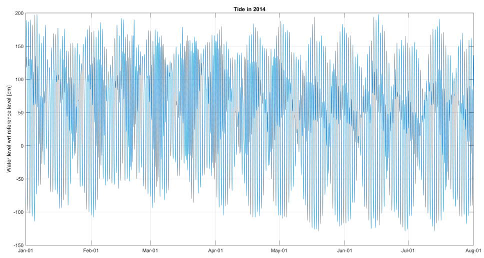


Figure G.12: Tide 2014. Based on data provided by the RID

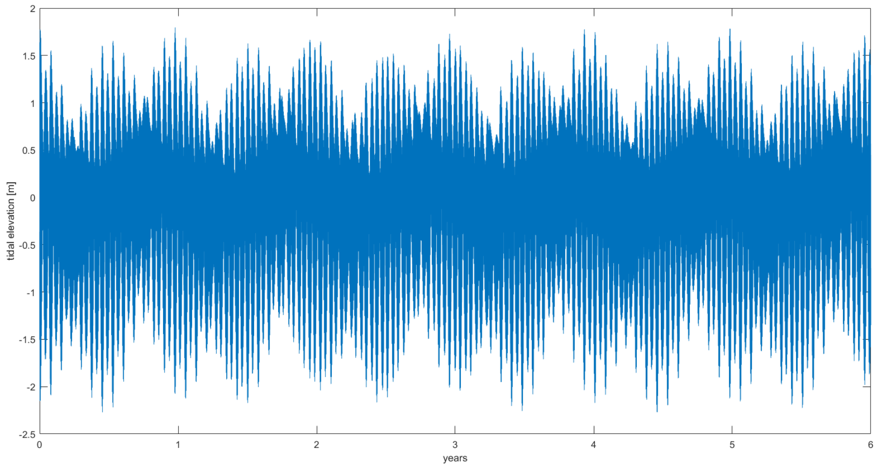


Figure G.13: Theoretical tide calculated over 6 years using the values from table G.1.

H

Dissolved Oxygen levels

The current DO levels can be seen In the figures H.1 to H.5. The years are in Thai years, so 2553 is 2010 and 2557 is 2014. The stations on the X-axis are the stations in the first part of the river, see appendix B. The DO levels should be above the threshold value of 2 mg/l. A big difference can be noticed between 2010 and later years. In 2010 the DO levels are always way to low.

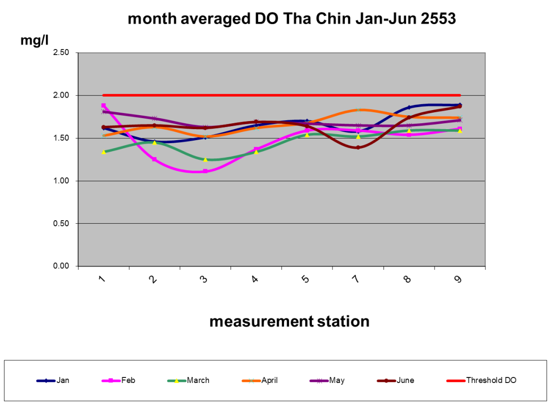


Figure H.1: DO levels in 2010. Based on values provided by RID

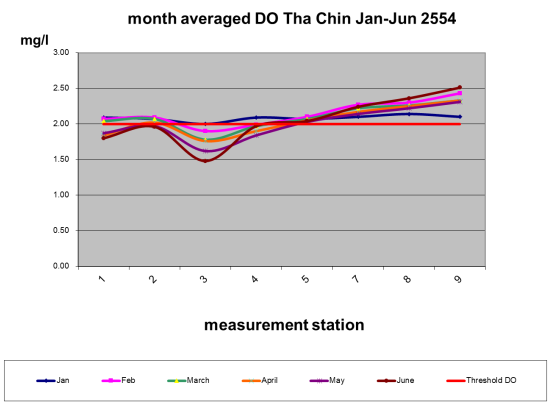


Figure H.2: DO levels in 2011. Based on values provided by RID

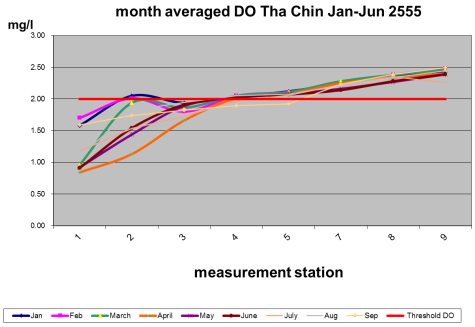


Figure H.3: DO levels in 2012. Based on values provided by RID

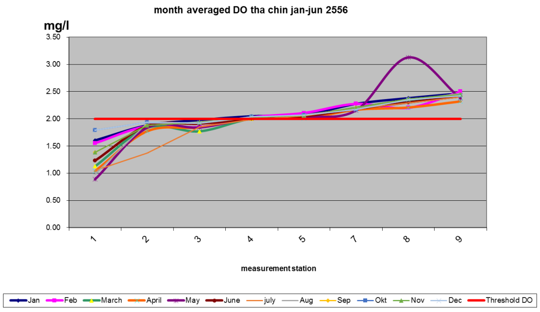


Figure H.4: DO levels in 2013. Based on values provided by RID

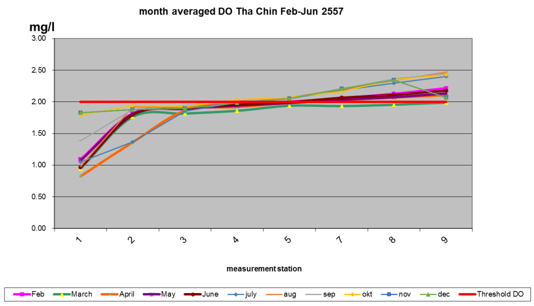


Figure H.5: DO levels in 2014. Based on values provided by RID

I
Stakeholder analysis

The framework for water management on an institutional level in Thailand is very fragmented; over 31 departments under 10 ministries are involved. Besides the ministerial departments, six national committees have been appointed advising in the water management sector.

In the Tha Chin River basin, not less than 8 ministries and 19 departments are involved in its management. Also, different institutions, NGOs and even users are involved in decisions about the basin.In 2002 the Thai government introduced a river basin committe (RBC) for each river basin in Thailand. The goal of the committees is to strengthen governance and to approach the water managament issues in a more integrated way. To achieve all parties (e.g. government, industry, farmers, etc.) involved in river water use and management have a seat in the committee.

I.1. Involved parties

I.1.1. Government

For the basic Representation of involved institutions in Water Management see I.1. The main governmental department that controls the water in the Tha Chin is the *Royal Irrigation Department (RID)*. Their duty is: *"Implementation of activities aimed at achieving, collecting, storing, controlling, distributing, draining or allocating water for agricultural, energy, household consumption or industrial purposes under irrigation laws, ditch and dike laws and other related laws"*. The RID is the official client of the project. Their interest is in water that can be used for irrigation and for this they have built a vast amount of structures to control and divert water. Water resources are managed by another department called *the Department of Water Resources (DWR)*. They are involved in water resource development too, but for non-irrigation purposes.

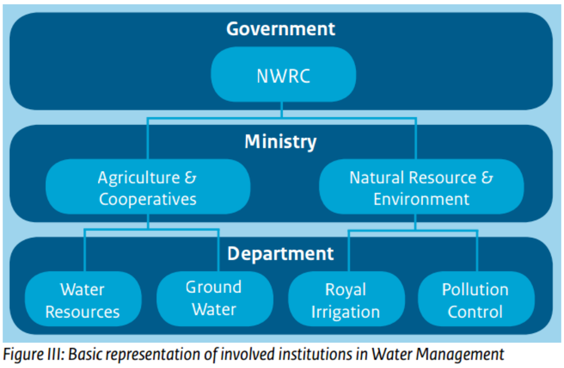


Figure I.1: Basic Representation of involved institutions in Water Management. Source: (NLDEmbassy, 2016) http://thailand.nlembassy.org/binaries/content/assets/postenweb/t/thailand/embassy-of-the-kingdom-of-the-netherlands-in-bangkok/import/factsheet-the-water-sector-in-thailand-3.pdf

Since a larger part of the water of the Tha Chin River is used for land irrigation, the RID does most of the water management. However, the DWR is also involved in policy making, up to the national level. It takes policy measures and they develop plans for every other agency involved in water. The DWR is waiting for the adoption of the new Water Act (see further below), which would authorized the DWR as the central organization for governance. Furthermore, the DWR manages water resource development: for example the construction and operation of the major water reservoirs in Thailand are the resposibility of the DWR.

The Marine Department (MD) controls transport up and down the river. Since there the Tha Chin is also used for (transport) traffic, the MD will play a role in the design of a solution, especially if it would be built in or near the river mouth. One of their key objectives is: *"To develop and maintain water transport infrastructure, including natural navigation channels and support the efficient water transportation system"* (MarineDep, 2016). Their only concern is keeping water levels high enough for traffic to pass. As the Tha Chin River is mostly used for other purposes than traffic, the MD has a low influence on water management.

An influential stakeholder is the *Pollution Control Department (PCD)*. Pollution plays a large role in the Tha Chin River, as the quality of the water is bad compared to other rivers. Their goal is to *"control, prevent, reduce and eliminate pollution and to conserve and rehabilitate the environment conducive for human life"*. Besides monitoring the pollution in the Tha Chin River, the PCD makes annual reports and advices other governmental departments on management. The department also investigates public complaints, so they are aware of the public opinion (PCD, 2016).

The Department of Groundwater Resources (DGR) was formed in 2004 from the Groundwater Division of the Department of Miner Resources. Its task is groundwater resource management and protection. This also includes making groundwater legislation. On everyday basis, it makes sure aquifers do not become depleted or polluted, and that groundwater distribution is done fair.

The Department of Fisheries manages aquatic resources and implement various fishery relating acts. Their role in this project is smaller, but significant due to the large amount of fish farms and shrimp farms. However, the organization is not focused on the opinions of the fishermen and therefore they do not play a large role in this project (DoF, 2016).

The large number of governmental departments alone already tells something about the fragmentation of the government. This causes practical problems: different kind of data is gathered and stored at different departments, which makes for a lack of appropriate information. Sometimes responsibilities to problems or areas are over lapping or conflicting and unclear. Problems are also on organizational level; a general view of water management on a province or national scale is absent. This makes for a culture were problems are only solved locally, not on a long-term, fundamental scale. This continuously makes way for new problems to show up, sometimes as a result of implemented projects (Feld et al., 2003). There are however attempts to solve the lack of decisiveness and integrated policy. The new Water Act is supposed to become the main legislative framework on water management. However, the act has been in the process of drafting since 1992. The DWR is in charge of drafting the act. After the act is adopted, DWR would be authorized as the central organization for governance. It would also separate regulatory and operational tasks between institutions, and encourage active participation by locals and users (NLDEmbassy, 2016).

The Tha Chin River project offers a chance to solve problems on a fundamental level. A proposed solution should also address its negative consequences, so no new problems will occur. In other words: it should strive to solve the salinity problem fundamentally.

I.1.2. Users

Water in the Tha Chin basin is used for farming, fish or shrimp farming, industrial and domestic use and some freight traffic. Farmers are in close contact with local RID offices and contact the RID when salinity levels are too high. Fish and shrimp farmers actually need salt water to grow their product. They will likely be affected by a change of the river system. Also, domestic water users will likely experience problems with salinity, but they have not been in the scope of research of this project. Another major problem in the river is water pollution, this problem was mentioned often during conversation with different stake holders during site visits. The river is polluted by several sources such as agriculture, sea traffic and industries. All users, except for traffic and industry, are affected by water pollution. Higher pollution levels already have made for example (shrimp) farms disappear near the river mouth (RID, 2011).

The local communities in the Tha Chin basin are tight-knit and have bad experiences with failing government water projects. They are not easily persuaded when an intervention in the river system is introduced.

I.1.3. Non-Government Organizations

Non-Government Organizations and local communities have been dealing with the processes of development and globalization. Support from NGOs has improved public awareness and participation in development projects in Thailand. Many NGOs are involved in mobilizing people and campaigning against construction projects.

A large acting NGO in the Tha Chin River Basin is *We Love Tha Chin River Society (WLTS)*. The Members of WLTS are local residents along the Tha Chin River. Their activities focus on organizing public participation in river water management, school education in environmental programs, outreach on pollution reduction and prevention, and raising environmental awareness via educative documents such as brochures (Khonthet, 2007).

The 1997 Thai Constitutional Law gives communities guaranteed communities the right to participate in the process of conducting Environmental Impact Assessments (EIA). When an EIA proves a project to have a large negative impact on its local environment, the project has to be cancelled. This hugely increases the power local communities have on infrastructure projects in Thailand. NGOs help local communities use this power by providing them with knowledge, media coverage and organizational help. In the case of the Tha Chin River, WLTS published two documents about negative consequences these dams would have on the environment. The presentation of these reports to the Ministry of Agriculture and Co-operatives, together with a public meeting held in May 2002,, see figure I.2, made We Love Tha Chin successful in blocking construction of the dams; the project was cancelled (Khonthet, 2007).

Figure I.2: Public forum organized by the WLTS. Source: Khonthet (2007)

Through We Love Tha Chin and other examples of local communities blocking infrastructural projects of the government see also J, the large influence of local communities together with NGOs becomes clear. The impact of an adjustment of the river system will have to be severely assessed. Also, explanation of the project to and clear communication with local communities is key for successful implementation of the project.

I.1.4. Labour unions

A few water user organizations have been set up such as the Thai farmers association and fishery association. The status of the organizations is ambiguous and the necessary legislation is lacking for them to obtain proper legal status. They focus on well-being of users on a national scale. For locals, the NGO's and RBC are more important.

I.1.5. Tha Chin River Basin Committee

This committee includes all relevant parties involved with the Tha Chin River and were set up to lead and strengthen integrated water management. However, generally the RBC's are *"poorly authorized and generally ineffective in maintaining consistent standards of river basin planning"* (NLDEmbassy, 2016).

The Tha Chin river basin committee consist of all relevant parties involved in the use, management, regulation and protection of the water in the river. They meet two or three times per year to discuss all projects in the area. Their main objective is to integrate water management. Another focus is to inform their parties about the projects going on. A full list of all parties can be found in figure I.3.

On the 27th of September 2016, the project team was able to attend a meeting of the Tha Chin RBC. A big part of this meeting was about budget allocation to different projects. Another topic was discussing last year's performance of projects and the weather compared to this year's. Performance of water projects was

Table I.1: Influence of different stakeholders and their interest in the project

Stakeholder	Influence on the project	Interest in the project	Type
RID	Large	Large	Government
DWR	Large	Large	Government
MD	Small	Intermediate	Government
PCD	Intermediate	Intermediate	Government
DGR	Small	Small	Government
DoF	Intermediate	Intermediate	Government
We Love Tha Chin	Large	Large	NGO
Tha Chin RBC	Small	Large	Government
Local factories	Small	Intermediate	Industry
Local farmers	Small	Large	Locals
Domestic users	Small	Intermediate	Locals
Fisheries	Small	Large	Locals
Transport ships	Small	Small	Locals

not discussed. Research noted lack of authority of the RBC and a general lack of integrated, long-term water management. The findings of the project team at the meeting confirmed this statement.

List of parties included in the Tha Chin river basin committee

- Ministry of Domestic Affairs
- Royal irrigation department
- Department of Land Development
- Harbour Department
- Ministry of Natural Resources and Environment
- Department of Water Resources
- Department of Groundwater Resources
- Department of Marine and Coastal Resources
- Department of National Parks, Wildlife and Plant Conservation
- Department of Disaster Prevention and Mitigation
- Local government officials
- Department of Local Administration
- Department of resources, provincial environment and nature
- NGO: We love Tha Chin River
- Humanitarian aid groups
- Enterprise users: Industry and agriculture
- Corporate users and commercial sectors: Hospitality and Tourism
- Scientists specialist: Division of the Industrial factories
- Scientists specialist: Professor of Kasetsart University

Figure I.3: List of parties included in the Tha Chin, provided by dr. Chaiwat.

I.2. Influence

Not all government parties are quoted in this list, see section I.1, because many have a very small influence on managing the Tha Chin and adding them on this list would not make the list more significant. The RID and DWR are the most influential parties involved, because of their main role in daily management and main role in water policy respectively. Because of the large influence of an EIA, NGOs have become powerful as well. The main interest of fishing ships and the MD is confined to the river mouth only.

I.3. Conclusions

The RID is the project's client. With an extensive network of local offices, it is the party with the largest influence in (daily) management of the river basin. Its duty is water collection and distribution and it proposes and implements projects to manage water, such as gates or diversion canals. The DWR is the party that makes and controls water policy and takes policy measures. However, because of the fragmented government system, they lack authority to force other parties to undertake action if necessary. The (since 1992) pending Water Act would give them the authority to draw a water master plan and make other parties take measures according to it.

The parties with a stake in the Tha Chin River are numerous and their interrelations, individual responsibilities and influences are varied and complex. The government is very fragmented, which makes for a lack of a single strong authority and a long-term integrated master plan in water management of the whole basin. As a result, policy often lacks overview, much problems are addressed locally only and cooperation between different parties is limited. The project will have to propose a solution that is feasible and durable under these circumstances.

J

Reference projects

In this appendix two reference projects are described. The first reference project is the Bang Pakong diversion dam which was also built as a salinity reduction measurement. The second reference projects consists of previously proposed projects in the Tha Chin river.

J.1. The Bang Pakong diversion dam

The Bang Pakong diversion dam (figure J.1) is part of a bigger Bang Pakong river basin project, designed to address increasing water needs in the basin. The diversion dam was constructed by the Royal Irrigation Department (RID) to divert and store freshwater for different uses, mainly urban, and to prevent saltwater intrusion into irrigation areas during the dry season. The dam came into operation in early 2000 but due to critical environmental problems, both downstream and upstream of the dam, RID was compelled to cease operations and evaluate options for future operation of the barrage. During the short period in which the dam was operational, several impacts were manifested. Downstream impacts of the dam included flooding by brackish water resulting in damage to houses and agriculture, erosion and collapse of the riverbanks and structures along the river downstream of the dam. At present, the dam is kept fully open as approval or consent of the public is necessary before further actions are implemented. However, demand for new dams and reservoirs will continue in order to ease urgent problems of water shortages, irregularity in supplies and water use conflicts (Pickaver and Sadacharan, 2007).

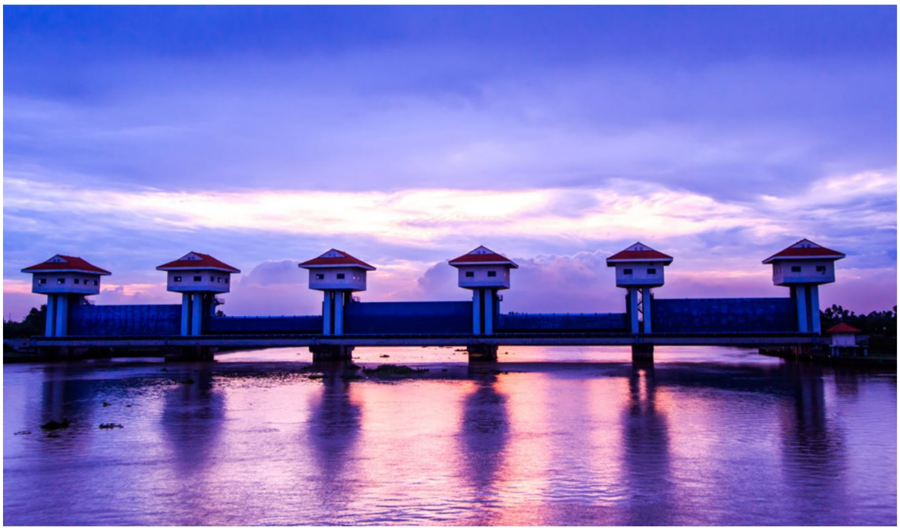


Figure J.1: The Bang Pakong dam, now continuously opened. Source: NLDEmbassy (2016)

J.1.1. Design of the dam

During the first meeting with the RID, the project team was told about the Bang Pakong dam and its short period of operation. The RID told that the reason for this was its location, which caused major tidal amplitude increases. According to Feld et al. (2003): *"downstream, (...) the river rose to a level that caused severe bank erosion. Upstream, the dam prevented tidal flushing of the river laden with municipal sewage and the considerable effluent from pig farms and prawn culture ponds."* Thus the location both caused bank erosion as well as pollution problems.

An extensive design report has been composed in 1993 by the Japanese company Sanyu Consultants, for the Japan International Cooperation Agency and the RID. This reports states: *"The location of the diversion canal was selected at a site about 71.0 km upstream from the estuary of the Bang Pakong river, so that the proposed canal to be constructed for making a short-cut of the meandering section of the river. ... the proposed diversion dam site was selected at the straight section of the diversion canal"* (JICA, 1993).

J.1.2. Organization of the project

For the Tha Chin project group, the reason why the exact location of the dam has been chosen remains obscure. In an analysis about the Bang Pakong River Basin Committee, Molle et al. (2009) found that *RID's age-old conception is that it is entrusted with the duty to dam every single stream that happens to offer a convenient site for building a reservoir, and has some agricultural land that can be irrigated in its vicinity."* Furthermore, he states that *"RID's policy is still largely based on the perception that it has a mission to endlessly develop water resources, largely independently of their social, economic and environmental consequences."* Also, he made notes about the supply and demand of water in the basin. He found that current procedures mostly aim at increasing demand, often beyond the availability of water. Each time a new dam is constructed, the prospect that downstream problems can be solved are paralleled by an increase in demand that is even higher than the new potential supply. Therefore scarcity reappears.

In a proposal for an ILWRM system, Feld et al. (2003) also studied the organization of the river basin. They concluded that a lack of appropriate information for basin-wide planning was a significant underlying problem in managing the river basin. Also, at the moment, overlaps and conflicts in administrative jurisdiction occur at the central level among government agencies, as well as between central and provincial authorities. This image of a lack of overview in the water management of the river basin is shared by Molle et al. (2009), who states: *"Another problem related to the requests made by the sub districts is that these are made without a general view of water management in the Province or in the basin. For example dredging a ditch or canal may have an impact on the flows within the larger system; constructing a dike in a particular place may just increase flood damage somewhere else"*.

Both Feld et al. (2003) and Molle et al. (2009) draw an image of a local culture where water is regarded as a common good and therefore everyone feels entitled to all the water they want. Local populations consider that rivers flowing nearby are *'theirs'* and do not understand that they cannot receive water through systems when at the same time more downstream areas are planned for irrigation. Again, a view rises of a culture with a lack of overview of the whole river basin.

J.1.3. Conclusion

Over the years, the RID has developed multiple projects in search of further developing of the water resources. One of these is the Bang Pakong diversion dam, which opened in 2000. Quickly after it came into operation, its functioning had to stop due to multiple environmental problems. The reasons of its malfunctioning could serve the Tha Chin river project as valuable references.

The main cause of the problems was the location of the dam: the location was such that tide water levels rose significantly, which caused the downstream river beds to erode. Upstream, since the tide flow had stopped, major pollution problems occurred. Molle's analysis of the Bang Pakong river basin committee stated that the main focus of the RID lies on building water structures and endlessly developing water resources (Molle et al., 2009).

Furthermore, after desk research, an image appeared of the institutional system as being divided and having a culture where people think and act locally (instead of also having the greater picture in mind). This leads to situations where a water project solves problems at one place in the estuary, while simultaneously creating them at another place more downstream or upstream. One of the challenges for the Tha Chin river project will be to find a way to deal with these problems.

J.2. Previously proposed projects in the Tha Chin

In 1995, the Royal Irrigation Department (RID), proposed the construction of a water retention barrage consisting of two gates in the Tha Chin River. The purposes of the project were to retain and store fresh water for consumption and to prevent salinity intrusion and impacts from tidal effects. However, from the start there were protests from locals because the project did not meet the actual needs and that building a gate would worsen water conditions (Manowong and Ogunlana, 2004).

Locals gathered in the *We Love Tha Chin River Society* (WLTS), an activist group on organizing public participation in river water management and raising environmental awareness. In 2001, WLTS undertook a health impact assessment (HIA) about the proposed gates. As a result of the HIA, WLTS published two documents about the consequences these dams would have on the environment. The water would get even more polluted, the tidal amplitude would increase and the water level would change significantly.

On the 21st of May 2002, WLTS arranged a public forum on *'The advantages and Disadvantages from the dam construction'* to listen to locals. At the hearing, the public decided that the impacts of the dams would be too high. Through this meeting and the presentation of the reports to the Ministry of Agriculture and Co-operatives, We Love Tha Chin successfully blocked construction of the dams. The project was cancelled. (Khonthet, 2007).

J.3. Protests against other projects in Thailand

An example of cancellation of a project elsewhere in Thailand is of the Kon Chi Mun water diversion mega project in the Mekong River basin in North East Thailand, started in 1992. This was a project which composed of dams, water tunnels and water diversion infrastructure, to divert four billion cubic meters of water. Construction would take multiple decades and costs billions of US dollars (BankokPost, 2016).One part of this project was the Sakhrom river dam in Isan. When local communities began to learn about the Sakhrom dam, with previous big problems of the similar and controversial RasiSalai Dam and Pak Mun Dam in mind, they formed a strong movement to stop the construction of dams in the Sakhromriver. After implementation of the EIA, in which locals were involved, the project committee found the project inappropriate and construction of the dam was canceled (Terashima, 2011). Other parts of the KCM-megaproject have been criticized intensively by locals and academics as well, causing delays and partial cancellation of the project (of which the Sakhrom dam is an example). On top of this, many local farmers refuse to use irrigation infrastructure that has been built, because they don't find it profitable to grow a second rice crop in the dry season (Kamkongsak and Law, 2001).

Similarly, the vast Flood Control Project, a project aiming to avoid a repeat of the 2011 floods, received massive criticism. The 11 billion US dollar project to build reservoirs, detention basins and other infrastructure to control water has been delayed through a verdict by the Thai Central Administrative Court in 2013. Environmentalists had brought the Thai government to court, claiming the project would displace many people and be "harmful" to the environment. The government was ordered to first get adequate public input or environmental assessment from the communities most affected. Another example is the Pak Mun Dam project in UbonRachathani province, North East Thailand. This was a multi-purpose river scheme project, with both large electricity generation and irrigation development purposes. It was financed by the World Bank and construction was completed in 1994 (Manowong and Ogunlana, 2004). However, after construction it turned out that fish populations were reduced significantly and that villagers suffered floods that caused the loss of valuable land.

Different NGOs acted to support demands for compensation of the villagers, permanent opening of the gates and even decommissioning of the dam. It also became clear that the dam did not meet its performance goals on multiple levels. Including protests before construction of the dam, protests and demonstrations against the dam have continued for over 10 years. In 2001, following numerous other acts of protest, around 700 people gathered at the Ubon Ratchathani Provincial Hall to rally in hope that the dam would permanently be opened. As a result of the bad performances of the dam and of the huge of amount of protests by local communities, the government eventually decided in 2001 to open the dam gates 4 months per year.

J.4. Conclusion

Especially in the last 20 years, there has been a strong tradition of revolting local communities in reaction to infrastructural projects proposed by the Thai government. These include, but are certainly not limited to, water management projects (WallStreetJournal, 2013). Supported by NGO's, which provide (legal) knowledge, attention from the media and organizational help, they demand a say in the government decision making on large projects. Especially by using the mandatory environmental impact assessment, they have often successfully blocked the construction of large water structures. It will be very important for the salt intrusion solution to minimize negative consequences on the environment. Moreover, if the positive effects do not outmatch possible negative environmental consequences, chances are very slim that the solution will not be blocked by local communities.

K

Demands, wishes and boundaries

During the analysis phase of the project, as a result of several conversations with stakeholders in the river and as a result of studying reference projects, a list of demands, wishes and boundary conditions for the eventual solution was drafted. Note that demands are firm requirements to a possible solution, while wishes have a more soft nature – there is a lower priority in fulfilling them.

K.1. Demands

- The solution has to make enough usable fresh water available during the year, especially in the dry season for three different purposes:
  - Farmers for irrigation purposes
  - Domestic use
  - Industrial use
- The solution has to deal with the salinity problem in the river
- The solution has to maintain or decrease current water pollution levels (DO, pesticides etc.)
- The solution has to function for a long period, for example 100 years.
- The solution has to be feasible in Thailand

K.2. Wishes

- Decreasing salinity in the river to the threshold level
- An integral solution – 'one water system, one solution'
- Minimize environmental impact
- Minimum forced home movements
- Maintain or improve current transport capacity of the river
- No dams in the river
- Maintaining or improving current fishery capacity
- Maintaining or improving current agricultural capacity
- Minimize flood risk
- Decrease water pollution level
- Maintain current water level
- Minimized conflicts between stakeholders on all levels
- Durable solution
- Sustainable solution

K.3. Project boundaries

After analysis of the problem and the river basin, a list of project boundary conditions has been made. Also, possible conflicts in the project have been identified. In proposing a solution, these possible conflicts have to be addressed with care.

K.3.1. Geographic

- Upper geographical boundary: Polthep water gate
- Lower geographical boundary: Gulf of Thailand
- The Tha Chin River basin between upper and lower boundaries, including all irrigated land

K.3.2. Hydraulic

- Upper river boundary: Polthep water gate with a known discharge. For the salt intrusion the Pho Praya gate is the upper boundary
- Lower river boundary: mouth of the estuary.
- Sea level including a sea level rise at the mouth of the estuary and an incoming tide with a tidal range of 3 m.

K.4. Conflicts

K.4.1. Possible conflicts between stakeholders

- RID and DWR about the amount of water needed for irrigation
- Harbour Department and RID and/or DWR about the significance of transport over the river
- Industry and farmers about water pollution
- Different kind of farmers with one another about salinity of the river (e.g. salt or fresh water)
- Farmers and fisheries about salinity of the river
- Governments and NGO's/locals about the solution

K.4.2. Possible conflicts between criteria

- Not building a structure and decreasing salinity
- Maintaining or improving agricultural and fishery capacity and decrease water pollution level
- Maintaining or improving agricultural and fishery capacity and maintaining the current water level
- Minimize environmental impact, forced home movements and transport capacity and decreasing salinity

L

Preliminary solutions

This appendix elaborates on the different solutions that came our of the first brainstorm session.

L.1. Apply (temporary) friction to decrease intrusion length of the penetrating tide in the river

L.1.1. Description

The theory behind this solution is relatively simple. The intrusion length of the salt water may for a large part depend on the amount of tidal damping (caused by friction and river discharge) (Savenije and Veling, 2005). In this solution, the friction part will be attended. Increasing friction can be done in several ways. One is increasing friction at the river bed through adding for example (plastic) plants or artificial dunes (small weirs or sand banks). The river could also be made more meandering, by building groynes that redirect the flow, or by redirecting river flow by excavation. Any remaining shortcut-channels in the river can be closed off. All these examples are aimed at disrupting water flows, so salt water flows in less easy.

L.1.2. Alternatives

Creating extra friction can also be done temporary. If water flow interruption is applied for a shorter period every year, the equilibrium situation of the upstream estuary will be less affected, benefiting the ecosystem. A temporary system may be placing and removing concrete poles to create groynes.

L.1.3. Technical layout

Increasing bottom friction can be applied over the whole river. Artificial banks have to be implemented at locations where large ships are not affected by a water depth decrease. At the moment, the bed level differences along the river. In the current situation, the river is already meandering a lot. Adding more bends by excavation will only be possible at a few locations.

L.1.4. Advantages

- If applied temporary, the equilibrium situation of the upstream estuary will not be affected much. If applied permanently, the equilibrium situation of the river in time will change. However, this will be a gradual process and therefore people can adapt to the new natural ecological equilibrium.
- This solution is (almost) invisible to the eye. It will be easier to persuade the local communities to implement this solution.

L.1.5. Disadvantages

- The effectiveness of this solution is unknown, since the friction coefficient of the river at the moment could already be large. Adding extra friction may then not increase tidal damping significantly enough.
- Water depth may decrease, this may harm shipping opportunities.
- Friction has to be applied over a large stretch of river to have a significant effect.

L.1.6. Cost

The cost depends on the alternative chosen. In any case, a large stretch of river has to be covered with this alternative. This will have large initial costs. However, maintenance cost can be low if the river assumes a right equilibrium position.

L.1.7. Reference projects:

This solution is based on the theory of tidal damping, not on any existing project. No reference projects with the goal of increasing friction in a river are known.

L.2. Balance Islands

L.2.1. Description

Balance Island is a concept in which sand banks are constructed in front of the river mouth which alter water flows. See figure L.1. Because of the new water flows, fresh and salt water will be more mixed at the river mouth. In the river mouth, a brackish area, thus having lower salinity levels than seawater, will form. This causes the transition from salt to fresh water to smoothen. In general, the amount of salt penetration into the river is proportional to the difference in density between fresh and salt water. Therefore, salt water will penetrate less far into the river if the estuary would become less salt (van Rooij et al., 2012). By lowering the salinity level of water penetrating the river, the salt will penetrate less far.

Figure L.1: Artist impression of the he Balance Islands in the Netherlands. Source: DutchWatersector (2012)

L.2.2. Possible alternatives

The Balance Island can be developed in different ways. The local ecosystem could be strengthened by making more space for mangroves. Mangrove forests could be grown on the islands, which could have multiple benefits: the mangroves could serve as coastal protection, a habitat for numerous flora and fauna species and a source of economic activities. Successful development of mangrove forest is very dependent on understanding the local hydromorphological environment. For this, nearby references of mangrove forests have to be inspected (Raadgever et al., 2016). Another alternative is one that focuses on tourism and recreation on the island. A combination of these two might be possible. A completely different solution is simply building Balance Island and creating no other features on the island. Building this might be cheaper, but in this way the island won't provide any additional income and commercial/societal functions.

L.2.3. Technical layout

The core of the island(s) will probably be made out of clay, since this is widely available in the surrounding area. However, rock or other heavier material may also be used to realize the island(s). Further research with more complex models is needed to determine the final shape and location. The salt reduction can only be met when the balance islands are placed at the correct location. A wrong placement, for example too close to the mouth, could even increase the salinity levels (de Kort and van Rooij, 2013). Extensive modeling of the area and the islands is absolutely necessary.

L.2.4. Advantages

- This is a solution that has a relatively low negative impact on the river system (ecosystem, pollution), while still reducing the salt intrusion problem.
- If the barrier is developed as islands, these can have commercial functions.
- The islands could be used to strengthen the local ecosystem.
- No big alterations to the direct surroundings (riverbanks etc.) needed. This increases the chance of acceptance of the solution by locals.
- If designed well, river traffic won't be blocked.

L.2.5. Disadvantages

- Salinity in the inner bay could decrease, which can have a consequence on the ecosystem on / near the shoreline.
- The effect of a Balance Island on salinity is very sensitive to the design and location. This again stresses the need for an extensive analysis and hydrological model of the river mouth.
- Pollution levels may increase due to more stagnant water.
- In case of floods, the islands could interrupt the water flowing out.

L.2.6. Cost

In a project study in the Netherlands, the Balance Island concept at Haringvliet was estimated at 31 million euros (van Rooij et al., 2012). As most of the costs comes from the purchase and depletion of materials, the exact cost will depend on the final size and layout. Reference projects: In the Netherlands at the Haringvliet sluices, this solution has been designed and proposed for implementation. Research done for this design found that salinity levels at the Haringvliet can be reduced by 30%. After numerical modeling, it was concluded that Balance Island could possibly be applied in different estuaries all over the world. For some concept models, the reduction of the salinity levels can reach up to 50% (de Kort and van Rooij, 2013).

L.3. Barrier in the Bay of Thailand

L.3.1. Description:

Building a permanent barrier (e.g. a breakwater or a dyke) in the Gulf of Thailand. Depending on its location and layout, the barrier would shut off the river mouths of some or all of the biggest rivers of Thailand, see figure Q.1. In this way, a fresh water basin at the river mouths will be created and salt water from the Gulf of Thailand will be prevented from penetrating the rivers. The new water basin can also be used as a retention area in case of floods. In that case, excess fresh water could be pumped out into sea, keeping the basin artificially low. When determining the location of the barrier it is very important to account for the tidal amplitude. A wrongly chosen location could cause a rise in tide near the barrier, which could potentially destroy the barrier.

L.3.2. Possible alternatives

Design alternatives for this solution focus on its location and layout. It can be chosen to both shut off only the Tha Chin river mouth as well as (in the extreme case) the whole Gulf of Thailand. The most important points are which river(s) should be shut off and what the size of the fresh water basin should be.

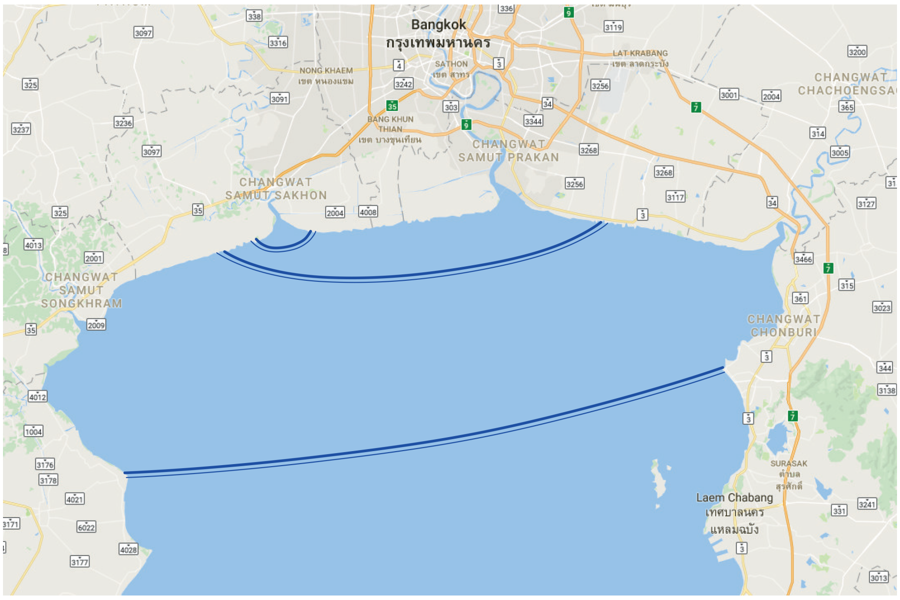


Figure L.2: Possible layout of the dam in the Bay of Bangkok.

L.3.3. Technical layout

The barrier that would close-off the bay would be a breakwater or a dyke. Including gates (for example sluices) to still provide access to sea traffic are imperative. Waste water treatment is absolutely necessary as the rivers flowing into the basin are heavily polluted. Depending on the size of the retention basin and the rivers to be closed off, the barrier could have multiple locations and layouts.

L.3.4. Advantages

- No alterations to the existing surrounding land of the Tha Chin River are needed. This means no forced change of land-use or allocation of land are needed, reducing the amount of protest this solution will cause.
- A large fresh water storage basin will be created, which can be used as a new fresh water resource.
- This is an integral solution to both the salt intrusion as the flood problems. The river will become completely fresh and the reservoir at the mouth can be used to store excess water in case of large rainfall. Any surplus of (rain) water can be pumped to the sea, thus creating new space for flood water. High water sea levels are also taken care of.
- Both the barrier as the basin have a large potential to be developed commercially.

L.3.5. Disadvantages

- Because of the disappearance of salt water and tidal amplitude, the existing ecosystem in the river will be severely altered. Existing plant (mangrove) and fish species could become extinct. Also, protests from locals because of this will occur.
- River water pollution levels will rise due to a lack of tidal amplitude. Additionally, pollution in the closed off bay will rise. These problems have to be addressed when implementing this solution.
- The river mouth will become completely fresh. This will conflict with existing fisheries and possibly farmers near the mouth who use salt water. This will result in protests.
- Sluices will have to be built to accommodate existing ship transport. Nevertheless, ships will be delayed by the barrier.
- Large pumps will be needed to pump out incoming fresh water. This, in combination with the sluices, will probably make for high maintenance and operation costs.

- The large scale of this solution could be a limiting factor in its feasibility, since a large amount of parties have to be involved and in agreement on this solution

L.3.6. Cost:

The initial investments will likely be very high (for example, costs of the very extensive Jakarta project will run in the tenths of billions (NCICD, 2014). However, the indirect revenues in terms of increased (agriculture) production and avoided flood costs will also likely be very high. Additionally, the barrier could be commercially developed, which has very high potential revenues as well.

L.3.7. Reference projects

The main reference for this kind of solutions is the Integrated Coastal Development plan for Jakarta, which consist of building several islands before the coast of Jakarta, connected by breakwaters so the bay is completely shut off. This would create a new lake with a water level that's artificially kept low, by use of several sluices and large pumping systems. The lake would serve as a retention basin for excess floods during extreme weather, as well as run-off from multiple rivers. Additionally the islands and breakwaters protect the capital against high sea water levels. This plan does not address water pollution, which will increase if all the water from the (severely) polluted rivers flows into the same basin. It does however firmly state that sanitation measures for river water are imperative in this solution. Additionally, it discusses the change in marine life in the new basin. It states that because of a gradual change in salinity over several months, marine life is given time to adapt to new conditions. Therefore sudden massive mortality should not be likely to show.

L.4. Building a salt barrier in the river

L.4.1. Description

Building a barrier that lets through the river discharge, but can be closed to block salt water when salinity levels become too high, see figure L.3. This will be during high tide in the dry seasons. Choosing the right location is crucial. This is not only because of the possible hydrological and pollution consequences, but also because of the local spatial and societal consequences of a structure in the river.

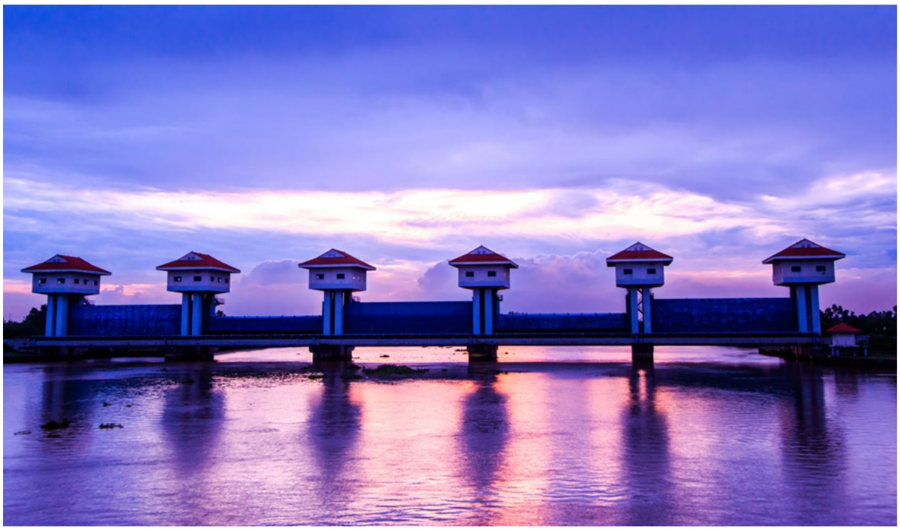


Figure L.3: The Bang Pakong dam, now continuously opened. Source: NLDEmbassy (2016)

L.4.2. Possible alternatives

A barrier can be executed in various ways. From a gate that can simply be lifted or lowered to let water in or out whenever necessary, to a movable underwater screen that works like a submerged weir or two movable barriers that be shoved in or out the river bed at the sides. The type of barrier will depend on the properties of the river and surroundings at the location.

L.4.3. Technical layout

The barrier would need concrete embankments and some moving parts which would be made of steel. The further design completely depends on the type of barrier. The design should focus on giving the least amount of influence to the river system, while still blocking water.

L.4.4. Advantages

- The solution is very familiar to the Thai government – water barriers exist in river basins all over Thailand.
- High control of the salt concentration in the river. If desired it may be even possible to automatically open and close the barrier at certain salinity levels.

L.4.5. Disadvantages

- This solution will cause much opposition from all involved parties, even the RID. This is because of the bad experiences with the Bang Pakong barrier (immediately after commencement, huge problems occurred). Local communities are also strongly opposed to placing a water barrier in the river (appendix V.1).
- The impact on the (local) ecosystem of the river could be large, as a structure that blocks the barrier for up to half the time will be placed. The impact on the environment should be assessed.
- Finding a suited location (both hydraulic as societal) could be difficult.

L.4.6. Cost

Costs depend much on the type of barrier built. However, although complex barriers could bring high costs, building a common type of water barrier will likely be a relatively cheap solution to stop salt intrusion.

L.4.7. Reference projects

Reference projects are abundant. In the Tha Chin River itself already multiple water barriers have been built. Another reference project which is studied is the Bang Pakong barrier, located in the Bang Pakong River. This dam started in 1999, but very soon the barrier was closed because multiple environmental problems occurred, e.g. water pollution and tidal amplification) (Feld et al., 2003). The design of a barrier should therefore be focused on reducing the effects of the barrier on the (local) environment.

L.5. Bubble screen

L.5.1. Description

Using a row of air diffusers (shower nozzles), a continuous flow of air bubbles is created over the width of the river mouth (figure L.4). This bubble screen or bubble plume creates a circulating current of mixed saline water from the sea and fresh water discharging from the river, de-stratifying the incoming salt wedge. This water mixture holds back incoming salt water, making the salt wedge penetrate less far into the estuary (WaterloopkundigLaboratoriumDelft, 1971). The bubble screen would be placed at the mouth or more upstream. Bubble screens as such have already been successfully introduced into sluice systems in the Netherlands to prevent salt intrusion. Also some tests have been done implementing it in an estuary (Hamilton et al., 2001). Its functioning in an estuary is however still not completely known, as the technology is relatively new.

L.5.2. Possible alternatives

A bubble screen in combination with a sluice or water gate could be an alternative. This has already proven to be very effective. For this, the river would be closed off by a dam, in which one or multiple sluices with bubble screens would be installed. The compression pump needed to create air bubbles could be powered by solar panels and be automated using salt sensors upstream and downstream of the screen.

L.5.3. Technical layout

To make sure the screen will have effect, it has to be located near the river mouth. This is because the tidal "wall" (the border between unmixed fresh and salt water) is still in shape here. Further upstream, fresh and salt water are mixed, preventing the bubble screen to function properly. To prevent erosion of the river beds because of changed water flows, bed protection will be needed.

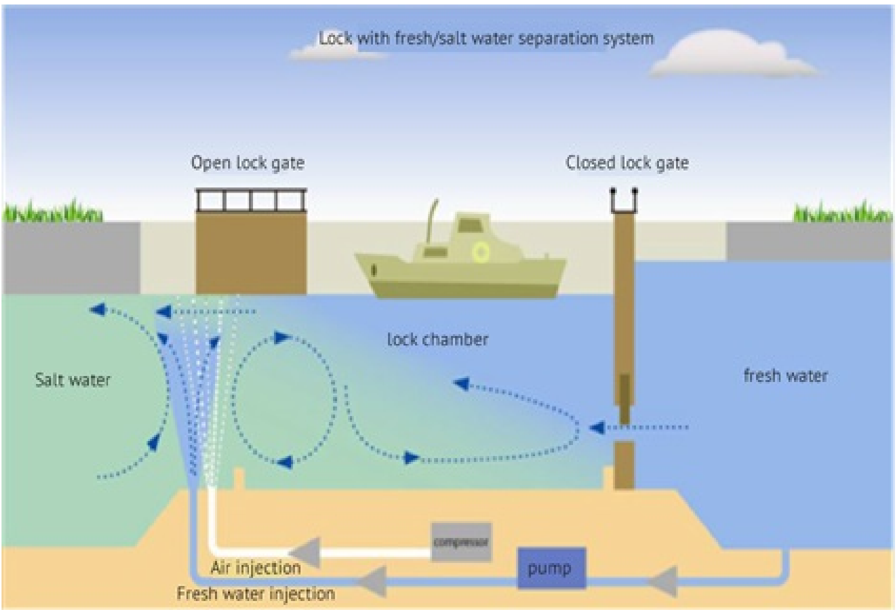


Figure L.4: Side view of a sluice with a bubble screen. Source: Friocourt et al. (2014)

L.5.4. Advantages

- No effect on the surrounding environment or ecology. Communities and other stakeholders will not be affected.
- Constructing this system is technically relatively simple. Operation is simple and can also be done remotely.

L.5.5. Disadvantages

- Implementing the bubble screen on this scale is likely to pose problems, since the estuary mouth is large and lateral differences in flow will not be the same as in sluices.
- Up to now bubble screens have only been implemented in combination with a sluice. Other options will be likely to pose various unseen problems.
- Estimating (salt) water flows and the effect of a bubble screen is very complicated. Therefore the amount of salt intrusion reduction is unknown.
- Works best with a stratified flow. However, the Tha Chin River is mixed.
- In order to function, the screen requires a constant energy supply, making it vulnerable to power failures.
- If implemented together with sluices or a water gate, river traffic will be interrupted significantly

L.5.6. Cost

Construction of a bubble screen across the width of the river mouth will probably be low in costs. Operational and maintenance cost are low as well. However, implementing a bubble screen together with sluices will raise costs significantly, making the bubble screen a relatively costly option.

L.5.7. Reference projects

Two reference projects consist of a bubble screen in combination with sluices. Both in the Terneuzen sea lock and the Krammerjachten locks, both in the Netherlands, compressed air is injected into the bottom of the lock to partially separate fresh and salt water. At the Krammerjachten locks, the bubble screen is further strengthened by the injection of fresh water next to the bubble screen. These situations differ significantly from the Tha Chin River, making unforeseen problems more likely to arise.

L.6. Change convergence length of the mouth of the river

L.6.1. Description

The mouth of an estuary has a very significant influence on the amount and penetration depth of salt water penetrating the river. Therefore, adjusting the river mouth will affect salt intrusion. The main parameter influencing salt intrusion is the convergence angle of the mouth: the amount of curvature of the river banks, where the wide river mouth converts to a narrower and straighter river. Increasing this angle, and thus the curvature of the banks, will cause the tidal amplitude to decrease and salt water to penetrate less far into the river. The river discharge is another factor influencing salt intrusion (Savenije, 2012).

L.6.2. Possible alternatives:

Alternatives can be sought in the execution of this solution: the way the convergence angle is changed. This can for example be done by 'increasing' the shores through dredging, as well as constructing concrete walls or breakwaters that would act as new river banks at the mouth, see figure L.5. Another possibility is constructing bamboo poles in the water, around which sediment can settle, (figure L.6). This sediment in turn could become occupied by plants and mangrove trees. In this way the convergence angle could be changed in a completely natural way.

L.6.3. Technical layout

As mentioned, the banks of the river mouth could be made of both sandy/clayey soil and of a concrete wall or breakwater. These have different implications for the current banks: for example, the current coastal area could remain its shape behind a newly built barrier, whereas it could also be significantly altered (expanded) when new parts are constructed through beach nourishment. Investigation in what type of option and material is most effective in reducing salt intrusion is necessary.

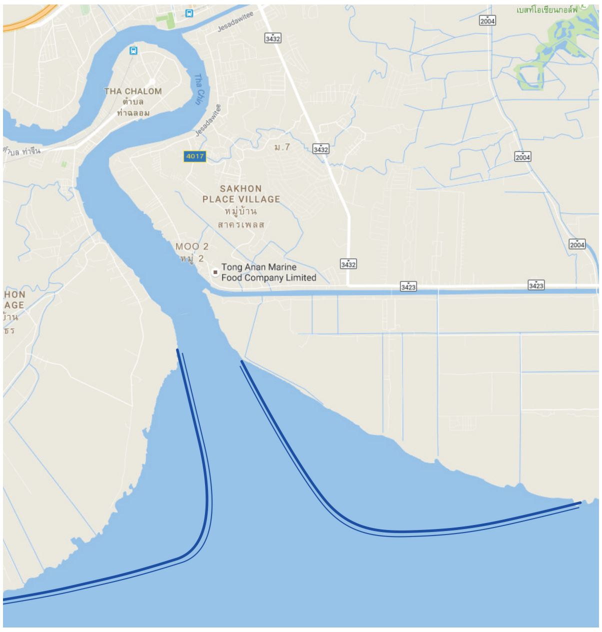


Figure L.5: Possible way to change the convergence length.

L.6.4. Advantages

- Water pollution levels will not rise.
- The river ecosystem and environment more upstream will not be harmed.
- The new parts of the coast / river beds may have the potential to be developed commercially.
- River traffic will not be affected.

Figure L.6: Possible way to change the convergence length.

L.6.5. Disadvantages

- Changing the current coastal area will probably cause some protests from locals.
- Depending on the implementation, the mangroves at the river mouth could be harmed.
- Water flows have to be analysed very thoroughly to indicate if this solution would work.
- A soft (e.g. sand banks) solution might require a lot of maintenance.

L.6.6. Cost

This solution is not applied a lot and therefore there are still a lot of unknowns. This makes cost prediction hard. If however the solution would turn out to be constructing a breakwater, a relatively simple structure, on both sides of the river mouth, costs may be kept low. The uncertainties in developing a design however can push costs up.

L.6.7. Reference projects

This solution is based on the theory of the effect of estuary mouths on salt intrusion, not on any existing project. Unfortunately, no projects that use this principle are currently known.

L.7. Desalination plant

L.7.1. Description

This solution is based on the desalination principle. Desalination is a process to remove salt (and other minerals) from saline water and can be used to transform some of the incoming salt water into fresh water. The idea is not to solve the salt problem in the Tha Chin directly, but to provide fresh water to water users that have problems with salt. If less fresh water is used by the users, more water will be available to push back the saline water. An option is to make a desalination plant based on the Multi-stage flash distillation (MSF) principle (Winter et al., 2006). This is the most common used desalination plant in the world. The capacity of the plant could be calculated using current and future water usage.

L.7.2. Possible alternatives

Another desalination principle could be used, depending on the required capacity. Fresh water provided by the plant can also be put back into the river to push back the salt and reduce pollution. The advantage of this alternative is that the salinity and other minerals do not have to be removed completely (only to a certain level). This could make the plant much more efficient since desalination is an exponentially decaying process regarding removal capacity. See figure L.7 for an example of a desalination plant

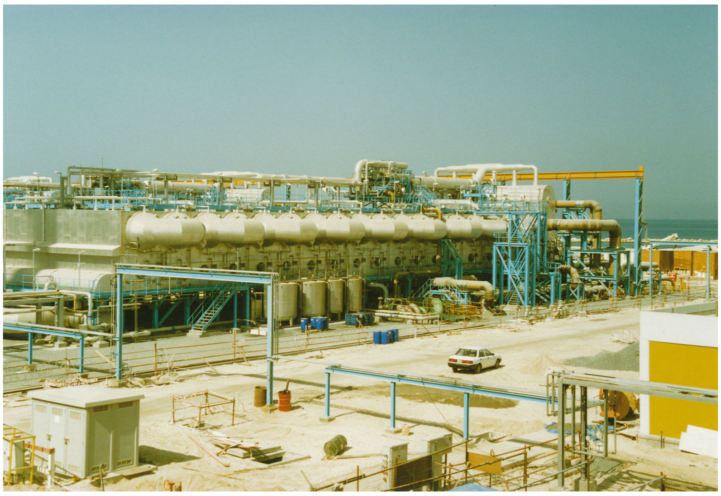


Figure L.7: Example of a desalination plant. Source: Ltd (1994)

L.7.3. Technical layout

If the plant would be used to increase river discharge, the water output from the plant to the river should be designed in a certain way to increase the discharge effectively. For example the location of the output in the river and the flow velocity are important. If the plant would be used to directly provide fresh water to users, a distribution system will be needed. The current canal system may be used for this.

L.7.4. Advantages

- Using a desalination plant solves the problem locally; the ecology of the river will not be harmed directly by a new geometrical equilibrium of the river.

- The surrounding communities and other stakeholders in the Tha Chin River will not be affected by this solution.

L.7.5. disadvantages

- The energy consumption of such a plant is very large. Operational energy cost can be between $23kWh/m^3$ and $27kWh/m^3$ of fresh water produced. Cheaper options are available, but then the capacity will also decrease.

- The excess waste has to be treated. However, this could likely end up in the river which causes an increase in pollution levels.

L.7.6. Cost

Costs of such a plant are very large. Not only initial construction cost are large, but also operation and maintenance will require a lot money.

L.7.7. Reference projects

Numerous desalination plants exist around the world, for example the Jebel Ali G station in Dubai. However, these stations pump seawater up to provide fresh water through a pipe distribution system. This goal differs from the Tha Chin situation, where the goal is less straight-forward. Also, apart from canals, a distribution system is not present in the Tha Chin basin.

L.8. Increasing river area at the mouth

L.8.1. Description

This solution is based on diversion of salt water. The principle is that by increasing the area of the river system near the mouth with canals or a tidal basin, the tide will penetrate this area first before moving upstream. In other words, the water will move in lateral (east or west) direction first instead of going directly north. There are several ways of increasing this area. Using extra canals or creating a tidal basin are some of these options. See figure L.8 and L.9 for the possible areas that could be used to increase the area in the mouth

Figure L.8: Possible additional area.

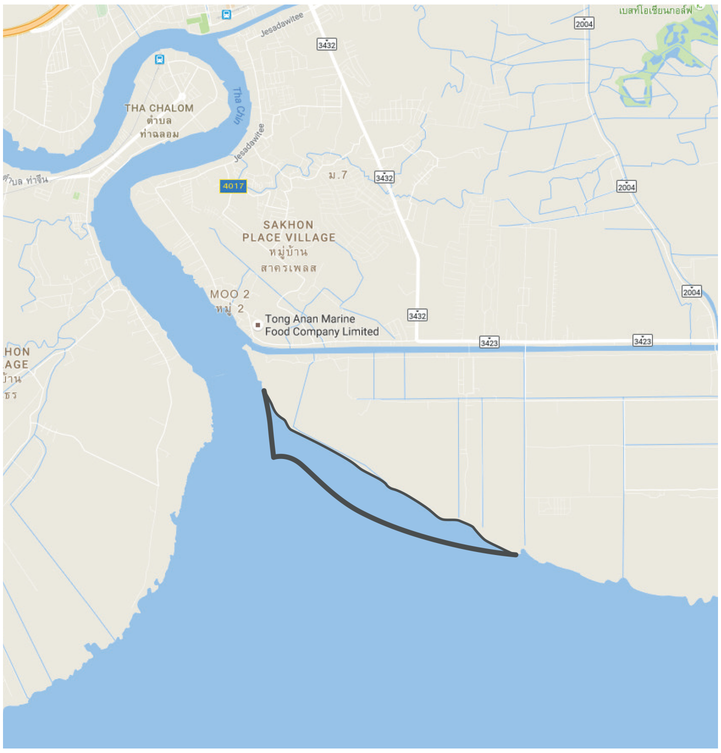


Figure L.9: Possilbe additional area.

L.8.2. Possible alternatives

An alternative to this solution is to build this extra area just before the mouth. This would mean closing off a part of the mouth by creating a large ring dyke. This basin could be controlled by a gate. The basin fills up to high water level when the tide rises, after which the gate is closed. This gate will open at low water slack when tidal rise starts again. The stored saline water could actually be used to push back the incoming saline water. When the basin and the sea are at the same level, the basin can start to fill up again. About half the time during the flood period, this system could be used, slowing the incoming water down for this period.

L.8.3. Technical layout

The Mueng Samut Sakhon district west of the river mouth already has a large system of small canals with gates, which makes it possible to manage and retain salt water into this area. The retention volume of the area may have to be improved. When building a basin before the river mouth, this will probably be constructed of concrete and the exact shape will be very important for its functioning.

L.8.4. Advantages

- No blockage for ships
- Relatively low environmental and ecological impact
- Possibility to add a commercial function (maybe fisheries or recreation) to the basin

L.8.5. Disadvantages

- Does not reduce salinity significantly enough according to the theory. This because the tidal prism (the volume of water that enters the estuary on the tide) will not be reduced when increasing retention area volume. The definition of tidal prism is: area times tidal amplitude. If the area is increased, the tidal prism will be increased. Reducing the intrusion length will not be significant since this depends for a large part on the tidal prism. Additionally, building a basin just before the river mouth will again not reduce the tidal prism, it might even increase it.
- Allocation of land needed when building in land
- Mangrove trees will have to be removed when building in sea

L.8.6. Cost

Very high investment cost for both alternatives. High maintenance cost. Possibility to use the basin for commercial activities will reduce these costs. Reference project: This solution would be similar to the Kaem Ling Project which was conducted among other places also in the lower Tha Chin basin. However, Kaem Ling was about storing excess rainwater from upstream and letting it flow out during low tide – creating a flood retention area. This solution is about storing and retention of salt water. Additionally, during the meeting with the Department of Water Resources it was noted that an extensive water management area already (has) exist(s)(ed) at Mueng Samut Sakhon, but that its capacity has shrunk significantly due to filling canals to create extra land area (meeting minutes are in appendix V.4).

L.9. Local alternative irrigation systems

L.9.1. Description

This solution does not focus on preventing salt intrusion. However, it focusses on solving the bigger problem: a water resource for irrigation purposes during the dry season. A new technology has been developed by British engineers; the dRHS irrigation system. The irrigation pipes use pervaporation to divide water and non-water substances. Pervaporation is a process where in this case the river water permeates through a membrane first and after that evaporates (at which case it is pure water vapour). In this case, water vapour diffuses through the pipe walls. It works at ambient temperature and pressure and is controlled by the humidity gradient between the inside and outside of the pipe. The inventor claims that once the pipes have been laid, the system will require little maintenance. This is partly because it is fed by gravity from an elevated supply tank, and partly because water diffuses through the porous pipe walls, so there are no holes to get blocked up (LAUNCH, 2016), (IFAD, 2016).

L.9.2. Possible alternatives

Other local desalination devices can be used to do the same job.

L.9.3. Technical layout

The system is still very new. All kinds of technical and implementation difficulties can arise given the large variety of agricultural purposes it has to be used for. The system has to be tested on different crops, plants, trees etc., to know if it will work. Additionally, irrigation in Thailand is done through open canals directly on the fields, which receive water from increasingly bigger canals. Because of this completely different irrigation principle, implementation will be very hard.

L.9.4. Advantages

- The solution is local and therefore directly aimed at the ones that actually experience a problem.
- The ecological system remains unchanged.
- Water pollution is not getting worse

L.9.5. Disadvantages

- Only works for irrigation through the ground. Land in Thailand is irrigation through small open canals on the fields. This makes it almost impossible to implement this system.
- This solution does not work for pumping up water for domestic use for example.
- It is unknown what happens with the groundwater when the salt intrudes more upstream in the future.
- The capacity of the system is unknown. This means, it is unknown how much pipes are needed. Implementing this on the scale of the whole river can cause organizational problems.
- Does not solve the salt intrusion into the canals.

L.9.6. Costs

Costs are very low for governmental institutions, because it could be chosen to let the farmer implement the device himself. However, the system can be subsidized by governmental institutions to persuade the farmers to install it.

L.9.7. Reference projects

The system has been tested in the UK, US and Chile and implemented in Jordan. Results are yet unknown.

L.10. Partial dam in the Bay of Bangkok

L.10.1. Description

Constructing a barrier in sea that will partly close off a part of the Gulf of Thailand, the Bay of Bangkok in which the mouth of the Tha Chin is located (figure L.11). This inner gulf is not closed completely, so the tide is still able to flow and the water in the whole Gulf will stay salt. When the gulf is closed only partly, a slightly brackish water basin will be created behind the barrier. It's expected that because of the barrier the tidal amplitude in this basin will be lower than the current tidal amplitude in the inner gulf. When the tidal amplitude is lower, the salt water will penetrate less deep into the river. A positive side effect is that the salt water that penetrates the river will have a lower salinity, also benefiting salinity levels decrease.

7

L.10.2. Possible alternatives

There are many ways to execute this barrier. It can be a specific structure, a breakwater or it can be in the form of islands. When one of the last two options is chosen, it can also provide additional features such as recreational area.

L.10.3. Technical layout

This solution requires more complex and detailed models in order to determine the technical layout, as the exact location and size are crucial to its functioning. A wrong location could even increase the tidal amplitude. The barrier could be build out of clay (abundant in the Gulf), rock, concrete or a mixture of these. Water flows through the openings could be severely accelerated. Therefore the openings need special attention in

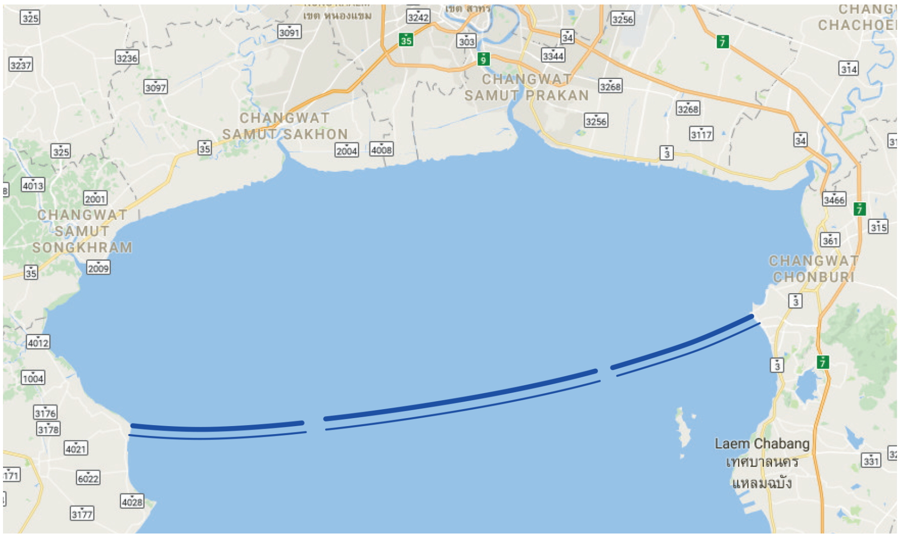


Figure L.10: Possilbe layout of the partial dam in the Bay of Bangkok.

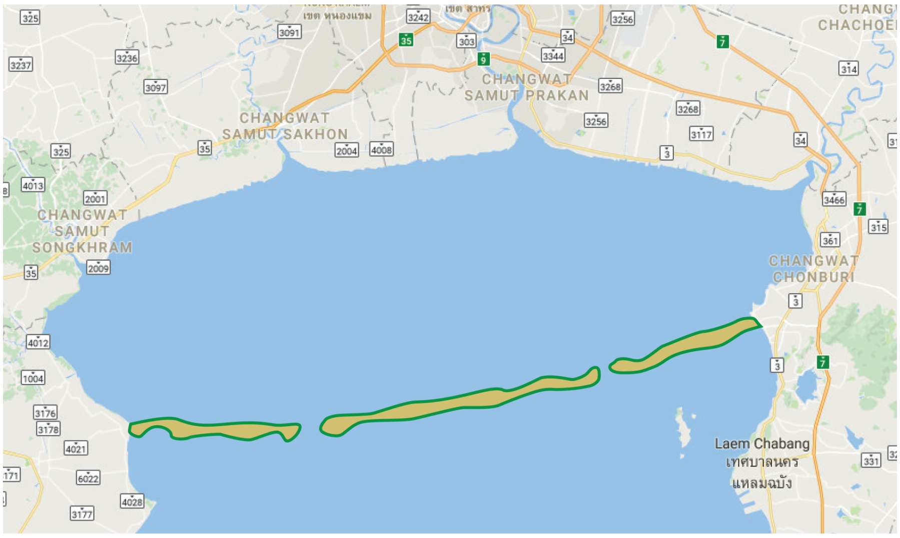


Figure L.11: Possilbe layout of the partial dam in the Bay of Bangkok.

the design, so this acceleration may be prevented. The barrier could also be submerged. In this way, tidal amplitude could still be decreased will costs will be limited because less material is needed.

L.10.4. Advantages:

- The barrier has potential for commercial development.
- No alterations to the existing surrounding land or shores needed.
- Technical construction is relatively simple and thus practical.

L.10.5. Disadvantages

- The size of and lack of experience with this solution make its functioning uncertain. To be fully sure this solution will lower salt penetration, an extensive model of the basin and tidal flows is needed. Than still, unforeseen problems are likely to occur.
- Although ships can pass the barrier, sea traffic will be interrupted.
- Pollution levels may increase due to more stagnant water.

- The sheer size of this solution makes implementation harder, as many stakeholders have to be informed and in agreement.

L.10.6. Cost

Due to the size of the barrier this can be a very cost intensive solution. Construction has to be done partly via sea, which is harder than via land and therefore it can be more expensive. Additionally, the depth of the Bay of Bangkok will make construction expensive, as much material will have to be depleted. However, when the barrier is built as islands or a breakwater (with additional space on top), there could be major commercial development.

Up to now, no reference projects are known.

L.11. Salt basin with sluices

L.11.1. Description

Creating a basin that allows salt water to migrate into inland areas instead of migrating further upstream. This basin can also be used to store water during high river discharge. After some research it became clear that a basin should be combined with a sluice that can trap incoming salt water from the sea. After the sluices are closed, the trapped salt water is pumped into the basin, after which only fresh water can enter the sluices again from the river side. In this way this solution works more like a normal gate, with the exception that salt water is first trapped and then pumped. Note that the sluices could be kept open during low tide, when salt problems don't occur.

L.11.2. Possible alternatives

Creating a basin without a sluice seems impossible because it is hard to divert the water then. Also, when a basin is applied without a sluice, the tidal storage area will increase which would increase the tidal prism but has no decreasing influence on the tidal amplitude. Therefore a basin without a sluice will not work to reduce the salt intrusion length. Another alternative is instead of an external basin, creating a 'pit' (a deepened part of the river bed) right behind the sluices. Salt water could be stored here and afterwards be diverted back to sea (Delft, 1968).

L.11.3. Technical layout

As mentioned above, the salt basin will have to be combined with sluices to make it able to trap and divert salt water. The basin can't be made directly at the mouth, since this will block too much sea traffic. Its position will however be near the river mouth to block salt water as early as possible.

L.11.4. Advantages:

- The sluice completely blocks salt water.

L.11.5. Disadvantages

- Blocks the river flow during high tides.
- There is a risk for salt intrusion in groundwater because of the basin.
- Water pollution levels in the river will probably rise because of disrupted flow.
- Requires a structure in the river, which is likely to cause social unrest.
- Requires land allocation which is likely to cause social unrest.

L.11.6. Cost

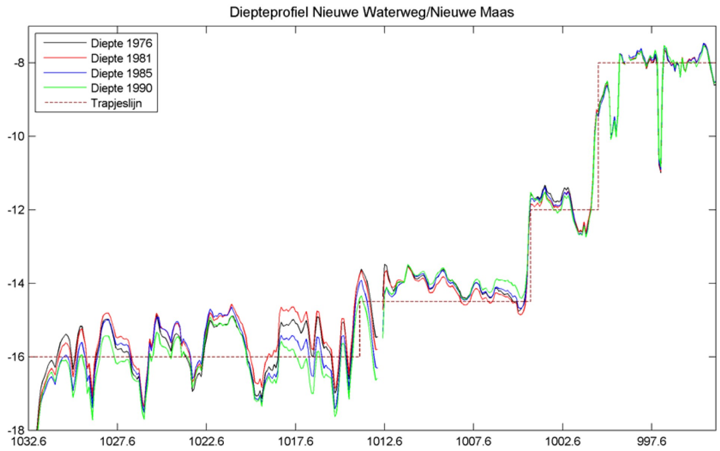
Due to the combination of a sluice and a basin much construction and thus high initial costs will be made. Additionally this solution requires a lot of operation and some maintenance. Therefore this will be an expensive solution.

No reference projects are known.

L.12. Salt Stairs

L.12.1. Description

In this solution, the river bed before the mouth will be dredged in a stepped profile to change its bathymetry (figure L.12). In this way, two mechanisms to block the salt will occur. The first one is the entrapment of salt water at the bottom of the river, due to being blocked by the 'stair steps'. A second mechanism is an increase of friction in the river mouth due to the steps. This will make the tide penetrate less far into the river.



Figuur 7.1 *Bodemligging Nieuwe Waterweg/Nieuwe Maas 1976 – 1990*

Figure L.12: Bottom profile van haringvliet. Source: Kaaij et al. (2010).

L.12.2. Possible alternatives

Cover material (stones) may be laid on the steps to prevent erosion. This could also be done by growing plants on the steps.

L.12.3. Technical layout:

The steps of the salt stairs need a certain elevation. Therefore because of the very flat slope of the river bed excavation of the river bed will be needed. In this excavation, the salt stairs could be dredged. For the entrapment of salt water by the stairs to work, a salt wedge in the river mouth is needed (Kaaij et al., 2010). Which means a relative high discharge compared to the incoming tide, which is not the case in the Tha Chin River

L.12.4. Advantages:

- No alteration to the surroundings needed.
- Probably no big complains of NGOs etc.
- Excavation and dredging are well-known techniques and thus practical.

L.12.5. Disadvantages

- The bed slope is very small in the whole river basin. Developing a stairs on a flat basin is challenging.
- This solution may need complicated maintenance because it requires a specific bed profile that should not change over time.
- A salt wedge in the river mouth will be needed for this solution to work.

L.12.6. Cost

As mentioned, because of the very flat slope of the river much excavation will be needed, which could prove to be hard. In combination with the required maintenance over time this could prove to be an expensive solution.

L.12.7. Reference projects
This solution is applied in the Nieuwe Waterweg in the Netherlands. The main advantage of this project is the reduction of the period of higher salinities in the river. At the same time, research of this salt stair concluded that it might be wise to consider other solutions when the river discharge is low. Therefore it is not likely a salt stair will work in the Tha Chin River as it does in the Nieuwe Waterweg (Kaaij et al., 2010).

L.13. Constructing sand banks as a natural salt intrusion barrier in the river

L.13.1. Description
Building one or more sand banks somewhere in the river that act as a natural weir, blocking salt water during low tide. Because of river water accumulation and following higher water levels, river discharge could still pass the weir, while at the same time salt water inflow would be blocked. The amount of blocking depends on the (sea) water level. During high tide in the wet season, water levels would be high enough for salt water to flow over the banks. During low tide, the banks would almost fall dry and water from the sea would be blocked. In between salt water would be partially blocked, thus still reducing salinity levels further upstream.

L.13.2. Possible alternatives
The banks would serve as a natural weir. Of course, this weir could also be made of for example concrete. This could be an option that's more feasible and can be constructed more easily, but at the same time may be a less flexible solution in shape and execution. Also, since this is not a 'building with nature' solution, this solution may cause more environmental impact and social unrest, although this has to be further examined. On the other hand, using concrete could provide a much more resilient structure.

L.13.3. Technical layout:
The location and layout of the banks will be key, as this will decide which parts of the river will experience reduced salt levels and also may become less accessible. The banks may be planted (with for example mangroves) to prevent erosion. The possibility of this is however very dependable on the size and execution of the banks. The river bed nearby the banks will have to be strengthened to resist the change in water flows. There's a possibility that pollution in the river will accumulate at the banks. The impact of the banks on water pollution will have to be investigated very thoroughly. The banks could be constructed from clay, as this is an abundant material in the surrounding area.

L.13.4. Advantages
- Building with nature: this solution (partly) blocks salt water, without putting a structure in the river. This increases feasibility significantly.
- No allocation of current areas is needed.

L.13.5. Disadvantages
- The question remains whether during high tide, salt intrusion will be adequately blocked, especially during the dry season when river discharge is low.
- The banks will be a major disruption of river traffic. The impact of this will have to be assessed.
- Because of the low slope of the river (but depending on execution), a small basin in front of the banks could form, affecting its surroundings.
- A very detailed model of river flows is needed to make an efficient design for the banks.
- Depending on execution and river flow, this solution could prove to be maintenance-intensive.
- Water pollution levels could rise.
- This could negatively affect the local river ecosystem.

L.13.6. Cost

This solution is not common and therefore has many uncertainties. Because of this costs are to some extent unpredictable. Building materials could be expensive. At the same time, constructing sand banks could prove to be relatively affordable.

L.13.7. Reference projects

A completely natural example exists in the Pungue estuary in Mozambique. In the middle zone of the Pungue river (approximately 50 km from the estuary mouth), the estuary experiences constriction by sand banks and falls almost dry during low tide. By this, salt intrusion is prevented. During high tide, water is able to flow over the banks (Graas and Savenije, 2008). Examples of traditional weirs are all over the world, including many in Thailand.

L.14. Building one or more extra upstream water reservoir(s)

L.14.1. Description

Creating extra water storage upstream in the river. In the rainy seasons these can be filled with fresh water. During periods of drought, this extra water can be used to create a higher river discharge and thus push back salt water. Additionally, more fresh water for users would be available. The reservoir could also be used for one of these two goals only. It is important to find the right place to construct it: it is questionable whether there is enough water supply left to create an additional reservoir.

L.14.2. Possible alternatives

Instead of construct one big reservoir, an alternative could be building multiple smaller reservoirs along the river basin which could use the Managed Aquifer Recharge (MAR) concept. This is a concept in which fresh water is stored in a water-bearing soil layer. Fresh and salt water only mix at the edges, thus keeping the majority of the water fresh. These local aquifers can be filled during the rainy season, after which locals pump up water according to their needs during the dry season (Tolk et al., 2014).

L.14.3. Technical layout

Depending on the scale of the reservoir, the water can be contained in multiple ways. Constructing a large reservoir would require a blocking structure, probably made of concrete. At a smaller scale, an artificial basin could be made of simple sand walls. Building a MAR would require pumps and a pipeline system to distribute water in and out of the MAR. MAR's could be located in old river meanders, as these are sandy aquifers (personal conversation, appendix V.4). These don't cover the whole area of the basin though.

L.14.4. Advantages

- This solution does not change the current water management nor the river system, smoothening implementation.
- The Thai government is very familiar with the construction and use of reservoirs.
- Could also be used as an instrument to accommodate flood water.
- Could be implemented very locally, thus having the potential of making demand and supply management and the amount of water use controllable.

L.14.5. Disadvantages:

- The major question is whether there is enough water available to sufficiently fill another reservoir. The current reservoirs that provide the majority of supply to the Tha Chin (Bhumibol and Sirikit) are completely filled only roughly 10% of the time (Appendix F) (Tebakari, 2016)).
- A large area is needed for a reservoir. Although depending on the implementation of the solution, allocating a large number of plots and/or houses will likely result in societal unrest and protests.

L.14.6. Cost

Costs and revenues will probably go hand in hand: the bigger the storage capacity, the bigger the water that can be used in the dry season. The water revenue however depends again on the amount of 'untapped' water still available in Thailand. Efficiency of the solution is very dependable on its scale and implementation, technically but certainly also socially. Nevertheless, initial costs will likely be very high.

L.14.7. Reference projects:

Reference projects are abundant. The two main reservoirs that feed the Chao Praya basin (of which the Tha Chin River is part of), the Bhumibol and Sirikit reservoirs, are good examples. At both projects, large dams were built in mountainous regions of Thailand, creating huge lakes. The discharge from the reservoirs is not only used as water supplies, but also to drive turbines that generate electricity. The MAR concept has been implemented in Bangladesh through a pilot program from UNICEF. Here, the MAR proved to be a cheap and simple and thus attractive way to store and later use fresh water. It was noted that not only the MAR itself has to be made, but that local social-economic aspects also have to be taken care of. This includes clear communication with and involvement of the local community.

M
First evaluation method

The goal of this chapter is to evaluate and eliminate the solutions that are least feasible. Up till now, every possible solution has been attended to. The next step is to evaluate these solutions and reduce the amount of possibilities to the most relevant outcomes. For a list of all solutions in detail, see appendix L. First, the work method will be explained. Then the results of the test will be discussed. At last, conclusions will be drawn from the results.

M.1. Work method

Evaluation can be done using different techniques. However, since the amount of information available on every solution is small in this phase of the project, a detailed evaluation is useless. E.g. performing an MCA on the given solutions is impossible and unnecessary. To evaluate, it was decided to first test every solutions (under the presumption that they'll work as designed) to the requirements only. To cope with the amount of uncertainty that a solution would comply with the requirements, a simple system is used. If a solution had a good chance to comply with the requirement a score of 1 is given. If it had potential in failing to comply, a score of 0.5 is given. If the solution had a large chance in failing to comply, a score of 0 is given. No weighing factor on different requirements is applied here, since the solution has to comply with all requirements in the end. The requirements are as follows:

1. The solution has to make enough usable fresh water available during the year especially in the dry season for three different purposes.
2. The solution has to deal with the salinity problem in the river
3. The solution has to maintain or decrease current water pollution levels (DO, pesticides etc.)
4. The solution has to function for a long period, for example 100 years.
5. The solution has to be feasible in Thailand

M.2. Results

The given scores are based on four judgements. These judgements are based on information acquired in the analyses. The conclusion drawn from the results (table M.1) can therefore be considered to be well founded. Factors that are playing a role are:

- Knowledge from articles about the physical principles
- Results from reference projects
- Discussions with different stakeholders

with:

Desalination construct a desalination plant next to the river to provide fresh water to the users

Table M.1: Results from first evaluation

Solutions vs. requirements	Fresh water	Salinity	Pollution	Functional Period	Feasibility	Total
1	1,0	1,0	0,0	1,0	0,0	3,0
2	0,5	0,5	1,0	0,5	0,5	3,0
3	1,0	1,0	0,5	1,0	0,0	3,5
4	1,0	1,0	0,0	1,0	0,0	3,0
5	0,0	0,0	1,0	1,0	1,0	3,0
6	1,0	1,0	1,0	1,0	0,5	**4,5**
7	1,0	1,0	0,5	1,0	0,5	**4,0**
8	1,0	1,0	0,5	1,0	0,5	**4,0**
9	1,0	1,0	0,5	1,0	0,5	**4,0**
10	0,5	0,0	1,0	1,0	1,0	3,5
11	1,0	1,0	1,0	1,0	0,5	**4,5**
12	0,5	0,5	0,5	1,0	0,5	3,0
13	0.5	0,5	1,0	0,5	1,0	3,5
14	0,5	0,5	1,0	1,0	0,5	3,5

Desalination Implement a desalination system in the form of irrigation pipes (dRHS irrigation system)

Diversion Constructing a tidal basin using a ring dike at the mouth to divert the salt wedge and increasing the estuary capacity

Diversion Constructing a saline water basin through excavation that can capture the incoming salt water

Block partially Constructing salt stairs at the river mouth to trap the incoming salt wedge

Block partially Constructing a partial barrier in the Gulf of Thailand to decrease tidal amplitudes at the mouth

Block partially Constructing islands near the river mouth to decrease tidal amplitudes and create a fresh water bubble (balance islands)

Block completely Constructing a dam in the Gulf of Thailand to eliminate tidal influences and create a fresh water basin (Jakarta)

Block completely Constructing a salinity barrier in the river to block the saline water from penetrating, but doesn't interfere with the river discharge

Change mixing situation Use a bubble screen to mix the salt wedge with the fresh water to reduce intrusion length.

Change mixing situation Change the convergence angle at mouth of the river to reduce inflow of saline water

Storage Constructing sandbanks at the mouth of the river to store fresh water at low tide (Pungue river)

Storage Constructing a reservoir upstream and transport (or store) the fresh water locally (not via the river)

Reducing tidal prism Apply (temporary) friction to increase tidal damping in the river

M.3. Conclusions

Looking at the results from table M.1, it can be concluded that five out of fourteen solutions score a 4 or higher. Note that not one solution meets all requirements completely. If this were true, the choice would be easily made. However, it's clear that solutions with a score of 0 at one of the requirements score the worst. The solutions that score a 0 and have a very small chance to comply with a requirement will therefore be eliminated.

N

Change the convergence length

N.1. Description

The bathymetry of an estuary is among others one of the parameters that influence the salt intrusion length. The bathymetry and friction in the estuary determine whether the amplitude of the tide is damped, amplified or constant over the length of the estuary. Due to the convergence the energy of the tidal wave will concentrate, shoaling, increasing the amplitude. Friction will decrease the amplitude. When friction is in balance with the convergence of the estuary the tidal amplitude stays constant over the estuary length. While the tidal amplitudes are amplified (damped) the tide will penetrate further (less far) into the estuary, consequently bringing more (less) salt water into the river (Savenije, 2012). For more detailed information see Appendix T.

One way to change the bathymetry is to change the convergence length of the mouth. The convergence length is the length scale of the exponential function that describes the exponentially varying width, $A(x) = A_0 \exp(x/a)$ where A_0 is the cross-sectional flow area in the mouth, a is the convergence length and $A(x)$ is the cross-sectional flow area at a distance of x from the mouth. If a channel is a purely prismatic the convergence length will go to infinity. The Tha Chin estuary has a trumpet shape, the most downstream part has a relatively short convergence length while the upstream part is more prismatic.

Increasing the convergence length of the most downstream part of the estuary, while keeping the upstream part the same can reduce the salt intrusion. Doing this the cross-sectional area at the river mouth will also reduce, reducing the tidal prism which also influences the tidal influence in the estuary.

Alternatives can be sought in the execution of this solution: the way the convergence length is increased. This can for example be done through dredging, as well as constructing concrete walls or breakwaters that would act as new river banks in the downstream part of the mouth. Another possibility is constructing bamboo poles in the water, around which sediment can settle, mimicking the effect of mangrove and other vegetation on the floodplains. The sediment in turn could become occupied by vegetation such as mangrove trees. In this way the convergence length could be changed in a natural way. The best way to do it is to provide space for mangroves so it will not harm the environment.

The advantage of this solution is really low impact on the environment. Pollution levels will not rise and it even provides additional space for mangroves. Next to that river traffic will not be blocked. Another advantage is that the friction in the channel and floodplains will stay the same or increase which has a positive effect on damping. Disadvantages are the fact that the current coastal area needs to be changed which probably will cause some protests. Also changing the mouth of an estuary will bring it out of its equilibrium state, this can cause sedimentation or erosion problems.

N.2. Technical layout

The current bathymetry of the mouth of the Tha Chin has two convergence lengths. One relative smaller one in the beginning, the trumped shaped part of the river. The flow area in this part decreases quicker than further upstream. A second one that starts around 20 km which is much larger, so the flow area decreases slowly along the river branch. The first the trumped shaped part of the river is the part where changes can be made and the convergence length can be increased. When changes are made it is important that the total flow area does not increase. In figure N.1, the floodplains in the mouth are enlarged and heightened, making the cross-section smaller and the convergence length larger. The orange areas in figure N.1 can be set out with

Figure N.1: Possible way to change the convergence length.

bamboo sticks. The area can be filled with a sediment suppletion and new mangrove preservation projects can be started there.

N.3. Cost

This solution is not applied a lot before and therefore there are still a lot of unknowns. This makes cost prediction hard. Sediment suppletion is a technique that is already applied in Thailand, the costs for the suppletion mainly depend on the total volume. Bamboo can be grown easily and placed, this is already done in some mangrove restoration projects in different places, also in Thailand (Winterwerp, 2016). This solution will not be very cost intensive in construction, maintenance will probably be necessary throughout its lifetime, this will rise the costs. On the benefits side there will be more nature and the restored and new mangrove will serve as habitat for different fauna.

N.4. Simulation and conclusions

To simulate the effects of this solution the analytical salt intrusion model, see appendix T, is used. To analyse the effect first eight different convergence lengths have been tested while the cross-sectional area in the mouth and in the upstream part were kept the same (figure T.12 in appendix T). In the second run the cross-sectional area in the mouth is changed while the cross-sectional area at the point where the original convergence length changes (x_1), the inflection point, is kept constant (figure T.13).

From those runs it can be concluded that when convergence length in the mouth decreases while the cross-sectional area in the mouth stays constant the salt intrusion length will decrease. In this case the the inflection point will be located closer to the mouth and a larger part of the estuary will have the large convergence length of the upstream part. The salt intrusion length might decrease up to 5%, which is not sufficient in case of severe salinity problems in the upstream areas. Next to this it was confirmed that while the cross-sectional area in the mouth increases the salt intrusion will increase. While solving salt intrusion problems the cross-sectional area in the mouth should not increase. Decreasing cross-sectional area in the mouth and thereby increasing the convergence length, possibly up to the length of the upstream part, will have a similar effect.

This solution can reduce the salt intrusion and salinity in the Tha Chin, however it will not reduce the salinity to the threshold value of 2 g/l at 30 km. Therefore this solution must be applied in combination with other solutions.

O

Balance Islands

O.1. Description

Balance Island is a concept in which sand banks are constructed in front of the river mouth which alter water flows. See figure O.1 Because of the new water flows, fresh and salt water will be more mixed at the river mouth. In the river mouth a brackish area will be formed, thus having a lower salinity than in the current situation. The salinity in the mouth of the river is, among other things, proportional to the difference in density between fresh and saltwater. Therefore, salt water will penetrate less far into the river if the mouth of the river would become less salt (van Rooij et al., 2012).

O.2. Technical layout

The core of the islands will probably be made out of clay, since this is widely available in the surrounding area. However, rock or other heavier material may also be used to realise the islands. Further research with more complex models is needed to determine the final shape and location. The salinity reduction can only be met when the balance islands are placed at the correct location. A wrong placement, for example too close to the mouth, could even increase the salinity (de Kort and van Rooij, 2013). This was also concluded in the feasibility study of vietnam (Raadgever et al., 2016), see next section, different layouts of the islands leads to a completely different salinity reduction. An important part of the layout is that it blocks the incoming tide but at the same time it should not block the outgoing river flow.

The balance islands can be developed in different ways. The local ecosystem could be strengthened by making more space for mangroves. Mangrove forests could be grown on the islands, which could have multiple benefits: the mangroves could serve as coastal protection, a habitat for numerous flora and fauna species and a source of economic activities. Since mangroves are very vulnerable a a successful development of mangrove forest is very dependent on understanding the local hydromorphological environment. For this, the current mangrove forests and mangrove forests nearby have to be inspected, in order to get a better insight on their natural hydromorphological environment (Raadgever et al., 2016). For additional information about mangroves see appendix C.

Another alternative is one that focuses on tourism and recreation on the island. A combination of these two might be possible. A completely different solution is simply building Balance Island and creating no other features on the island. Building this might be cheaper, but in this way the island won't provide any additional income and commercial/societal functions.

O.3. (Advantages and disadvantages

A big advantage of this solution is the relatively low impact on the environment. It even creates new opportunities for a better environment. That could lead to more fish near the mouth, which benefits the fishery companies. The basin that is created behind the islands will not lead to increased pollution levels because the outflow velocity near the mouth will, if designed well, increase slightly which make sure the polluted water is flushed out of the river. Next to this it will not block the river traffic very drastically. Besides all this another big advantages is the reactions that some stakeholders gave on this solution. They were quite positive due to low environmental impact, but they were afraid of an increase flood risk.

Figure O.1: Possible layout of the balance islands.

A disadvantage is the possible higher risk of floods during the wet period. Due to the fact that it should not be placed to close to the river mouth and that the outflow should not be blocked this risk is smaller. In a further research this should be something to look at.

O.4. Reference projects

In the Netherlands at the Haringvliet sluices, this solution has been designed and proposed for implementation. Research done for this design found that the salinity at the Haringvliet can be reduced by 30%. After numerical modelling, it was concluded that Balance Island could possibly be applied in different estuaries all over the world. For some concept models, the salinity reduction can reach up to 50% (de Kort and van Rooij, 2013). Haringvliet is a wave dominated coast. The Balance Island concept at Haringvliet was estimated at 31 million euros (van Rooij et al., 2012). As most of the costs comes from the purchase and depletion of materials, the exact cost will depend on the final size and layout In April 2016, a feasibility study for Balance Islands in the Mekong Delta has been conducted. This area in Vietnam suffers from similar problems as The Tha Chin River basin, salt intrusion during the dry season. Also, mangroves grow on the coastal area.

It was decided to build a numerical model of the Co Chien estuary using Delft3D software. The tide is

Table O.1: Runs in SOBEK-RE

run	Salinity in the mouth [g/l]	Dispersion	Tidal amplification factor	average reduction of 2 g/l salt intrusion length
1	30	125	*0.7	15%
2	25	125	*0.7	20%
3	25	150	*0.7	10%
4	25	150	*1	5%
5	25	125	*1	15%

comparable to the tide at the Tha Chin estuary, with an amplitude of 3 m and a mixed diurnal and semi-diurnal cycle, waves are damped due to the shallow foreshore. The current intrusion length in the mekong is higher than in the Tha Chin. Furthermore is the bottom roughness slightly lower, the depth is more or less similar and the discharge slightly higher than in the Tha Chin.

A first promising variant was extending the current river island. This would mean the Co Chien branch would become narrower, thereby increasing flow velocities and decreasing the tidal range, which results in a decrease in salt water intrusion. For two scenarios (current and a climate change scenario), 2 g/l salt intrusion length was reduced with 3.8 km. (which is around 10%) A second variant was extending the current river island and building a small arc-shaped island in the mouth of the Co Chien branch. The new island would reduce the river mouth width, which should again result in a lower tidal range and thus less salt intrusion. This would decrease 2 g/l salt intrusion length with more or less 4 km. (depends a bit on the scenario)

In the same study, financial-economic feasibility of the concept was considered. The benefits were, depending on the variant, ca. 8-40 million US dollars over 30 years. This did not include benefits from higher fruit production, better water quality for drinking water and industrial water use, new land that can be used as agricultural land (on the river island) and/or development of mangroves providing ecological values and related goods and services. Costs of the required sand nourishment were roughly estimated at 200-500 million US dollars. 25% of the total cost is estimated to be maintenance.

Already starting in 1965 as a result of warfare, but especially in the 1990's, the amount of mangroves in the coastal area has declined rapidly. This was due to various factors: shrimp farming, salinization, coastal erosion, reduction of the coastal zone, coastal squeeze etc. Balance Islands present possibilities for ecological restoration by planting mangroves on the additional surface. In addition to strengthening the local ecosystem, these could improve stability and decrease erosion of the islands.The salinity in the mouth will be reduced, this will slightly influence the flora and fauna in the river mouth.

The placement of the balance island will be near the mouth, so this is a very important part which needs more research but that is out of the scope of this project. For the salt intrusion the first 100 km of the river are important.

O.5. Simulation and conclusion

This solution requires complex 3D models, but in order to see whether the solution is suitable for salt intrusion and to obtain order estimates of the reduction SOBEK-RE can be used. In SOBEK-RE it is not possible to put the islands in the bathymetry because it is a one dimensional model. The effects of the balance islands can be modelled in SOBEK-RE by changing the boundary conditions. The parameters that change due to the balance islands are the salinity in the mouth, tidal amplitude and dispersion. The effect will be as follows:

- the salinity at the mouth will drop a little bit
- a small reduction in tidal amplitude is also possible
- due to smaller difference in salinity the dispersion will be lower as well

Those three criteria correspond with the following runs in sobek. For more information about the sobek model see table O.1. The showed reduction is the reduction in the average dry years, during the driest dry years (2015) the reduction dropped around 5 %

In the best case, run number 2, the threshold is not always met but it happens less often and when it happens the duration is shorter. see figure O.2. This one together with run number 5 are the most realistic effects of the balance islands. This is because the salinity in the mouth and the dispersion are linked, so if one of them changes the other one probably changes as well. It is not sure that the islands will have this effect, the reduction could also be lower. But the outcome of SOBEK-RE proves that the solution is very likely to work under the circumstances in the Tha Chin. This outcome is quite promising so further research with complex models could be considered.

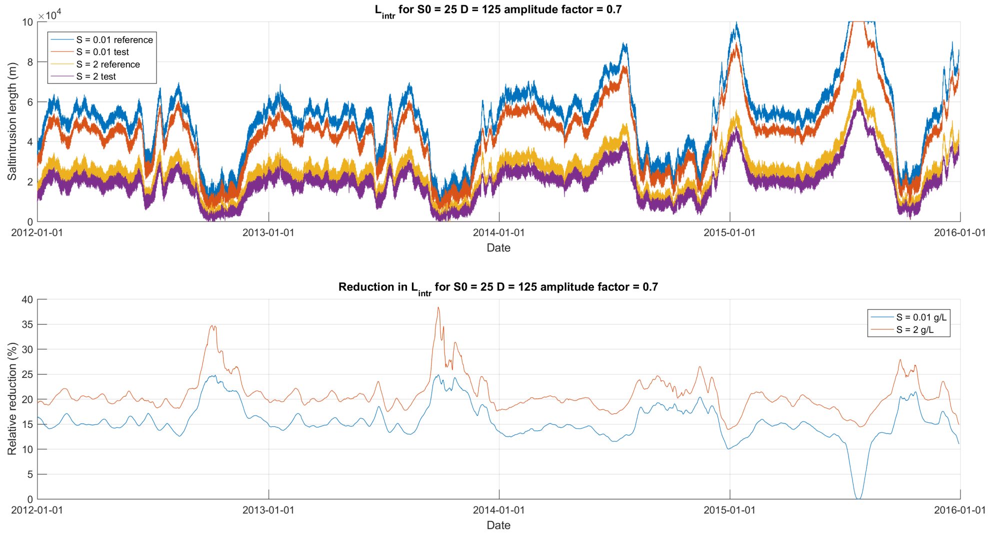


Figure O.2: Salt intrusion length when the Balance Islands are implemented.

P

Barrier in the River

in this chapter, the salinity barrier will be discussed. The barrier option is the only solution that can provide certainty about the effectiveness of salt blockage or significant reduction in concentration. Other options can only reduce the concentration and it is unclear yet how much. In the first section, a short description is given to have a good overview of the most important aspects playing a role in realizing the barrier. Second, an analysis of the surroundings, reference projects and stakeholders opinions will be addressed. In the third section, the resulting requirements and design objective is stated. In the fourth section the location, effective salinity reduction and environmental aspects are addressed. In the fifth section, the functional design aspects are discussed. Finally, some possible design options will briefly be presented.

P.1. Description

The principle is based on constructing a salinity barrier that lets through the river discharge, but can be closed to block salt water when salinity levels become too high. This will be during high tide in the dry seasons. The solution is very familiar to the Thai government, e.g. water barriers exist in river basins all over Thailand. Another advantage is that there is a high control of the salt concentration in the river. If desired it can automatically open and close the barrier to keep salinity levels constant or decrease them if needed. However, this solution will cause much opposition from most involved stakeholders. This is because of the bad experiences in reference projects. Also the impact on the (local) ecosystem of the river could be significant. Therefore the impact on the environment should be assessed. A barrier can be executed in various ways. From a gate that can simply be lifted or lowered to let water in or out whenever necessary, to a movable underwater wall that works like a submerged weir. The type of barrier depends on the properties of the river and surroundings at the location. The barrier will need concrete embankments and moving parts which would be made of steel. Costs are high for such a large structure. However, building a common type of water barrier could likely be a relatively cheap solution to stop salt intrusion.

P.2. Analysis

P.2.1. Surroundings

Focussing on the salinity barrier, some aspects of the river environment are important to establish. The river is made up of clay and mud. Hard structures are not likely to work on muddy beds because there are higher erosive stresses when waves are reflecting or large river currents are present. The large water content causes a small bearing capacity and the small permeability causes a higher risk of liquefaction. The mud is mostly formed by plant material coming from the water hyacinth. The water hyacinth is a large problem in the Tha Chin River. Most of this sediment ends up at the river mouth. According to the DWR, several mud banks have been formed in front of the mouth.

River profile

The mouth of the river is very wide and contains mangrove on the banks. The buildings of the city are directly positioned after the mangrove field. The river profile start at this point. Measurements have been taken at several points in the river given in figure P.1 and table P.1. This data has been plotted in appendix D. Notice that the river width does not change drastically after X1, only the bed level decreases.

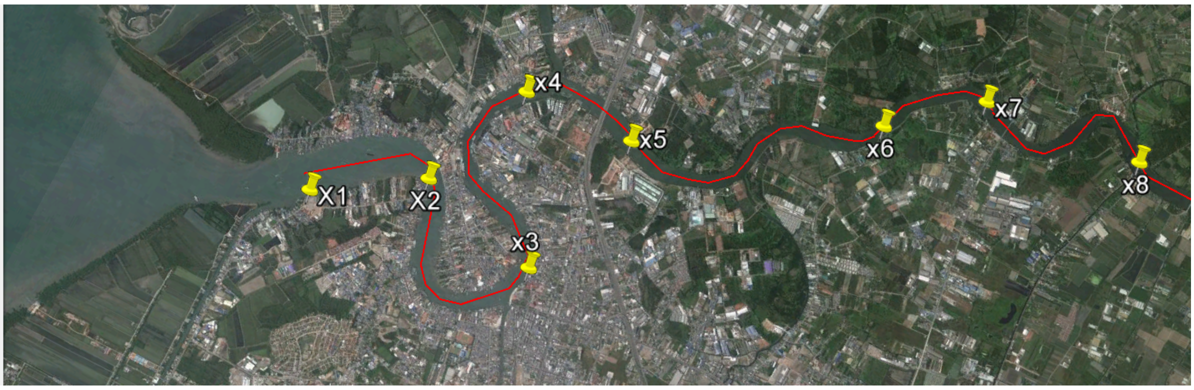


Figure P.1: Measurement points in the first part of the estuary, location data was provided by the RID

Table P.1: Exact measurement points

X0	X1	X2	X3	X4	X5	X6	X7	X8
0	2857 m	4879 m	7413 m	10385 m	12248 m	15712 m	17512 m	20309 m

Possible barrier positions between X2 and X4 can be ruled out due to the location of the city. A bridge is located between X4 and X5. This bridge can't be passed by the fishery ships. Therefore, these are located on the other side of the bridge. Starting from X5, the problem is inland shipping. Large but low vessels can pass these bridges. If a barrier is build, these ships have to be able to pass the structure. In case of a barrier at X1, all fishery ships have to be able to pass, as well.

Hydraulic conditions

Water level at sea The highest tidal elevation measured is MSL + 1.71 m in the past six years. The theoretical water level computed with the tidal constituents is MSL + 1.78 m and MSL +2.0 m for a thousand year return period. The storm surge level is about MSL + 2.7 m for a 100 year return period (WorldBank, 2009). For further tidal analyses the tidal constituents are used. For the design, a design height of MSL +2.7 or more are used.

River discharge and river water level The maximum river discharge measured in 2011 during the flooding was around 330 m^3/s (appendix G). River water level are not directly relevant for the design of the salinity barrier, since it will be opened during peak floods. It will also be opened when the water level is higher than sea level. It can be said that the design level at the river side of the barrier should be at least have the same level as the design sea water level.

Head difference The head difference between the two water levels is very important for the design. However this depends on the location in the river. At the mouth, this water level difference is the largest and equal to the maximum tidal range. However, when a barrier is implemented it can cause an increase in tidal amplitude. This amplitude is computed in section S. The head difference will be assumed to be the maximum tidal range. A larger head difference will not likely be recorded, since storm surges are often combined with rain (in the rainy season and not in the dry season) and therefore the river water level will be high enough so the gates won't have to be closed.

Shipping

The normal navigation channel in Tha Chin River reaches from the river mouth to Nakhon Chaisri (about 78 km upstream from the mouth). The draught from the river mouth to Bang Lane is still sufficient for water transport by barges even during dry season. However, from beyond Bang Lane upstream shipping must wait for high water. Some areas along the river beyond Bang Lane are even dry. Inland waterway in Tha Chin River is mostly transported by barges with the size of 50 x 15 meter width, and of 5 meters draught. A ship can tow about 3 barges. The amount of barges passage in the river is approximately 30-50 barges per day. The products that are transported as import goods are steel, coal, chemical materials, minerals, fertilizer, tin, lumber, wheat, and export goods are cassava, flour, rice, sugar, raw sugar, corn and cement. The problem is that if water levels are too high, the bridges become a problem and barges have to wait until the water is lower. A possible effect of salinity barrier on shipping is too high water during closure of the barrier. (MarineDep, 2016)

Fishing ships are located at the mouth of the river and their harbours reach up to the first bridge. According to the DWR about 4000 fishing ships are located in this area. The effect of a salinity barrier at the mouth would have a large impact on fishing capacity and it would complicate the design of the barrier.

P.2.2. Reference projects

In the past several salinity barriers have been built. The Bang Pakong barrier is an example of how barriers can increase the tidal amplitude significantly while also increasing pollution levels due to stagnant water. Further elaboration about this barrier can be found in J. Also the barrier at the Bang Nara River in the southern part of the gulf is a good example. Located only 6 km upstream of the mouth, this barrier caused a rise in tidal amplitude of 0.5 m. With respect to the tidal amplitude of 0.5 m, this is an increase of 100% (Vongvisessomjai et al., 2008). The observed water levels before and after the construction of the barrier can be found in figure P.2.

It doesn't seem right that such a large tidal amplitude increase is found at only 6 km upstream. Most of the tidal constituents present in the Gulf of Thailand have a very large wavelength and therefore a 6 km long basin is defined as a short basin in which the water level at the mouth is the same as at the barrier. This basin has an Eigen frequency that is nowhere near the frequency of the incoming tidal waves. However, since the river profile, upstream discharge and phase differences of the different constituents are all variables in the equation of energy conservation, this can differ significantly. Several studies have been done using analytical and numerical modelling to predict the tidal amplification of a barrier in the Tha Chin River at 15 km from the mouth. Most of them resulted in a small amplification that is unrealistically small compared to observed measurements from reference projects (Vongvisessomjai et al., 2008). The same holds for the Bang Pakong Barrier. The barrier is positioned around 70 km upstream of the mouth. In this case the semidiurnal constituents can contribute to resonance. In the Tha Chin River, the same problems could occur at certain locations. However, there are locations in the river where tidal amplification will not be significant In other words, tidal amplification may occur, but the resulting tidal range should be acceptable.

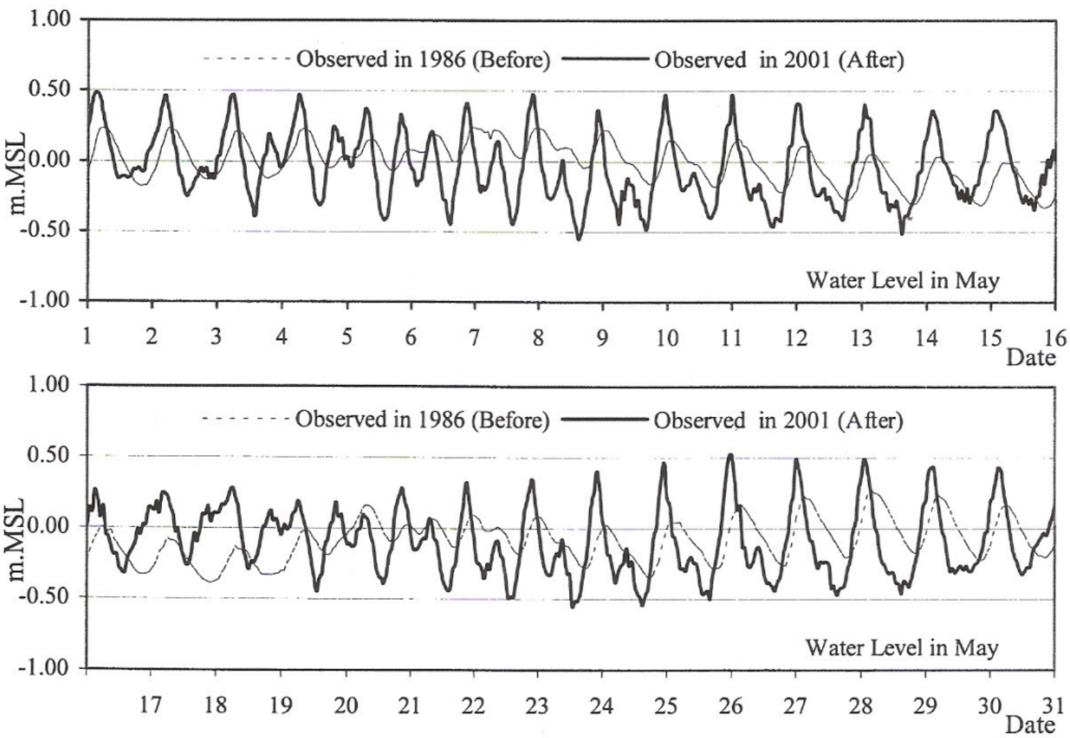


Figure P.2: The comparison of observed water level between before and after construction of the barrier in Bang Nara River. Source: Vongvisessomjai et al. (2008)

P.2.3. Stakeholder opinions
Constructing a salinity barrier is undesirable by many stakeholders. Especially the NGO We Love Tha Chin River is actively against a salinity barrier. This was further elaborated in the stakeholder analyses. Furthermore, since salinity barrier was already proposed in 2001 and rejected because of the many protests that it would increase pollution levels. The Tha Chin River basin committee is also against the barrier and according to them it will be hard to convince the local communities to implement this solution. It means that even if it can be proven that pollution levels will not increase significantly, it is still almost impossible to explain this to all stakeholders. (personal conversation, appendix V.1

P.3. Requirements and objectives
In this section, requirements for the design of a salinity barrier have been established. Finally, the main objective for further design is presented.

P.3.1. Requirements
- Block the saline water from entering to the threshold of salinity concentration at storm surge level.
- Release upstream river water into the estuary with no loss in river capacity. It can't cause upstream flooding
- It has to be able to partly open and regulate the size of the cross section for flows in both ways.
- No significant increase in tidal amplitude downstream of the structure
- Ships have to be able to pass the structure
- Minimize closure time
- It has to be practical and feasible in Thailand, that means:
  - Simple to construct
  - Little maintenance
  - Easy to operate
  - Simply manageable

P.3.2. Objectives
- Prove that the chosen position will not affect the tidal amplitude significantly
- Prove that the salinity intrusion will be reduced
- Prove environmentally that a gate will not increase in pollution levels
- Make a first preliminary design

P.4. Functional design aspects
Before going to the design options, three important functional aspect of the design are discussed:

1. It has to be able to partially or gradually open. This has the advantage that salinity can be regulated by salinity and upstream discharge measurements by letting less saline water into the estuary. Also it will decrease influences such as environmental impacts and full reflection causing standing waves. Partially open also means that it can regulate upstream flow. If the upstream water head is larger than the downstream head, it can release fresh water into the saline side of the estuary. Without this function, it can still block the saline water. However it will not suffice to the requirements from the RID.
2. Another important functional aspect is the reduction of effect normal water flow. This will have an effect on water pollution levels but it may also reduce river capacity during floods. To compensate for the river cross-section area reduction from the structure, it is proposed to widen the river at the structures location. In this way, the net river cross-section area will not be reduced, guaranteeing a minimum of impact on water flows. To minimize this impact, the barrier should be kept (partially) open as much as possible.

3. It has to be able to allow ships to pass with help of a: **Sluice:** The salinity barrier will have to be closed for a large part of the tidal cycle to have a significant effect. That is why a sluice for shipping is a minimum requirement for the salinity requirement. The system doesn't have to allow ships passing the structure when it's open

Sluice and a tidal window When the barrier has to be closed for most of the day during the dry season, it is better to look at options that are technically easier feasible when the gate is closed. However, the dry season will only take about 5 months of the year. The rest of the time, a sluice is required to let ships pass during the time the tidal window doesn't apply. During the tidal window and the other seasons, the structure has to be passable by ships without the use of a sluice. This means the structure has to open such that all ships can pass. Further requirements are as follows

- No significant increased current velocity on the sill
- No cross section area loss
- A management plan has to be made in form of a timetable with gate closure times. Any deviations from this table will have to be posted somewhere to inform the ships.

Both ship passing options are possible. What is exactly required can be chosen in a later stage op the project and is not relevant for this study.

P.5. Simulation

P.5.1. location

Location Possibilities

Placing a structure in the river will probably raise the water level downstream of the structure, because of its effect on the tidal amplitude. One of the design requirements is reducing the increase in tidal amplitude. It is assumed that it increases when a structure is placed further upstream. Another is reducing overall impact on the surroundings. Two locations are proposed: One at the mouth (X1 in figure P.5) and P.6 and one after the first bridge (figures P.3 and P.4).

Location 1 The first location is directly upstream of the Rama II-bridge at X5 in figures P.3 and P.4. Most of the river traffic in the river mouth is fishing ships coming from sea. Since they are too high to pass under the bridge, the amount of river traffic is heavily reduced upstream of the river. Therefore, the impact of structure is reduced a lot when placed upstream from this bridge, since most of the river traffic is not bothered. The structure's embankments are chosen on locations where currently no buildings exist. This layout would require a salinity barrier about 300 m in width. The cost for the barrier would be much lower than for location two since the width is significantly less. The ships that have to pass here are 30-50 barges per day. An impression of the barrier at location 1 is given in figure P.3.

Location 2 The second location is directly at the part where the mouth convergence greatly reduces, about 3 km from the river mouth at X1 in figures P.5 and P.6. This location would probably give no rise in water levels and thereby have a considerable lower impact on its direct environment. It would however have two major downsides. First, its location requires a very large structure of almost 700 m in width, bringing in high costs. These dimensions and costs could rise if further study would conclude that it should be longer to include the place of the current mangrove forest. Already a significant amount of mangrove forest would have to be removed to make way for the structure. Second, a structure would significantly interrupt the large amount of ships in the river mouth. This is even true with possibilities for the ships to sail through an open gate in the middle of the structure. When closed, the barrier would even completely block traffic; letting ships only pass through a sluice. The capacity of this sluice would have to be very high. The sluice can be positioned either in the middle or on the side of the barrier. An impression of the barrier at location 2 is given in figure P.5.

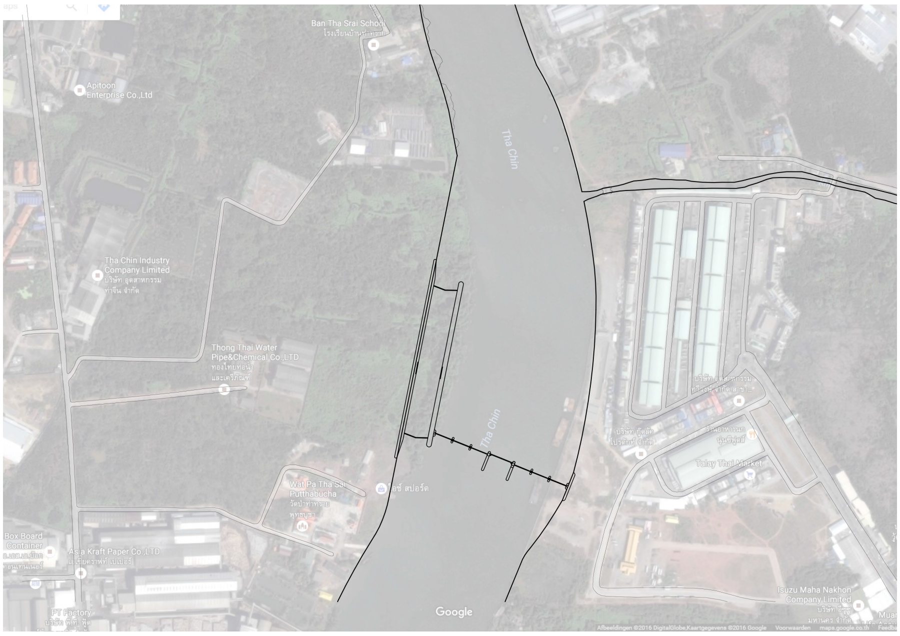


Figure P.3: Barrier at location 1, with sluice.

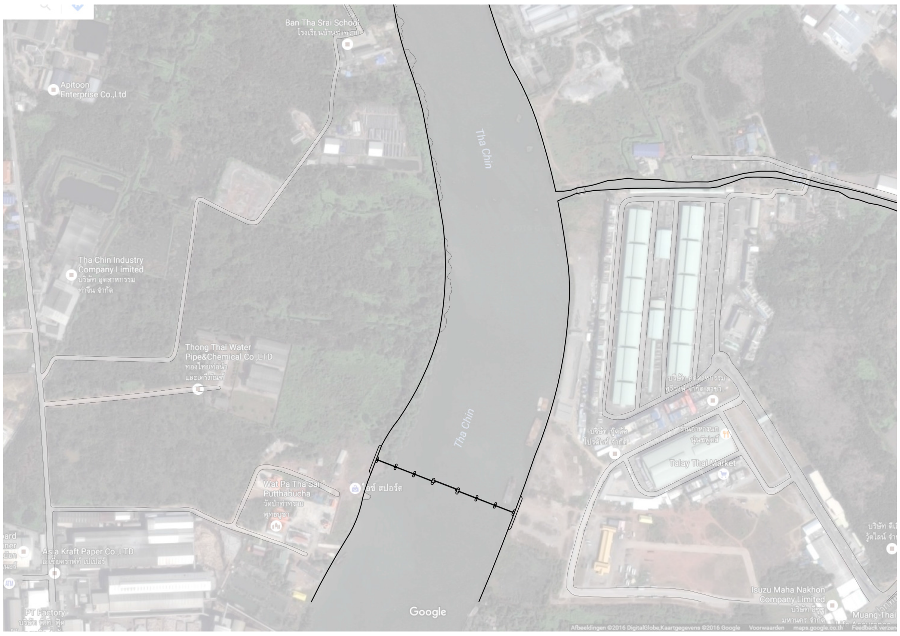


Figure P.4: Barrier at location 1, without sluice.

Tidal amplitude

To analyse the effects is from a salinity barrier on the tidal amplitude, several models have been used. The computations made with these models can be found in appendix S. The models that have been used are presented below:

- Analytical model with prismatic channel
- Analytical model with converging channel width
- Numerical model (SOBEK)

The result of the analytical models show that at X5 (12 km upstream) the increase in tidal amplitude is significant and can raise the tidal amplitude from a theoretical value of MSL + 1.78 m to MSL + 2.44 m, see

Figure P.5: Barrier at location 2, with sluice.

Figure P.6: Barrier at location 2, without sluice.

figure P.7 and P.8. This is a maximum increase of 37%. Placing it at X1 (3 km upstream), the tidal range will increase with a maximum of 10%, MSL +1.94 m. As can be seen in figure P.8, the tidal amplitude will exponentially increase. Placing the barrier more upstream would be unwise.

After the findings from the analytical model, the SOBEK model is used to compute the maximum water level at 12 km with and without the barrier. The results show the same shapes figure P.8. However, the tidal amplitude increase has a significantly lower order, the difference of the results can be explained by the influence of the bed level convergence. However, it should actually be called divergence, since the bed level of the channel is going down in the first kilometres. This will work positively on the tidal amplitude computed with the analytical model. The tidal amplitude increase given by SOBEK is based on tidal measurements and includes the discharge from upstream during four years. The relative increase is 7% and equals 12 cm which results in a water level of MSL +1.92 . The minimum water level is deviating more with 13% equal to 22 cm which results in a minimum water level of MSL – 1. 92 m.

In previous research a numerical model has shown more deviations from the actual water levels than the analytical model (Vongvisessomjai et al., 2008). However, in both models are still a lot of uncertainties.

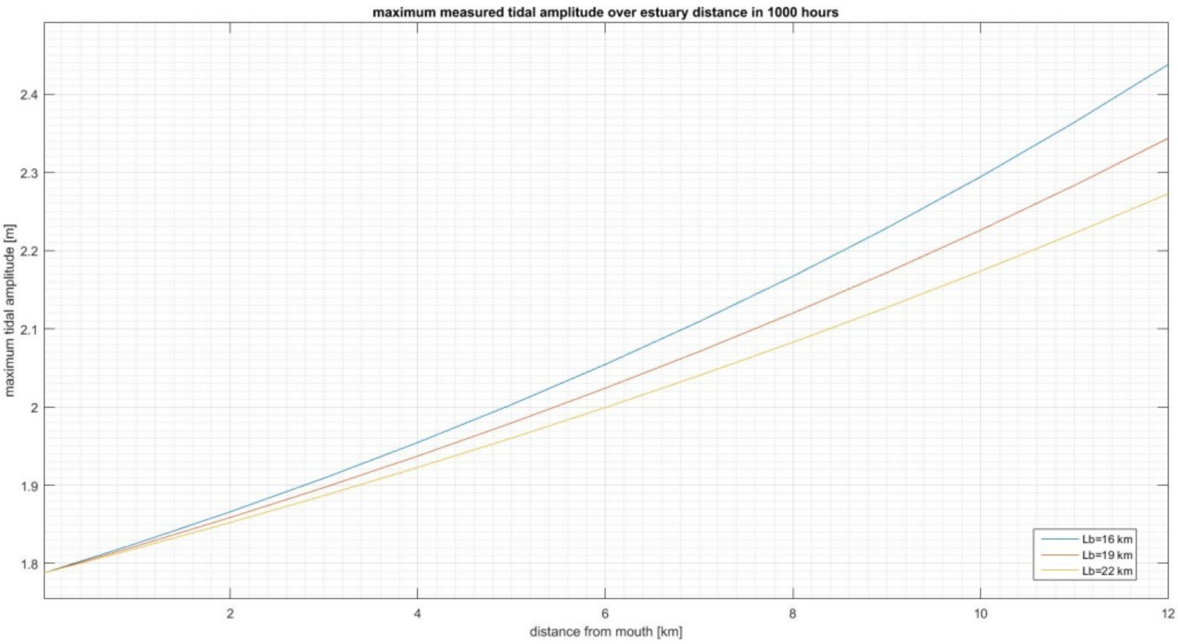


Figure P.7: Analytical tidal amplitude up to 12 km in the mouth. (SOBEK-RE results)

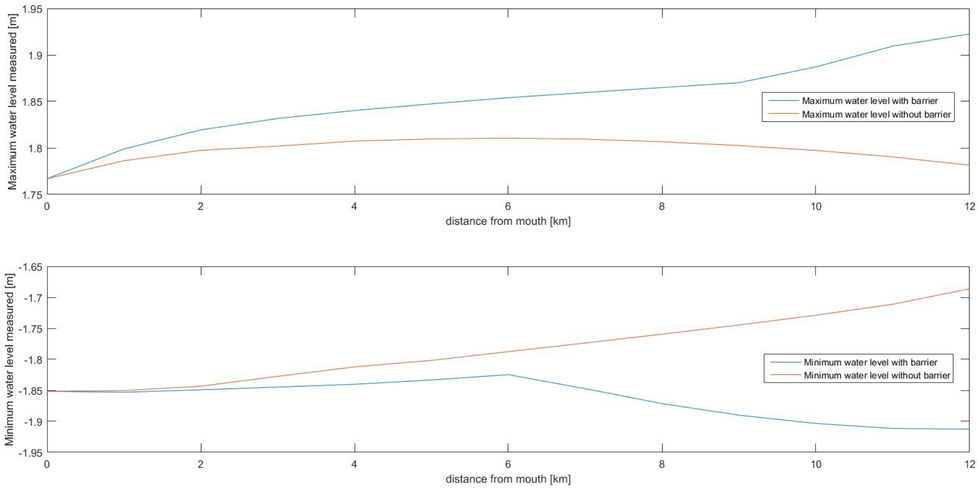


Figure P.8: Maximum and minimum water level up to 12 km in the mouth with and without the barrier. (SOBEK-RE results)

River and bank capacity

The question is if the increase in amplitude is significant for the banks between the mouth and the structure. To test this, the maximum river capacity according to the river basin committee (220 m^3/s) has been implemented into the numerical model SOBEK. This resulted in a maximum water level at 12 km of MSL + 1.95 m. This is an increase of almost 17 cm on top of the maximum theoretical tidal amplitude. It can be assumed that the banks of the river can handle this water level since this is the maximum river capacity. If the barrier is constructed, the banks of the river should be able to handle a maximum theoretical water level of MSL +2.44 m. In this scenario;

- The barrier is always closed, full reflection all the time

- A relatively small convergence length is chosen
- A theoretical maximum amplitude measured in 100 years is taken from the tidal constituents

The probability of exceedance of this value is assumed to be low. The storm surge height coming in from the sea is MSL + 2.7 m every 100 years. The tidal amplitude is still below this level and probably has a longer return period. This should however be further analysed. To be sure that this will not cause any problems, the current banks should be measured and inspected. Also the navigation channel has to be deepened with 0.5 meters to allow ship passage since the water level also drops 0.5 m at low tide.

Conclusion
Together the models give a good impression on how the downstream area will behave if a barrier is implemented. An increase in tidal amplitude can't be prevented. The tidal increase computed by SOBEK at 12 km is an acceptable one that is inside the capacity of the river banks. Furthermore, a salinity barrier at 12 km upstream has a lot more advantages in comparison with a barrier at the mouth. The first argument is the significantly smaller size of the structure. Secondly, the amount of shipping hindrance will be minimized. It is therefore highly recommended to investigate this location for further design options

P.6. Salinity reduction

To investigate the effectiveness of the salinity intrusion, a salinity barrier is implemented in SOBEK. In this way, analyses can be made of the consequences on salt intrusion with different opening and closing times. The different management schemes with controls and triggers for the opening and closing of the barrier can be found in appendix U. The conclusions of these experiments are discussed here. Two types of structures have been analysed; a general weir (crest level adjustable) on which water flows over the crest and a water gate (gate height adjustable) under which water flows, see figure P.9 and P.10.

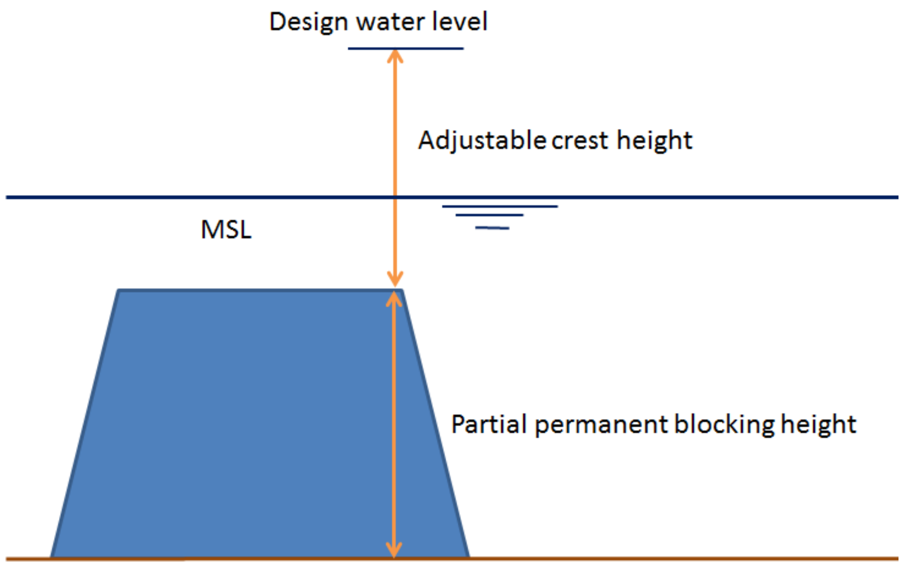


Figure P.9: Weir with adjustable crest height.

weir
Experiments with the weir resulted in the largest decrease in salinity concentrations. This is because a weir blocks the water partially at all times and can close to a level to block the saline water from penetrating when the discharge from upstream is too low. The salinity requirement of 2 g/L at a station 30 km upstream is easily complied. The average closing time percentage is 26 percent. The control parameter chosen is 30 m^3/s at an upstream point 240 km from the mouth to eliminate any influence of the structure.

The minimum partial blocking height that was tested is 5 m above bed level. If taken higher, the salinity concentration will decrease even further. The weir is closed up to MSL + 2 m to avoid the regular tide (MSL +1.94 m) from penetrating. If the river water level is higher than this level, it will overflow to avoid filling up

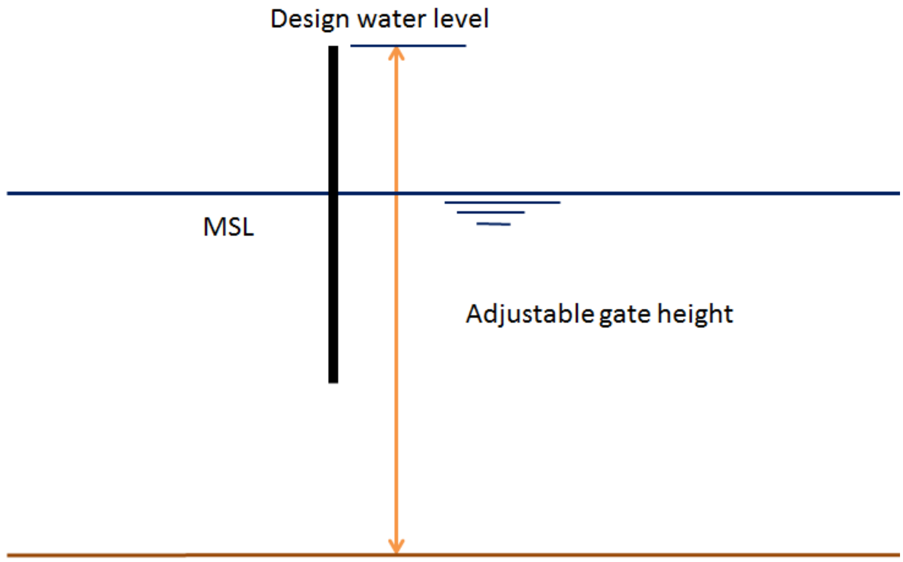


Figure P.10: Water gate with adjustable gate height.

the river. In reality, this level can be chosen just above the actual sea level and adjust itself according to the head difference between river water level and sea level. This will avoid the permanent rise in river water level that could block shipping (too high water levels means that they can't pass under bridges).

The downside is that the partial permanent blocking will cause changes in river equilibrium and decrease river capacity during floods. To solve this problem, the partial permanent sill height should be 0 m above the bed level. This case could unfortunately not be modelled. Further analysis is needed to investigate the consequences and salinity reductions if the weir can open completely.

P.6.1. Water gate

Experiments with the water gate resulted in a significant decrease in salinity concentrations up to the required level of $2g/L$ at 30 km upstream with some minor exceedances. The average closing time resulting from this management scheme was 35 %. The control parameter is the same as the weir. The result can be seen in figure P.11.

When the gate is open, normal salinity levels are almost instantaneously reached, thereby insuring regular flow in the river. When the gate is closed, the river water level will rise. The gate has been programmed to release water by lifting the gate 0.5 m above the bed level when the water level reaches MSL + 2 m. This ensures a maximum water level at MSL + 2 m. Again, this water level can be controlled to be just above the mean sea level to avoid a constant high river water level. The gate has to be raised just enough to release water from the river but not let any saline water flow under the gate. The principle is exactly the same as the weir but without a permanent sill.

P.6.2. Conclusion

The gate is obviously the only option that can be realized, since it doesn't reduce the river capacity. Although the weir is also a good option since the overflowing water is much easier managed. Under flowing water at the can also result in back flow of saline water. The management scheme of the water gate can be used to control the water gate. This management scheme is based on a control parameter upstream. The closing time percentage is about 35 % for this scheme and with that the requirement of 2 g/L at 30 km is complied with. Further closure time reduction in this scheme is certainly possible and can be realized through further experimentation.

P.7. Environmental consequences

A list of certain consequences of the salinity barrier is presented below:

- A backwater curve will form behind structure increasing water levels upstream of the structure. This

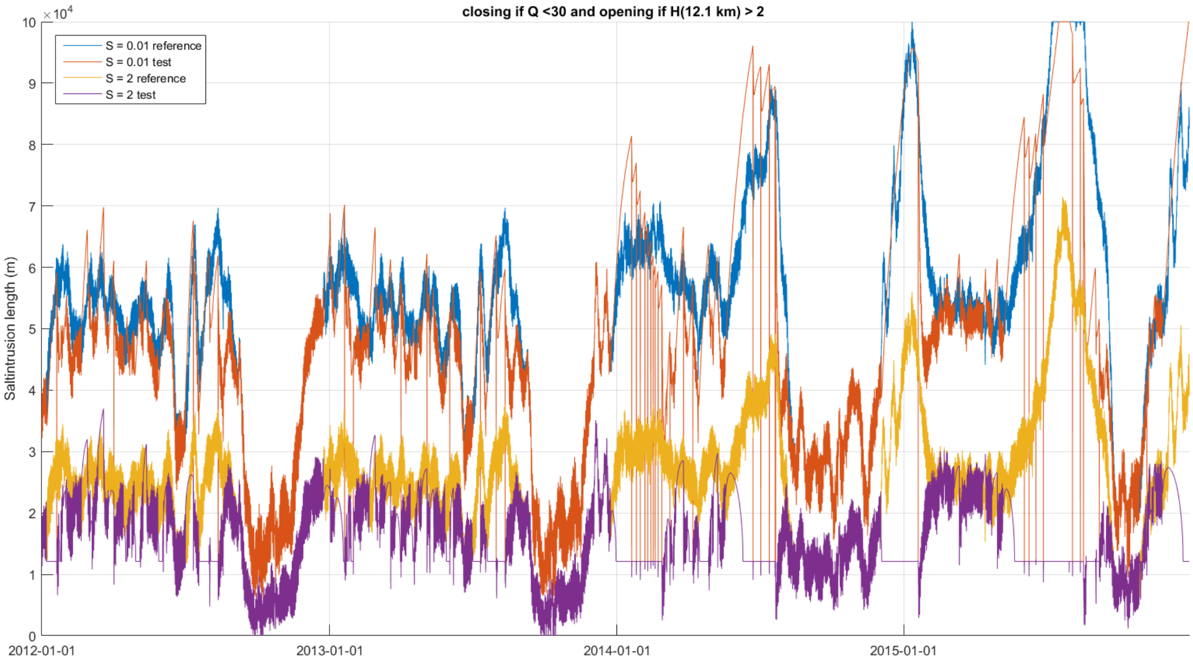


Figure P.11: Required salinity level (purple) and reference line (yellow) cannot exceed 30 km

curve will depend on the closure time of the barrier. Since the management scheme has been determined results of SOBEK-RE give a maximum and minimum water level of the river. These results have been plotted in figure P.12. The humps in the water levels are physically logical. As can be seen, a water level of MSL +2 m is reached up to 80 km upstream. This can be reduced significantly by letting more water flow through the gate at low water downstream of the gate.

- On the long term, the bed level upstream will increase near the structure. However, due to the longer opening times of the gate than closing times, the sediment will probably be flushed away to return to an equilibrium situation.
- The barrier will have an impact on pollution levels (negatively), because flow velocities upstream will decrease and water will be blocked. The exact flow velocities are unknown. However the maximum and minimum discharge is not changed with this structure. The longest closing time with the chosen management scheme is 47 days. However, this doesn't include partial opening to let fresh water through. The barrier will have an effect on oil pollution levels (positively), because the oil will not be taken upstream by the penetrating tide. This is true for the months that the gate will be closed.
- The ecology of the river will be altered due to changing equilibrium. Since the opening time is larger than closing time, it can be said that the environmental equilibrium that is formed when the gate is opened will dominate the river. Changes in river bed, water levels etc due to closure will likely return to this equilibrium

Most of these consequences can be modelled with a numerical model SOBEK. However, the results of the model are inaccurate because implementation of the barrier is in done using the simplest type of barrier without defining further flow regimes around the barrier. Further research has to be done. However, the SOBEK model that is made can be used for this analysis and further experimentation

P.8. Design options

It is stressed that these design layouts are preliminary and still need a lot of development. The key points to be kept in mind are minimizing the raise of tidal amplitude and minimizing the structure's impact, by designing a layout that interrupts current infrastructure as little as possible. Proposals are made here, but the exact design in which these two principles are translated is still open for change.

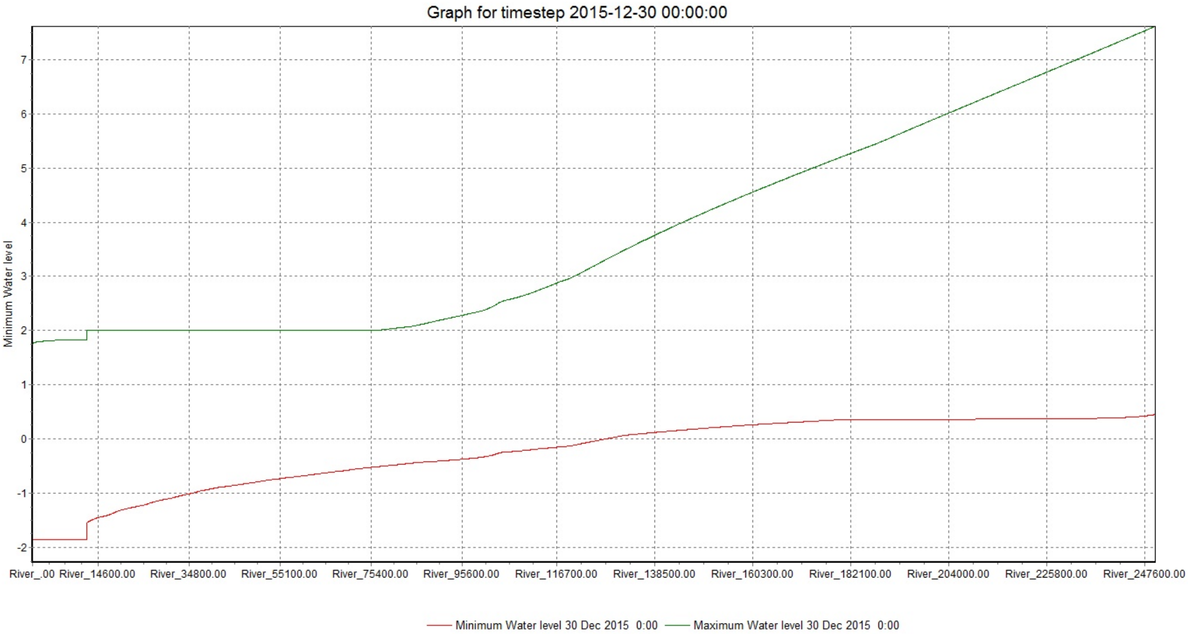


Figure P.12: Maximum and minimum water levels measured with SOBEK with chosen management scheme.

Table P.2: Gate properties

Gate type	Opening from	Opening mechanism	Blocks water from
Top and bottom weir	Top and bottom	Mechanical gate system	Both ways
Adjustable sill	Bottom	Mechanical or with use of air	Both ways
Rolling gates	Sides	Rolling on rail track	Both ways
Lifted gate system	Top	Mechanical gate system	Both ways

P.8.1. Barrier options

The most common design options have been listed below. Their properties have been listed in table P.2.

- **Adjustable sill:** Water flow could be blocked by a sill that's not fixed, but can rise from the river bed. The amount of blocking of water, as well as the water flow over the sill can thus be controlled.
- **Rolling gates:** The gate could consist of two parts that, rolling on a track, penetrate the river from the side, making a narrower river opening and eventually blocking all water.
- Lifted gate system: The gate principle that's found everywhere in Thailand. A gate is lowered in a structure from the top to partially or completely block water. It's used worldwide
- **Top and bottom** weir: A conventional gate, with the exception that the gate is made in an upper and bottom part, which are lowered from the top and rise from the bottom of the gate, respectively. Thus next to full blocking, only a certain part of the water flow can be blocked, for example when only the bottom part of the water is saline.

P.8.2. Advised barrier component

- To make sure river traffic is not interrupted when the barrier is open, special sluice doors are designed in the middle of the salinity barrier. These open to the sides (mitre gate) instead of to the top or bottom, creating an uninterrupted opening with a width of 40 m, they allow two average ships to pass at once.
- The other parts of the barrier are conventional salinity barriers, spanning 32 meters. This type of barrier is widely built in Thailand and therefore found to be feasible. However, again the barrier design is just an indication and needs a lot of elaboration still.

Impression of the barrier components are sketched in figure P.13, reffig:scheepsdeur.

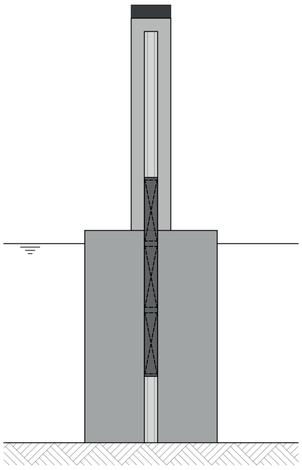


Figure P.13: Normal lifting gate for easy control (side view).

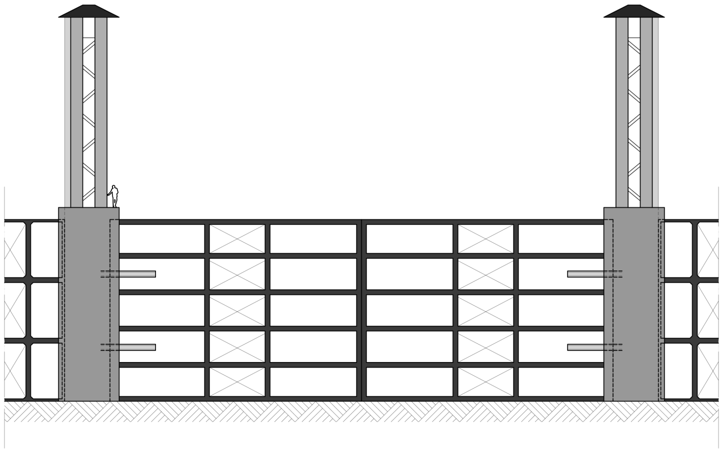


Figure P.14: Mitre gate for ship passing

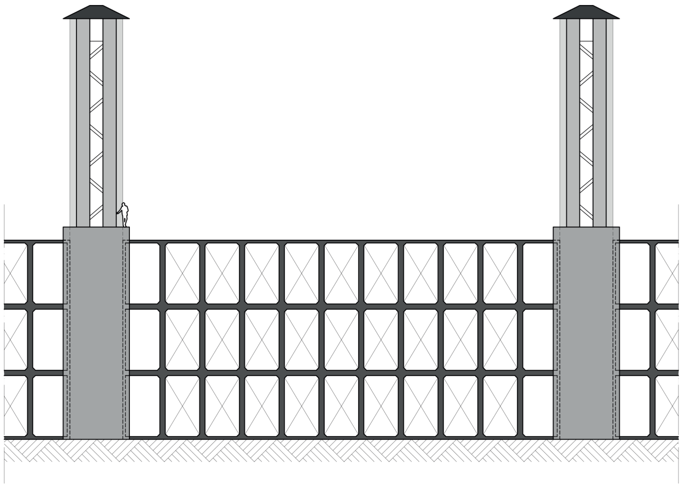


Figure P.15: Normal lifting gate for easy control (front view)

P.9. Conclusion

The salinity barrier is the only solution that is able to block the saline water completely and therefore it has a large certainty that it will work effectively. The principle is based on a barrier that lets through the same river discharge without losing any capacity during floods, but can be closed to block salt water when salinity levels become too high. These levels will become too high when the upstream discharge becomes lower than 30 m^3/s. At this moment the gate will be closed. This results in an effective reduction in salinity that fulfills the requirement stated by the RID. Closing any longer is unnecessary. Also, a release system had to be implemented to avoid high water levels. To be able to function as a weir and optimize the management scheme even further, the gate should be able to partly open and regulate the size of the cross section for flows in both ways. The total cross section when the barrier is held the same as the current maximum flow area of the river to kept

If the barrier is closed, reflection of the incoming tide will occur and increase the maximum tidal amplitude. This increase is modelled and results look promising if the barrier is positioned at 12 km upstream from the mouth. Any further upstream and the amplitude will increase exponentially. Constructing it any closer to the mouth is an option. However, due to the larger width, shipping traffic, mangroves and other spatial problems, this is not feasible. Further research has to be done in order to know the exact increase in tidal amplitude. The amplitude boundaries are quite well modelled in this report and can be used for detailed modelling or to assess if the banks are high enough.

Environmentally, the barrier will have great consequences for the river. However, these are minimized by reducing the closing period. A significant reduction of closing time is reached by modelling several barrier management schemes. These can be further improved with further research. An even larger decrease in closing time is certainly possible by looking more into opening at outflowing tide. With the chosen scheme, the barrier will be closed on average 35 % of the time. In this time, fresh water is still released by opening the gates partly to maintain a certain requested water level upstream of the barrier. This can be set greater or equal to the downstream water level to minimize environmental consequences. 35 % closing time also means that the dominant equilibrium in the river will likely be the same as the current equilibrium. Any perturbations after a long closing period will likely diffuse and return to this equilibrium. An environmental impact assessment is still to be done when further researching the barrier.

Shipping is blocked when the barrier is closed. Since about 30-50 large ships pass the location every day, a sluice is probably needed. However, when the barrier is open, the ships should be able to pass the structure. This is because the opening period accounts for the larger part of the year. However, the barrier can also be executed without a passing option, off course.

To finalize, the solution is very familiar to the Thai government, e.g. water barriers exist in river basins all over Thailand. However, this solution will cause much opposition from most involved stakeholders. This is because of the bad experiences in reference projects. Most of the problems from the reference projects have been discussed. However, it's still difficult to explain this to the local communities and other stakeholders. The type of barrier depends on the properties of the river and surroundings at the location. The barrier will have concrete embankments and moving parts made of steel. Design options have been presented and can be chosen in a later phase. Costs are high for such a large structure. However, building a common type of water barrier will be relatively cheap due to the large experience of the RID with barriers.

Q

Dam in the Gulf of Bangkok

Q.1. Description

This solution proposes building a permanent dam (e.g. a breakwater or a dyke) in the Bay of Bangkok (figure Q.1). Depending on its location and size, the dam would shut off the river mouths of some or all of the biggest rivers of Thailand. In this way, a fresh water basin at the river mouths will be created in front of the coast of Thailand and salt water from the Gulf of Thailand will be completely prevented from penetrating the rivers. River water would thus become permanently fresh. Also, the new water basin could be used as a retention area in case of floods. In that case, excess fresh water could be pumped out into sea, keeping the basin artificially low, allowing new river flood water to enter. Finally, the dam could serve as a storm barrier, protecting the Thai shore and Bangkok from high sea water levels. This solutions would thus not only solve salt intrusion in the Tha chin, but multiple other large-scale water problems in (different parts of) Thailand as well. This is a solution on a very large scale, with a huge impact on central Thailand's coast. However, it is also a very integral solution, as it solves multiple major water issues in Thailand at once

Figure Q.1: Possible layout of the dam in the Bay of Bangkok.

Q.2. Technical layout

The barrier that would close-off the bay would be a breakwater or a dyke. As sea traffic still has to have access to the Bay of Bangkok, including gates (for example sluices) is necessary. The length and layout of the barrier partly depends on which amount of (both positive and negative) impact is preferred. The barrier's function could also influence its layout, because the barrier could (partly) be constructed as new islands, thus creating new area, which could be commercially developed as living and leisure areas.

One of the biggest negative consequences will be its impact on the ecosystem. Not only will coastal waters which are now salt become fresh, but this fresh water basin will mostly contain stagnant water with a lack of tidal amplitude. This will kill most of the current marine life in the Bay. However, in a concept study for a similar barrier at the shore of Jakarta, it was stated that the changes in the water's ecosystem will be relatively gradual over the course of a year. Sudden mass starvation of plant or animal species was therefore not expected there (NCICD, 2014). But the Bay's ecosystem will still experience major changes.

Also, the rivers flowing into the basin are very polluted. In order to not let the basin become a giant sewage system, the pollution sources absolutely need to be assessed. Current marine life will vanish for a big amount. New, fresh water marine life could start in the basin, but for its development, it is vital to find a way to establish water flows in the basin. Water discharge from the rivers alone will probably not be sufficient to keep water in the new basin flowing.

Depending on the size of the retention basin and the rivers to be closed off, the barrier could have multiple locations and layouts as shown in figure Q.2. A few of the possibilities are displayed in the figure below. When determining the location of the barrier it is very important to account for the tidal amplitude. A wrongly chosen location could cause a rise in tide near the barrier, which could potentially destroy the barrier.

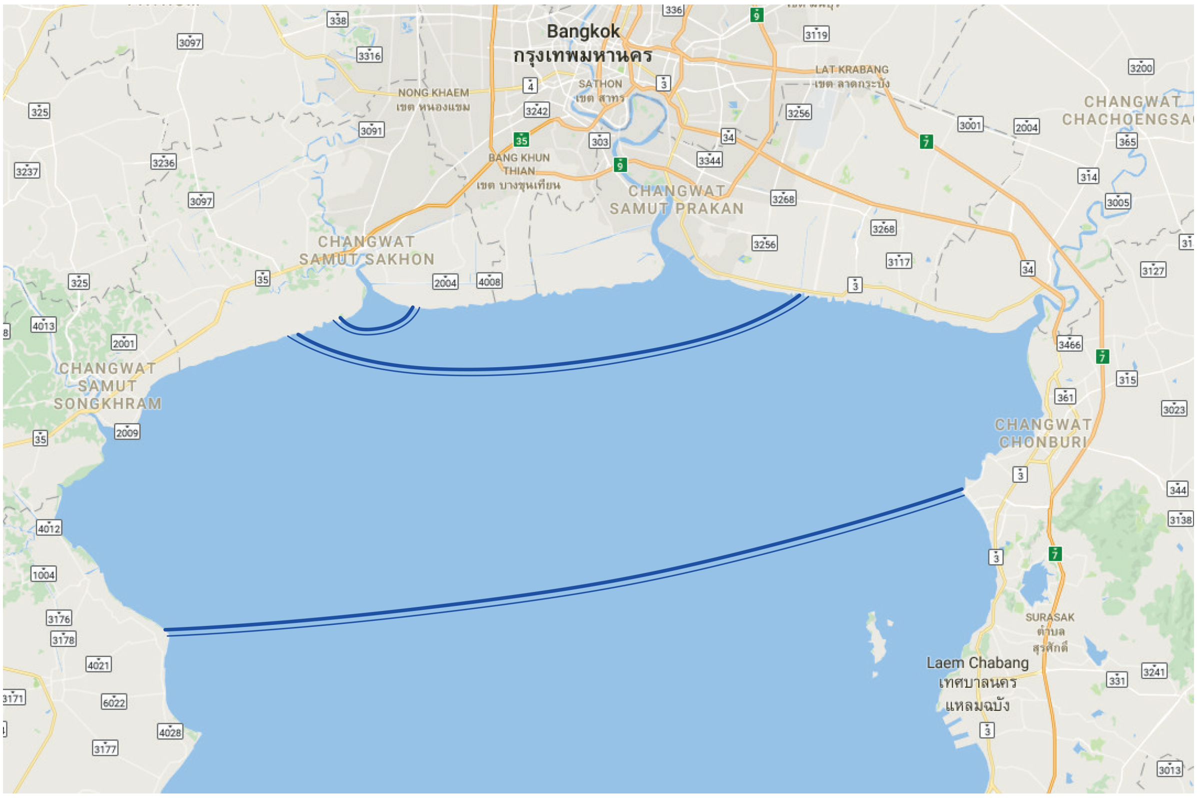


Figure Q.2: Possible locations of the barrier in the Bay of Bangkok.

Q.3. Costs, impact and reference projects

The Jakarta project mentioned before composed of building one big island in front of Jakarta's coast, which by barriers was connected to a few smaller islands. If the barrier in this solution will be built across the whole Bay of Bangkok, its size will be significantly bigger thus also entailing significantly higher costs. The costs of the Jakarta project were estimated at 26.5 billion US dollars. However, revenues were estimated at 29.4 billion US dollars, making the project financially feasible. Most of these revenues came from reclaiming and developing 1250 ha (7812.5 rai) of land (NCICD, 2014). However, it is very questionable if reclaiming and developing land in the Bay of Bangkok would be feasible. Except for the Bangkok area, no large-scale land shortage exists near the Thai shore. Together with the barrier's location, which is not a prime location, and the competition of several popular islands in the whole Gulf of Thailand, this gives the barrier a low competitiveness level in both leisure and real estate. Building the barrier would mean the current infrastructure of the Tha Chin basin would not be changed at all. However, the project would still have a large impact on a group of potentially millions of people. First of all, they would experience a complete new fresh water basin, without any tide, instead of the sea that was always there before. This will change the whole ecosystem of the Bay of Bangkok. Additionally, the size of the dam and location in the Bay of Bangkok may make this solution of such a scale that construction may bring all kinds of unexpected problems.

R

Partly barrier

R.1. Description

Constructing a barrier in sea that will partly close off a part of the Gulf of Thailand, the Bay of Bangkok, in which the mouth of the Tha Chin is located (figure R.1). This inner gulf is not closed completely, so the tide is still able to flow. The water in the whole Gulf will stay salt and a slightly brackish water basin will be created behind the barrier. It is expected that because of the barrier the tidal amplitude in this basin will be lower than the current tidal amplitude in the inner gulf. When the tidal amplitude is lower, the salt intrusion length will be lower. A positive side effect is that the salt water that penetrates the river will have a lower salinity, also benefiting a reduction in salinity. At the same time, the change in ecosystem would be limited because water would remain salt and would still be able to flow

Figure R.1: Possible layout of the partly dam in the bay of Bangkok

Table R.1: The reduction of the intrusion length of the 2 g/l limit for different model settings

	Salinity in the mouth [g/l]	Dispersion amplification factor	Tidal	average reduction of the 2 g/l salt intrusion length
1	30	100	*0.5	30%
2	20	100	*0.5	40%
3	20	150	*0.5	17%

R.2. Technical layout

This solution requires complex and detailed models in order to determine the technical layout, as the exact location and size are crucial to its functioning. A wrong location could even increase the tidal amplitude. The barrier could be build out of clay (abundant in the Gulf), rock, concrete or a mixture of these. Water flows through the openings could be severely accelerated, which would harm sea traffic and increase bank erosion. Therefore the openings need special attention in the design, so this acceleration may be prevented.

The barrier could also be submerged. In this way, tidal amplitude could still be decreased will costs will be limited because less material is needed. Either way, considerable attention should be given to bed protection, as the barrier will be subject to sea water flows of significant velocity.

R.3. Impact and Costs

A project of this scale would have impact on a very large amount of land and people. Construction costs will be very high, possibly running in the billions of US dollars. These are two factors threatening this solution's feasibility. Due to the size of the barrier this can be a very cost intensive solution. Construction has to be done partly via sea, which is harder than via land and therefore it can be more expensive. Additionally, the depth of the Bay of Bangkok will make construction expensive, as much material will have to be depleted.

In contrast to previous assumptions, commercial development potential of the barrier will likely be limited. Except for the Bangkok area, no large-scale land shortage exists near the Thai shore. Together with the barrier's location, which is not a prime location, and the competition of several popular islands in the whole Gulf of Thailand, this gives the barrier a low competitiveness level in both leisure and real estate.

Building the barrier would mean the current infrastructure of the Tha Chin basin would not be changed at all. However, the project would still have a large impact on a group of potentially millions of people. First of all, they would experience less saline, maybe even brackish water near their coasts. This will change the whole Bay of Bangkok's ecosystem. Due to more stagnant water, pollution levels may increase. Sea traffic will be able to flow through, but it has to take an alternative way. Additionally, the barrier's size and location in the Bay of Bangkok may make this solution of such a scale that construction may bring all kinds of unexpected problems.

R.3.1. Simulation and conclusion

This solution requires complex 3D models, but in order to see whether the solution is suitable for salt intrusion and to obtain order estimates of the reduction SOBEK-RE can be used. In SOBEK-RE it is not possible to put the partly barrier in the bathymetry because it is a one dimensional model and they should be placed in the Bay of Bangkok, a part that's not included in SOBEK-RE. The effects of the balance islands can be modelled in SOBEK-RE by changing the boundary conditions. The parameters that change due to the balance islands are the salinity in the mouth, tidal amplitude and dispersion.The effects will be as follows:

- the salinity at the mouth will drop quite a lot
- a reduction in tidal amplitude is also possible
- due to smaller difference in salinity the dispersion will be lower as well (appendix T)

Those three criteria correspond with the follow runs in SOBEK. For more information about the sobek model see appendix U.

In the best case, run number 2, the threshold is not always met but it happens less often and when it happens the duration is much shorter. See figure R.2. This run number is the most realistic effect of the partly barrier. This is because the salinity in the mouth and the dispersion are linked, so if one of them changes the other one probably changes as well. A reduction of 40% of the 2 g/l salinity intrusion length is very promising. If this solution is chosen more research should be performed on the exact layout and reduction

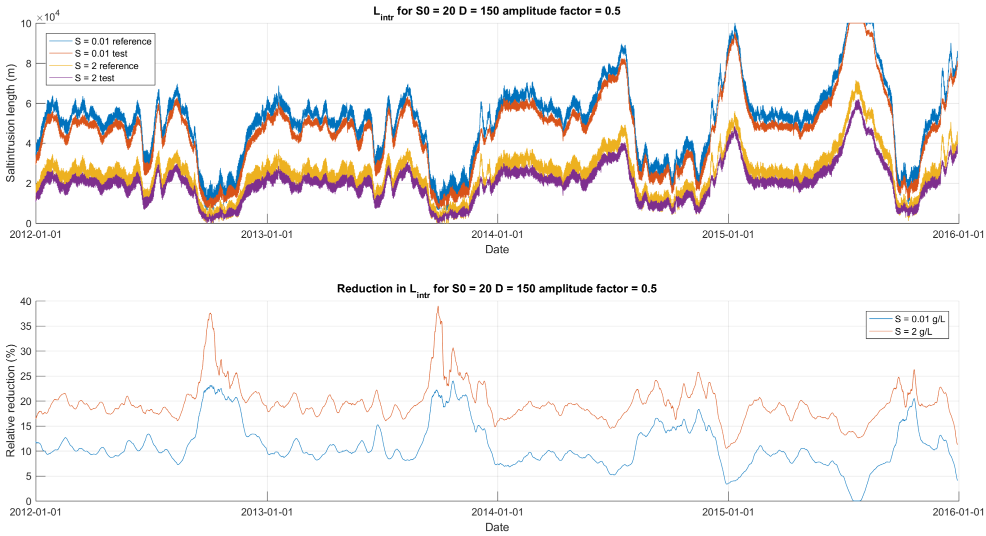


Figure R.2: Salt intrusion length of run 2.

S

Analytical model of the tidal range in the Tha Chin estuary

In this chapter an analytical model for the tidal range in the Tha Chin estuary is presented. The reason to make an analytical model is to get a good insight in the physics of the tidal behaviour in the estuary. Additionally, it can be determined which variables are significantly contributing to the total tidal range along the river. The model will be mostly used to determine the location of the salinity barrier. The results of the analytical model can also be used in the numerical model SOBEK to validate both models. It will also help reduce computation time by reducing the amount of computations needed. In section S.1, the theory about wave and estuary characteristics will be discussed. In section S.3, a simple analytical model for tidal amplification in prismatic channels is presented to get an insight in the contributions of friction and phase differences. In section S.4, a detailed model for a converging channel based on a model from DELTARES is discussed.

S.1. Theory

S.1.1. Wave deformation

A progressive harmonic wave propagating in deep water without wave deformation/distortion is known as an ideal wave. However, there are some phenomena that affect this ideal situation. The basic phenomena affecting the propagation of waves are:

Reflection This is an important phenomenon in estuaries. In case of total reflection a standing wave pattern is generated. Resonance may even occur if the channel length is approximately a quarter of the wave length.

Amplification Amplification is defined as the increase of the wave height due to the gradual change of the geometry of the system (depth and width) Green et al.'s law (1837). Assuming that there is no reflection and no loss of energy (due to bottom friction), the energy flux is constant resulting in equation S.1.

Deformation A wave experiences deformation as it travels into shallower water, since the crest is moving faster than the trough. This wave skewness can be described by higher harmonics of the basic sinusoidal wave.

Damping Due to friction, energy will be lost and the wave height will decrease. This decrease is exponential and therefore the friction term is non-linear. To linearize this term, a Fourier series can be used. From this the higher order harmonics can be neglected. The terms that are left are also known as the Lorentz friction parameter The energy principle of Lorentz explains that the total energy dissipation during one tidal cycle is for both linearized and quadratic friction the same.

$$E_0 c_0 = E_x c_x \tag{S.1}$$

Where E represents the wave energy in J and c the wave celerity in m/s.

$$n = \frac{8g|\widehat{Q}|}{3\pi C^2 A^2 R} \tag{S.2}$$

Where n is the Lorentz-friction parameter $m^{-2}s^{-1}$, $|\hat{Q}$ is the tidal peak discharge in m^3/s , C the Chezy value in $m^{1/2}/s$, A the cross section area of the estuary in m^2 and R the hydraulic radius in m.

S.1.2. Estuary characteristics

The shapes of alluvial estuaries are similar all over the world (Savenije, 2012). The width and depth decrease in landward direction resulting in a convergent (funnel shaped) estuary. The tidal range in estuaries is affected by the phenomena discussed before. The variation of the tidal range (H) along the estuary can be classified, as follows:

ideal tidal range is constant

amplified tidal range increases

damped tidal range decreases

S.2. Tidal motion

Offshore, the tide consists of several tidal constituents. In the Gulf of Thailand a study has been done and the influence of 25 tidal constituents has been found. These constituents with their characteristics are presented in table G.1 in appendix G The wave speed of the wave in a prismatic channel can be derived from the mass balance and momentum balance equations and is equal to $c = \sqrt{g * h0}$. This approach can also be used to approximate the wave speed in converging estuaries with constant depth. In this approach the reduction in width is given by the exponential function of equation S.3

$$B = B_m \exp\left(-x/L_b\right) \tag{S.3}$$

Where B_m is the width at crest level at the mouth in m, x is the distance from the mouth in upstream direction in m and L_b is the convergence length in m.

For the wave velocity in a converging channel holds :

$$c = \alpha_1 c_0 \tag{S.4}$$

With α_1 is wave celerity factor for converging channels which depends on the convergence (L_b) and the wave-length (L):

$$\alpha_1 = \sqrt{\frac{L}{4L_b} \frac{\sqrt{1+\exp(0.5L/L_b)}}{\sqrt{-1+\exp(0.5L/L_b)}}}$$

and c_0 is the shallow water wave velocity.

$$c_0 = \sqrt{g h_0}$$

Note that α_1 is an approximation of based on equalities of discharges at the mouth. Therefore this is not completely correct. Using the wave velocity the average peak velocity can be computed using equation S.5

$$\hat{\bar{u}} = c\left(\hat{\eta}/h_0\right)(4L_b/L)\,\frac{-1+\exp(0.5L/L_b)}{1+\exp(0.5L/L_b)} \tag{S.5}$$

Where $\hat{\bar{u}}$ is the time averaged peak velocity in m/s and $\hat{\eta}$ is the water level at the mouth m.

The friction is still neglected in the equation, therefore c_0 has to be multiplied by another factor: α_2.

$$\alpha_2 = \sqrt{\frac{1}{1+mT}} \tag{S.6}$$

Where m is the Lorentz friction coefficient and T is the tidal period in s. m can be calculated with the time averaged peak velocity the Chézy friction factor and the depth (h_0).

$$m \cong \frac{8g|\hat{\bar{u}}|}{3\pi C^2 h_0} \tag{S.7}$$

Table S.1: Averaged measurements river cross section for the first 20 km from the mouth.

Total width	360 m
Conveyance width	270 m
Depth	10.5 m

S.3. Analytical model of tidal wave equations for prismatic channels

In this section, an analytical model will be presented for a prismatic channel. This model makes use of the amplification factor, r, which is calculated with equation S.8 (Battjes, 2002). The model is based on a friction parameter μ and a resonance parameter k the wave number. If friction is normative over resonance the amplification factor will be smaller than 1. If the resonance frequency is reached for some waves and the friction parameter is small amplification can occur and the amplification factor will be larger than 1.

$$r \equiv \frac{\hat{\zeta}(0)}{\hat{\zeta}(\ell)} = \frac{1}{\cosh p\ell} = \frac{1}{\sqrt{\sinh^2 \mu\ell + \cos^2 k\ell}} \tag{S.8}$$

Where $\hat{\zeta}(0)$ is the amplitude at the closed end (m), $\hat{\zeta}(\ell)$ is the amplitude at the mouth (m), ℓ is the estuary length (m).

In this model, the 25 theoretical incoming constituents will used. For every wave an amplification factor is computed. This factor will be multiplied with the tidal amplitude at the mouth to compute the amplitude at the closed end. Finally, the amplitudes will be summed up to get the total amplitude. The assumptions that have been made to realize this model are listed as follows:

- The channel bottom is flat
- The channel cross section is constant in space and time
- The convection acceleration is neglected
- Linearized friction is used
- Constant density, barotrophic flow.
- there is no river discharge
- the X coordinate is positive in landward direction

S.3.1. Input

For this model, some unknown variables have to be defined.

Estuary length The channel section that is interesting to model is the first 20 km from the mouth. This is where the barrier possibly could be positioned. In the model the estuary length will be the variable. At this location, the amplitude will be computed.

Tidal constituents A list of all theoretical tidal constituents is given in table G.1 in appendix G In this list the tidal characteristics of all constituents are also displayed.

Chezy value The Chézy value for the Tha Chin river varies significantly. In literature, the values are between 20 and 45. The value is further elaborated in appendix T In this model, the given range will be used.

Channel dimensions Because the boundary condition is at 20 km from the mouth, the channel dimensions can be averaged out of the measurements obtained from the Marine Department. Important dimensions are the depth, conveyance width and total width. The result of averaging is given in table S.1

S.3.2. Results

In figure S.1 and S.2 the results of the model have been plotted for two Chézy values. It can be seen that the amplitude is 271 cm at the mouth. This is an unrealistic high value. That is because this this a summation of all tidal constituents. In reality this will never happen. The second notion that can be made is that in case of a Chézy value of 20 $m^{1/2}/s$, the tidal amplitude is damped after some distance. In case of a Chézy value of 45, the tidal amplitude rises exponentially with a maximum at 20 km of 280 cm.

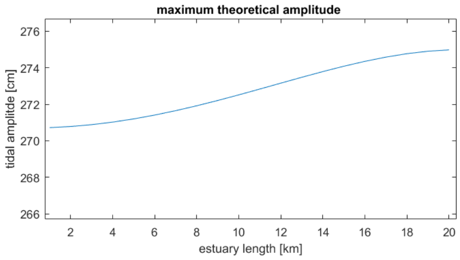


Figure S.1: The maximum theoretical amplitude for the prismatic channel with $C = 20 m^{1/2}/s$

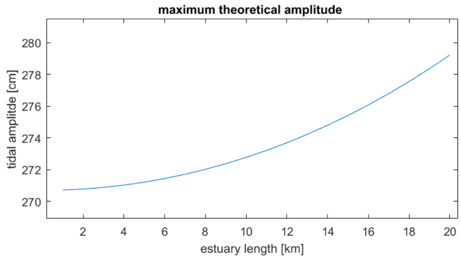


Figure S.2: The maximum theoretical amplitude for the prismatic channel with $C = 45 m^{1/2}/s$

S.3.3. Conclusion

In both situations, the tidal amplitude for a prismatic channel rises in the first 20 km. It can be said that resonance dominates over friction. However not by much. In the second case with low friction, the tidal amplitude is 9 cm higher than at the mouth. However it is only an increase of 3.3 % of the initial tidal amplitude. It can be concluded that for a prismatic channel the increase in amplitude is notable because it will only increase more for converging channels. The increase is very small and therefore not significant. Furthermore, the model for a prismatic channels is only used to get a good look at the influence of friction and resonance. The results are not accurate and the computed values are not correct for the Tha Chin River.

S.4. Analytical model of tidal wave equations for converging channels

Because the Tha Chin estuary is not a prismatic channel the model has to be adjusted in such way that the convergence of the width and flow area is taken into account.

S.4.1. The model

In 2010, prof. dr. L.C. van Rijn published a report about tidal phenomena in the Scheldt estuary (Van Rijn, 2010). In this report a model is discussed for the tidal wave equations for converging channels. It is a relatively easy model based on the analytical solution of mass and momentum balance equations. This means that the model is based on the conservation of energy flux in a converging channel represented by an exponential function. (b = b* exp(β*x)) (Prandle, 2009). A detailed elaboration of the mode can be found in the report. The following assumptions are made to realize the model:

- Channel depth is constant in space and time
- Channel bottom is flat
- Convection acceleration is neglected
- $\beta = 1/L_b$: convergence parameter
- Linearized friction is used
- Constant fluid density
- No river discharge
- X coordinate is positive in landward direction

Two models are used to calculate the surface elevation in time and space $\eta_{x,t}$. The first is the model with a converging channel with an open end, no reflection, (equation S.9), the second model has converging banks and reflection is taken into account(equation S.10).

$$\eta_{x,t} = \widehat{\eta_0} \exp(-\varepsilon x) \cos(\omega t - kx) \tag{S.9}$$

With $\varepsilon = -0.5\beta + \mu$

$$\eta_{x,t} = 0.5\widehat{\eta_0} f_A^{-1} \left[\exp(\varepsilon_1 x + \mu\ell) \cos(\omega t - k(x-\ell)) + \exp(\varepsilon_2 x + \mu\ell) \cos(\omega t - k(x-\ell))\right] \tag{S.10}$$

With $\varepsilon_1 = 0.5\beta - \mu$, $\varepsilon_2 = 0.5\beta + \mu$, $f_A = \sqrt{\cos^2(k\ell) + \sin^2(\mu\ell)}$ = the amplification/damping factor.

In both models the wave number (equation S.4.1) and friction parameter (equation S.12) have to be determined. Since these values vary for different kinds of estuaries, two cases are presented, one for an amplified estuary and one for a damped estuary. Scheme in equation S.13 is to avoid complex values in the solution.

$$k = \sqrt{0.5}\frac{\omega}{c_0}\sqrt{\alpha}\sqrt{-1+\sqrt{1+\frac{m^2}{\omega^2\alpha^2}}} \tag{S.11}$$

$$\mu = \sqrt{0.5}\frac{\omega}{c_0}\sqrt{\alpha}\sqrt{1+\sqrt{1+\frac{m^2}{\omega^2\alpha^2}}} \tag{S.12}$$

$$\begin{array}{llllll} \text{if} & \beta \geq 2\frac{\omega}{c_0} & \vee & L_b \leq \sqrt{gh_0}\frac{T}{4\pi} & \rightarrow & \alpha = 0.25\beta^2\left(\frac{c_0}{\omega}\right)^2 - 1 \\ \text{if} & \beta \leq 2\frac{\omega}{c_0} & \vee & L_b \geq \sqrt{gh_0}\frac{T}{4\pi} & \rightarrow & \alpha = 1 - 0.25\beta^2\left(\frac{c_0}{\omega}\right)^2 \end{array} \tag{S.13}$$

The output of the model is a sinusoidal wave equation depending on space and time. To get the right results for the Tha Chin River, the 25 theoretical tidal constituents have to be used as input. The amplitude and phases of these constituents will be taken up in the computation. The input waves are in the following form:

$$\eta_{x,t} = \eta_0 \cos(\omega t - kx - \phi) \tag{S.14}$$

For each wave, the resulting field in space and time of the incoming and reflected wave is computed using the model. Using superposition, the 25 wave fields are summed up to get a total wave function in space and time. Because the estuary length is also a variable in the equation, it is practical to use this as the spatial coordinate. This means that the tidal amplitude will be computed at the location of the closed end.

S.4.2. Input

In this model several variables have to be predetermined. Some variables have already been defined in section S.3.

Convergence length The convergence length is a property of an exponential function. Because the target area is situated between the mouth and 20 km upstream, the cross section measurements can be used to compute this property. The convergence length is based on the conveyance width of the channel. With measurements and an exponential fit function, the convergence length results in 19 km. This is close to the measured convergence length that was determined by Savenije (2012). This was 22 km. The fitted curve is however not accurate since its R^2 value is 0.6697 and has a standard deviation from the mean of 135.3. see figure S.3

Tidal constituents These are determined theoretically and presented in table G.1 in appendix G the phase difference is an important factor in this model.

Peak tidal velocity The peak tidal velocity is computed differently than a prismatic channel. The tidal wave velocity also varies. with equation S.5 the peak tidal velocity is computed.

S.4.3. Validation

Validation of the model can only be done using existing water levels in the estuary. However, these are not available on the scale needed. The only thing that is known, is for the first 20 km of the estuary, the tidal amplitude does not decrease significantly (in the order of centimeters). This is a good approximation, since it holds for an ideal estuary in equilibrium. Also the results from SOBEK-RE give a decrease in this order.

Calibrating the model can be done using different Chézy values. This is also done in the report of the Scheldt estuary (Van Rijn, 2010). To calibrate first a model without a closed end which simulates the current situation, is used. The discharge from upstream does not have to be compensated for in the calibration, because in the closed situation, the discharge from upstream will be zero and will therefore not contribute to the dampening of the tide. The highest measured tidal amplitude in 5 years at the mouth is 1.71 m. The model results are given in figure S.4. From this figure, it is clear that for Chezy values between 26 $m^{1/2}/s$

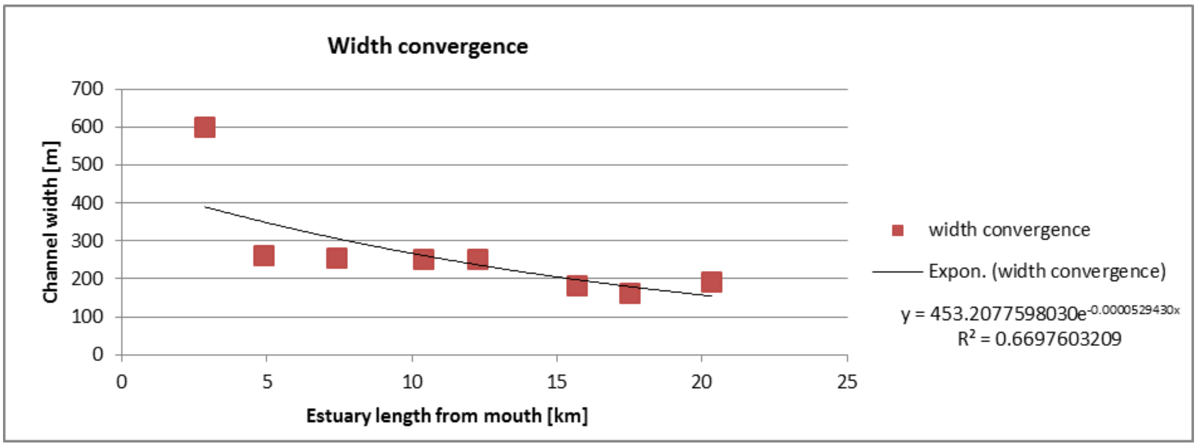


Figure S.3: Measured channel width in the first 20 km of the tha chin river [m].

and 30 $m^{1/2}/s$ the tidal amplitude decreases in the order of centimeters. With this range of values, further computations can be made. It can also be seen that the maximum theoretical amplitude at the mouth is 1.78 cm above MSL. This is 7 cm above the maximum measured amplitude. The model is therefore slightly overestimating the amplitude. However, not enough measurements have been done to confirm this. The approximation is in the right order of magnitude and therefore usable for further computations.

S.4.4. Results and conclusions

The results that will be discussed here are from the second model, the one with the salinity barrier at location x. The tidal amplitude is plotted for different values of all relevant variables in the equations: Chezy (figure S.5), depth (figure S.6) and convergence length (figure S.7). It has to be noted that the value on the x-axis is the location of the salinity barrier. In other words, the tidal amplitude that can be seen in the figures is the maximum tidal amplitude in the wave field if the salinity barrier is positioned at that location. In almost all situations this is equal to the maximum tidal amplitude at the salinity barrier.

From figure S.5 it can be said that the Chézy value is not significantly contributing to the amplification. Also the depth of the channel does not contribute much either. However, the depth starts to influence the amplitude when it is smaller than 8m. In that case it will work positively on the damping because it reduces the amplitude, because friction becomes more important. The significant variable is the convergence length, because this will change the tidal amplitude. The larger the convergence length, the lower the tidal amplitude. This is very logical, since the rate of convergence will be smaller.

Following these results, a plot has been made of the 2 possible locations on the map. Locations X1 at 2860 m from the mouth and X5 at 12250 m from the mouth. In the model locations are taken at 3000 (figure S.8) and 12000 m (figure S.9) respectively. Since Savenije (2012) gives a convergence length of 22 km, this convergence length is also plotted as upper boundary. As lower boundary, 16 km will be taken.

The final result of the model is that the amplitude will always increase if a salinity barrier is built. The second note is that the amplification of the tidal amplitude increases exponentially with increase of the barrier distance from the mouth. If the barrier will be placed at 3 km from the mouth than the tidal amplitude will increase between 7% and 10% with a maximum amplitude of 1.94 m. If the barrier is placed at 12 km, the amplitude increase will be between 28% and 37% with a maximum amplitude of 2.44 m.

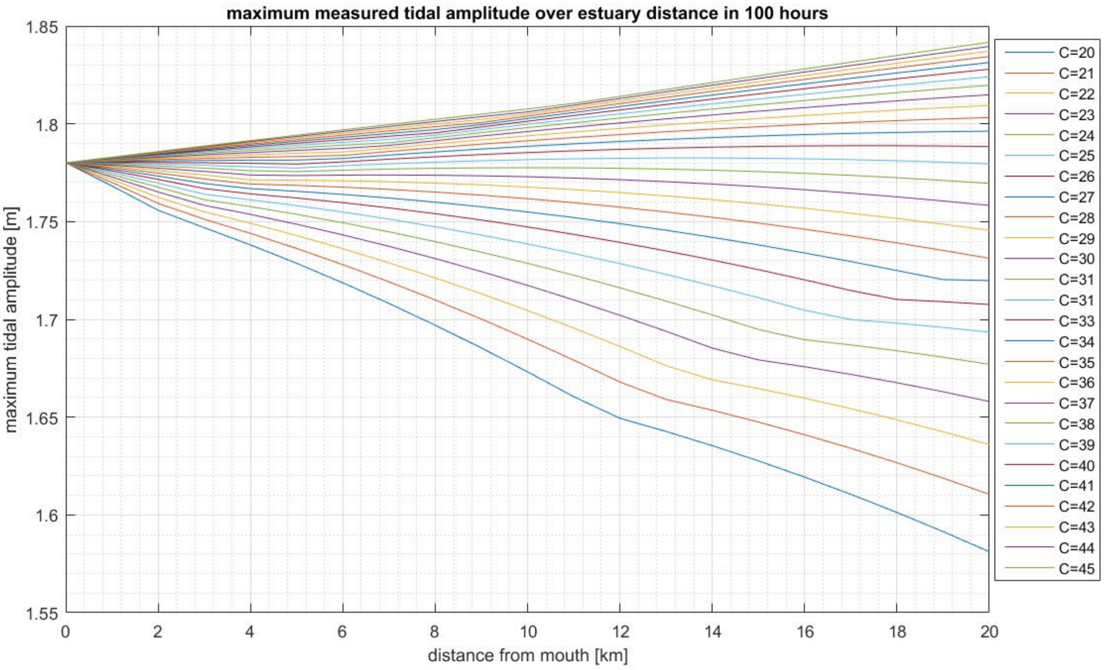


Figure S.4: Maximum tidal amplitude as a function of the distance in the river mouth in the situation without reflection for different Chézy values

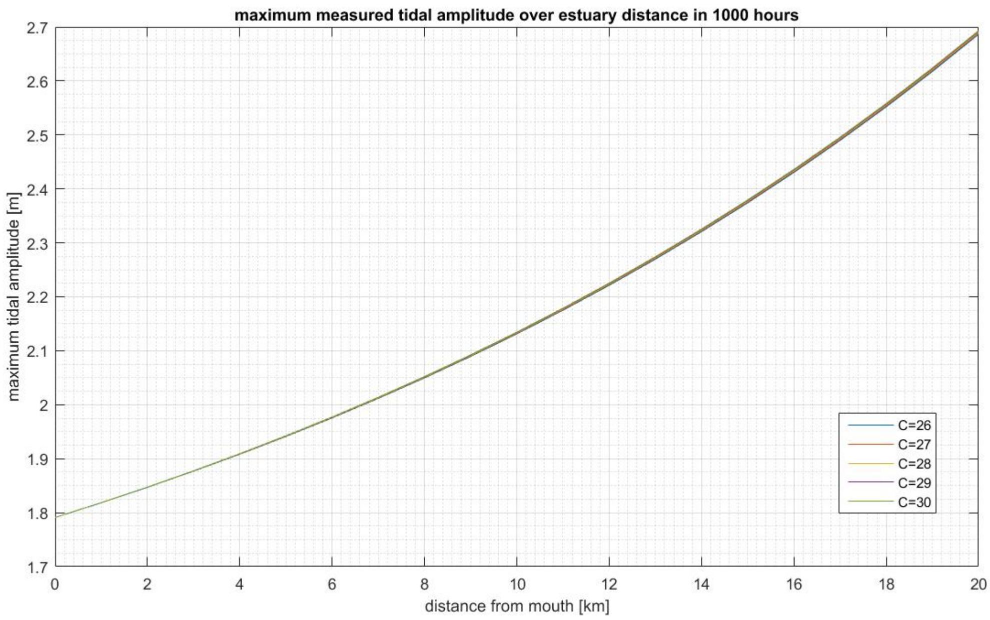


Figure S.5: Maximum tidal amplitude downstream of the closed end as a function of the location of the closed end in the river mouth. In the situation with reflection for different Chézy values.

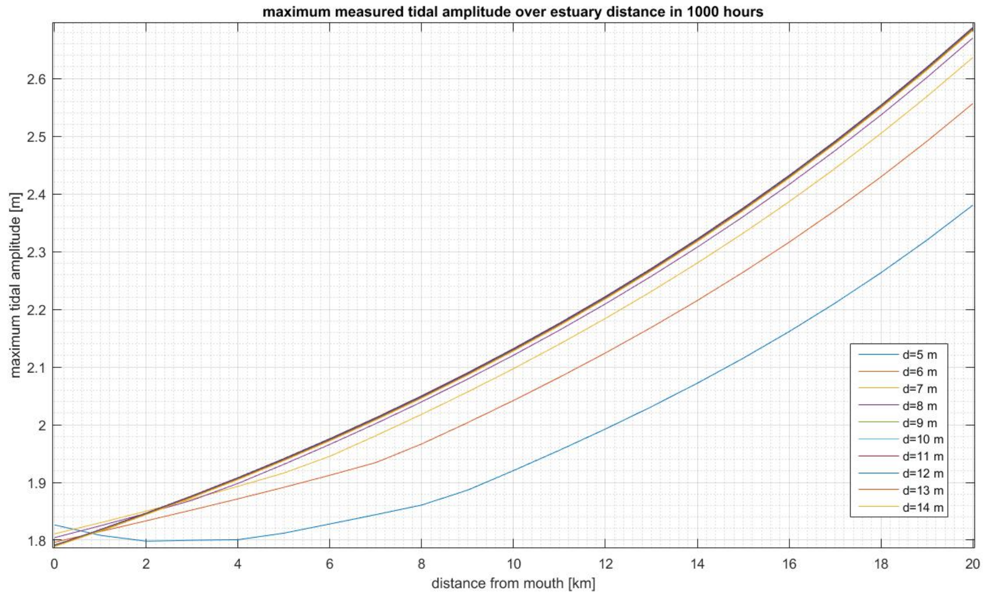


Figure S.6: Maximum tidal amplitude downstream of the closed end as a function of the location of the closed end in the river mouth. In the situation with reflection for different depths.

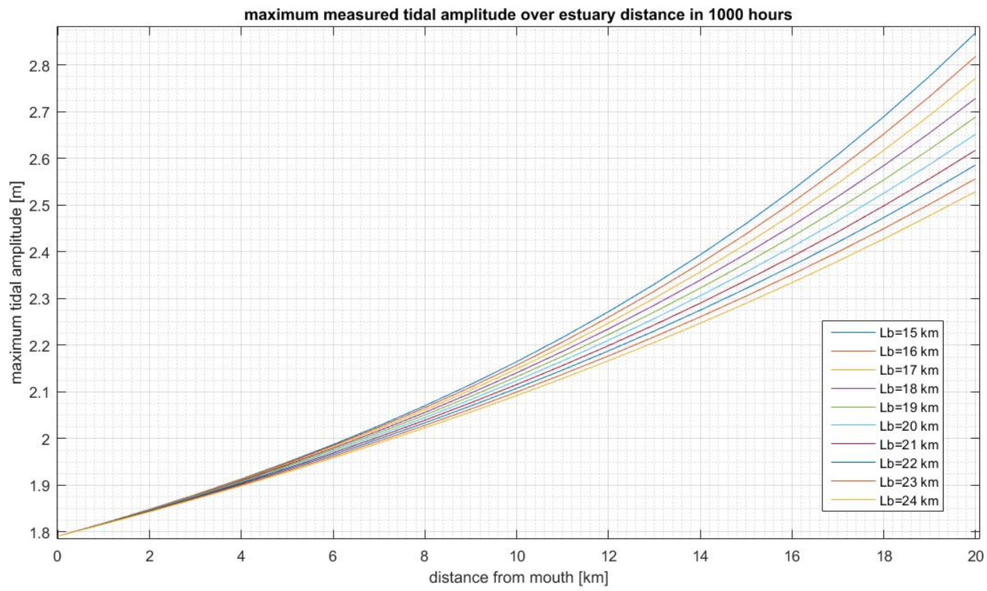


Figure S.7: Maximum tidal amplitude downstream of the closed end as a function of the location of the closed end in the river mouth. In the situation with reflection for different convergence lengths.

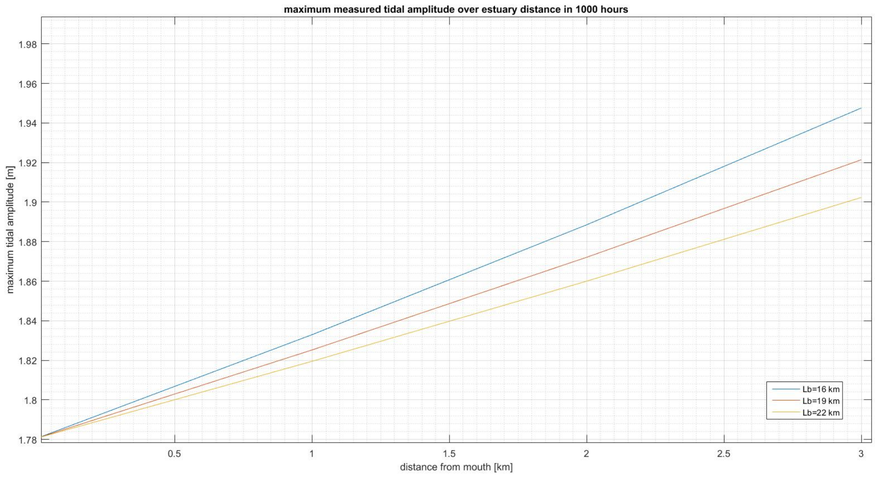


Figure S.8: The maximum tidal amplitude in the mouth when the salinity barrier is situated at 3 km from the mouth for three different convergence lengths.

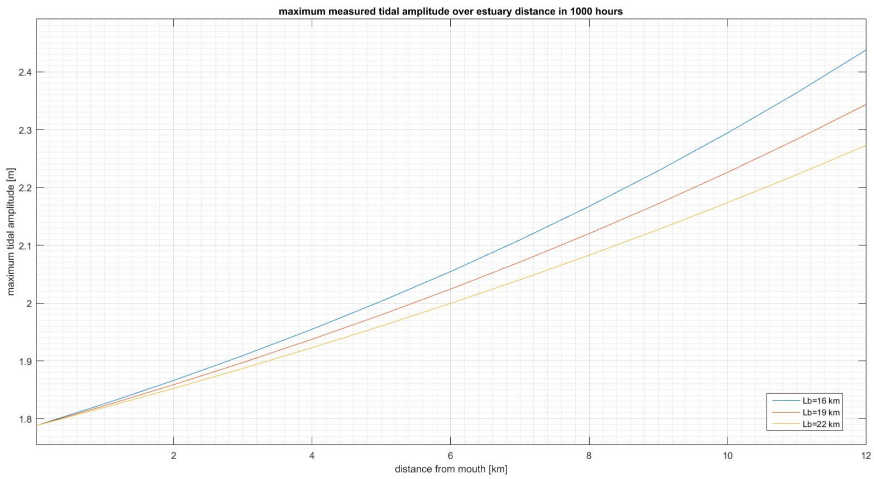


Figure S.9: The maximum tidal amplitude in the mouth when the salinity barrier is situated at 12 km from the mouth for three different convergence lengths.

T

Salt intrusion model

In order to see whether the solutions that are suitable for salt intrusion and to obtain order estimates of the reduction in salt reduction different models are used. In this report an analytical model on salt intrusion will be explained. The theory behind the model has been used in the preliminary studies in the search for design alternatives. Further in the project the model has been built and the outcomes are, together with the outcomes of the SOBEK RE model (appendix U), the proof of the effectiveness of the different solutions.

The model has been built to obtain rough estimates of the salt intrusion after changes in the lay out of the basin and changes in tidal amplitude. The model has been built based on the findings in the book Salinity and Tides (Savenije, 2012), this book is the main source for this appendix. In the book the Tha Chin river is also used as one of the reference cases, the given data has been used to set up the model for the reference case. Although this data has been measured in 1986 and 1987 it is still representative for the current situation in the Tha Chin River. The first part of this appendix deals with the theory and setup of the model, secondly an elaboration on the data is given. In the third section different model parameters are tested with respect to the decrease of the salt intrusion length. Finally some conclusions will be given which are used for testing some of the solutions for the salt intrusion problem in the Tha Chin River.

T.1. Theory

Salt intrusion in estuaries depends on a complex interaction between the tide, freshwater discharge and bathymetry. During a tidal cycle salt water flows in and out with the tide, while the freshwater discharge pushes the salt water back to the sea. The relative strength of tide versus the discharge determines how the salt intrudes, this determines the stratification. When the freshwater discharge is dominant a salt wedge will form at the bottom, in this case the the estuary is stratified and a vertical salinity gradient is present. When the tide is dominant over the freshwater discharge the estuary will be well mixed and the salinity gradient will be in the horizontal. Two dimensionless numbers can serve as indicators for the mixing: the Canter-Cremers number (equation T.1) and the Estuarine Richardson number (equation T.2).

The Canter-Cremers number gives relative volume of the fresh water discharge (Q_f) in a tidal period (T) over the tidal prism (P_t). A value above 1 indicates that the total flood volume during one tidal cycle is large than the tidal prism, thus a discharge dominated system.

$$N = \frac{Q_f T}{P_t} \tag{T.1}$$

The Estuarine Richardson number is the ratio of the potential energy provided by the fresh water discharge as buoyancy and the kinetic energy provided by the tide. This number can give an indication what kind of mixing is present in an estuary.

$$N_R = \frac{\Delta\rho}{\rho_0} \frac{gh}{v^2} \frac{Q_f T}{P_t} \tag{T.2}$$

Where ρ_0 is the fresh water density, $\Delta\rho$ is the density difference between fresh water density and the density at the river mouth, g the gravitation constant, h mean water depth and v the amplitude of the tidal velocity.

While both of these numbers are small an estuary is of the well mixed type and while both these numbers are large the estuary will be stratified. In general the salt intrusion length is longer in a well mixed estuary.

During flood the tide pushes salt water into the estuary, while ebb the salt water flows out again. During a tidal cycle the maximum salinity levels will be reached at high water slack and the lowest levels at low water slack. The salinity in the mouth will be lower in during low water slack since the outflow is diluted with freshwater discharge.

The bathymetry and friction in the estuary determine whether the amplitude of the tide is damped, amplified or constant over the length of the estuary. While the tidal amplitudes are amplified the tide will penetrate further into the estuary, consequently bringing more salt water further upstream. In an ideal estuary the friction, bathymetry and the tide are such that both the horizontal and vertical amplitude of the tide are constant over the estuary length. Most natural estuaries are 'ideal' or in equilibrium. While estuaries are not ideal there will be either erosion or deposition of sediment.

While the bathymetry of the estuary mouth is governed by the hydraulics in the system, in a well mixed the bathymetry can also tell something about the salt intrusion beforehand. In figure T.1 the different types of salt intrusion curves. Type 1 corresponds to a narrow estuary with a long convergence length; Type 2 corresponds to an estuary with a trumpet shape, where the mouth has a short convergence length which changes to a long convergence length further upstream. The Tha Chin is an example of a trumpet shape estuary; Type 3 has a strong convergence over the whole estuary length. The last type only occurs in arid areas.

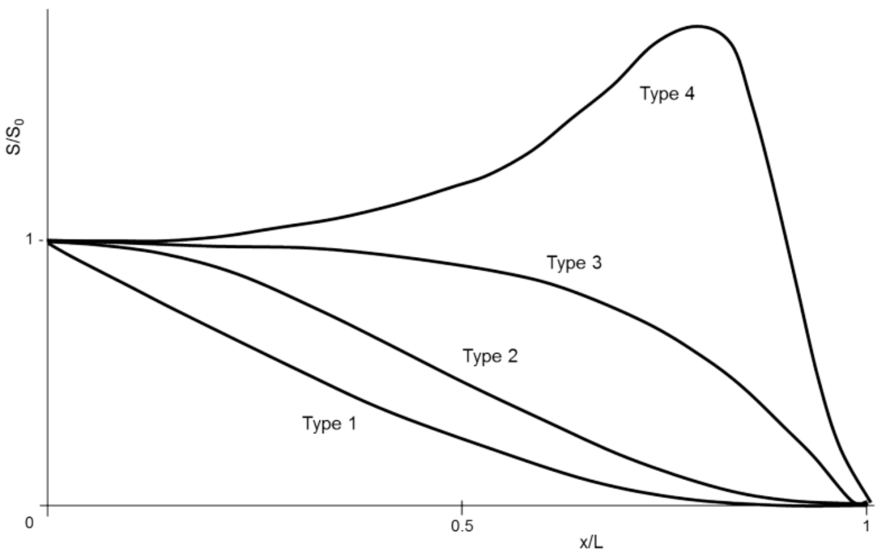


Figure T.1: Different types of salt intrusion curves, corresponding to different geometries. From Salinity and Tides (Savenije, 2012, chapter, p. 18)

Next to tide, freshwater discharge and bathymetry, dispersion is the last and most complex factor in salt intrusion. Dispersion is the result of averaging flow over a certain period, in case of an estuary over the tidal period. The net distance a water parcel has traveled during a tidal cycle, neglecting freshwater discharge, is equal to zero. However, during that tidal period the water parcel has moved along the estuary and back. While moving dissolved tracers can be exchanged with the surrounding water parcels. As long as there is no gradient in concentration the water properties will not change during that exchange, when there is a gradient this exchange tends to smooth the gradient. Because there are changes in concentration during the averaging period which are not accounted for dispersion needs to be added to the equation. A longer averaging period gives a larger dispersion. Also the dispersion depends on the salinity gradient; a larger salinity gradient will give a larger dispersion. Theoretically the value of the dispersion might be calculated by calculating the contribution of different mixing processes; tidal mixing, gravitational circulation and wind. However the contribution and mechanisms still needs to be well understood.

In order to obtain a reasonable value for the dispersion it can be calibrated by using measured salinity curves and relating the dispersion to the change in salinity. Savenije (2012) suggested a relation as shown in equation T.3, where he related the relative change in dispersion to the relative change in salinity to the power of K; the Van der Burgh's coefficient, which is a characteristic of the estuary and can be calibrated.

$$\frac{D}{D_0} = \left(\frac{S}{S_0}\right)^K \tag{T.3}$$

With some mathematical rewriting, using the relation can also be rewritten in:

$$\frac{D}{D_0} = 1 - \beta\left(\exp\left(x/a\right) - 1\right) \tag{T.4}$$

With:

$$\beta = \frac{K a Q_f}{D_0 A_0} \tag{T.5}$$

With: D_0 is the dispersion in the mouth, A_0 is the cross sectional area in the mouth, a is the convergence angle, Q_f the freshwater discharge and K the Van der Burgh's coefficient.

The salt intrusion curve can be calculated when equation T.3, T.4 and T.5. In these equations the only parameters that need to be calibrated are the K D_0. When the dispersion is calibrated on measurements that are taken during high water slack this value can be used to calculate the salt intrusion length at high water slack, which is the furthest point the salt will reach during a tidal cycle. The salt intrusion during low water slack can be calculated by taking the salinity where the distance from the mouth is equal to the tidal excursion in the salt intrusion curve. Next the dispersion in the mouth during low water slack can be calculated, this value is lower than the dispersion during high water slack.

T.2. Data

During four measuring dates in between 1980 and 1990 a salinity profile and geometrical data of the Tha Chin river were measured during high water slack, with the equations mentioned earlier the K and D were calibrated. This data will also be used to do a first check with the model. The geometrical data of the Tha Chin river mouth can be found in table T.1, the trumpet shape can be is represented with two convergence angles; one for the first part at the mouth and one for the upstream part where the channel is more prismatic. The salinity data on which the model is built is given in T.2.

Table T.1: The geometrical data of the Tha Chin. Source: Salinity and Tides, page 139, Savenije (2012)

Date	A_0 (m^2)	a_1 (m)	a_2 (m)	h_{avg} (m)	x_1 (m)
16-04-1981	3000	22000	87000	5.60	22000
27-02-1986	3000	22000	87000	5.60	22000
01-03-1986	3000	22000	87000	5.60	22000
13-08-1987	3000	22000	87000	5.60	22000

A_0 is the cross-sectional area in the mouth, a_1 is the convergence angle for the cross-sectional area in the downstream part of the estuary, a_2 is the convergence angle for the cross-sectional area in the upstream part of the estuary, h_{avg} is the average depth taking floodplains into account and x_1 is the point where the convergence angle changes.

Table T.2: Data for the analytic salinity intrusion model, Source: Salinity and Tides, page 139, Savenije (2012)

Date	T (s)	H_0 (m)	E_0 (km)	Q_f (m^3/s)	S_0 (g/L)	D_0 (m^2/s)	K $(-)$
16/04/1981	86400	1.6	12	55	26	853	0.35
27/02/1986	44400	2.6	20	40	31	600	0.35
01/03/1986	86400	1.8	14	40	34	660	0.35
13/08/1987	44400	2.0	15	39	27	468	0.35

T is the tidal period, H_0 is the tidal range, E_0 is the tidal excursion (vertical tide), Q_f is the freshwater discharge, S_0 is the salinity in the mouth, D_0 is the dispersion in the mouth and K is the Van der Burgh's coefficient. The Tha Chin has a mixed tide, in this data set two sets with a semi diurnal tide and two sets with a diurnal tide.

T.3. Model setup

A small model is built that uses the theory to check whether some of the salt intrusion measures may work in reality. First the model is tested on data of the Tha Chin that is already available, after that some of the model parameters will be changed. Since the Tha Chin river has a trumpet shape the model is slightly more complex as it needs to take two convergence lengths into account. The model assumes a horizontal bed in the estuary, the mean water level over the whole estuary length is constant. The model gives a curve for the area that uses the following equations:

$$A(x) = \begin{cases} A_0 \exp(-x/a_1), & \text{if } x <= x_1 \\ A_1 \exp(-x/a_2), & \text{if } x > x_1 \end{cases} \tag{T.6}$$

A_1 can also be calculated by:

$$A_1 = A_0 \exp(-x_1/a_1) \tag{T.7}$$

For the dispersion a similar scheme is set up:

$$D(x) = \begin{cases} D_0 \left(1 - \beta \left(\exp(x/a_1) - 1\right)\right), & \text{if } x <= x_1 \\ D_1 \left(1 - \beta_1 \left(\exp((x - x1)/a_2) - 1\right)\right), & \text{if } x > x_1 \end{cases} \tag{T.8}$$

β_1 is calculated with equation T.5, where all geometrical values are now at x_1. Also D_1 can be calculated by substituting $x = x_1$ into the first equation of equation T.8. At a certain point D becomes negative, when this happens D needs to become $0m^2/s$. With the calculated D.

Now the salinity at each point can be calculated:

$$S(x) = \begin{cases} S(x) = S_0 \left(\frac{D(x)}{D_0}\right)^{1/K}, & \text{if } x <= x_1 \\ S(x) = S_1 \left(\frac{D(x)}{D_1}\right)^{1/K}, & \text{if } x > x_1 \end{cases} \tag{T.9}$$

The calculated salinity curve depends on the dispersion, in this model there is no feedback from the calculated salinity back to the dispersion. Changes in bathymetry and hydraulics will give changes in dispersion, these changes need to be estimated in order to make estimations about the effectiveness of salt intrusion measures. The salt intrusion curves are calculated for the first 100 km of the estuary.

T.4. Results

This section first gives the results of the reference cases. For the four different data sets. Secondly the results of tests with different dispersion values in the mouth, different discharges and salinity levels in the mouth. The last tests are done by changing the bathymetry in the mouth while keeping the upstream part the same.

T.4.1. Reference case

In this case the values given in table T.1 and T.2 are used to see the different salt intrusion curves. The geometry is given in figure T.2.

The point where the dispersion curves (figure T.3) crosses the x axis is the salt intrusion length. The curves that correspond to salt intrusion during diurnal tide start at a higher dispersion and the salt intrusion length is longer than with the semi diurnal tide. The slopes of the dispersion increases with increasing freshwater discharge. In ht salinity curves (figure T.4) salt intrusion curve on the days with similar fresh water discharge have the same slope, only start on a different salinity level.

T.4.2. The influence of discharge, dispersion and salinity

When the dispersion increases, as a result of increased tidal amplitude or the difference between the semi diurnal and diurnal dominant days, the salt intrusion length increases. Also an increasing fresh water discharge reduces the salt intrusion length significantly. Figure T.5 shows that effect of the increase of the fresh water discharge is larger than the decrease of dispersion. Figures T.6 to T.9 show that the increase of freshwater discharge makes the gradients in x direction, both in dispersion and salinity, larger. Changing only the salinity, as in figures T.10 and T.11

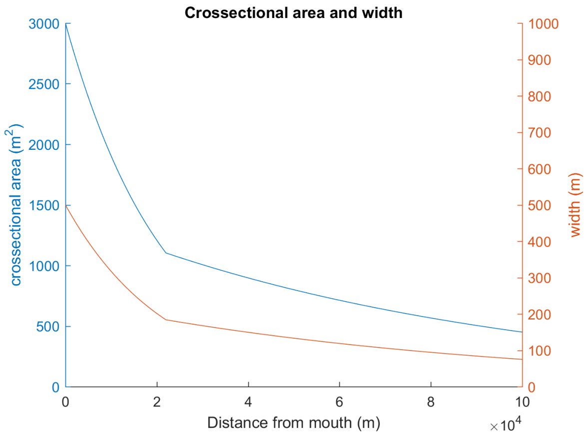


Figure T.2: The convergence of the width and cross-sectional area of the Tha Chin

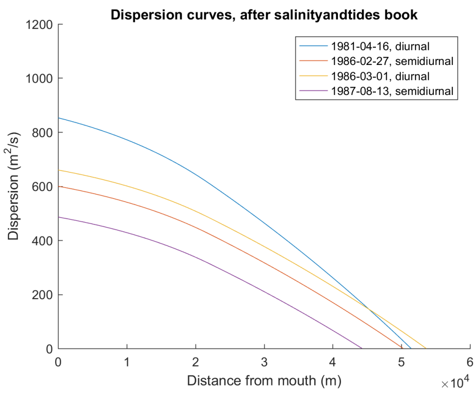


Figure T.3: Dispersion curves for the values as given in tables T.1 and T.2

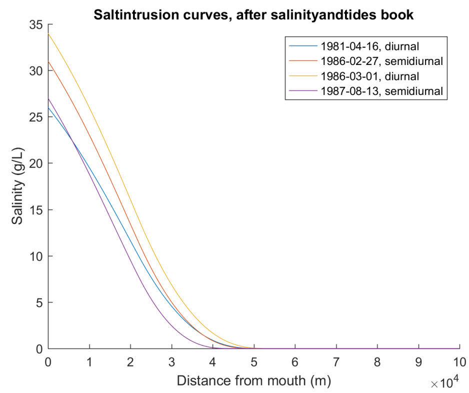


Figure T.4: Salinity curves for the values as given in tables T.1 and T.2

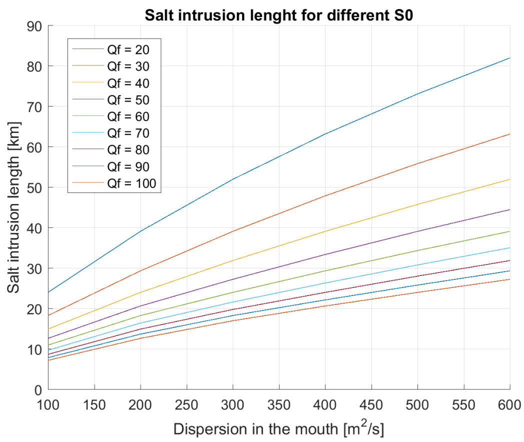


Figure T.5: The Salt intrusion length as function of the dispersion in the mouth (D_0) for different values of freshwater discharge(Q_f)

T.4.3. Changes in the estuary mouth

Changes in the bathymetry also influence the salt intrusion. To analyze the effect first eight different convergence lengths have been tested while the cross-sectional area in the mouth and in the upstream part were kept the same (figure T.12). In the second run the cross-sectional area in the mouth is changed while the cross-sectional area at x_1 is kept constant (figure T.13). The salinity, dispersion and discharge from the reference case are used.

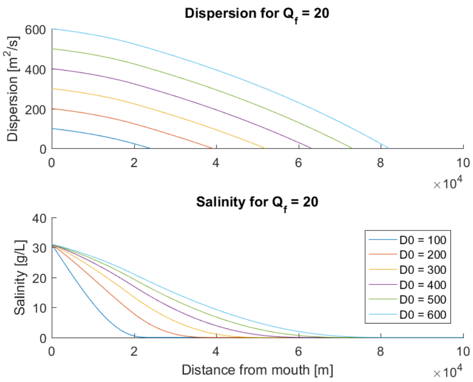


Figure T.6: Dispersion and salinity curves for $Q_f = 20m^3/s$ and different values of D_0

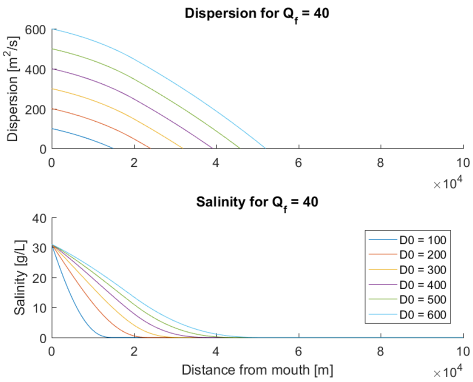


Figure T.7: Dispersion and salinity curves for $Q_f = 40m^3/s$ and different values of D_0

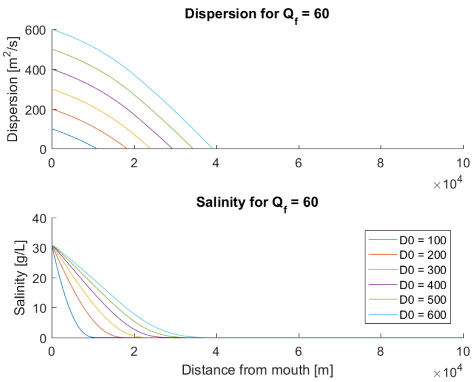


Figure T.8: Dispersion and salinity curves for $Q_f = 60m^3/s$ and different values of D_0

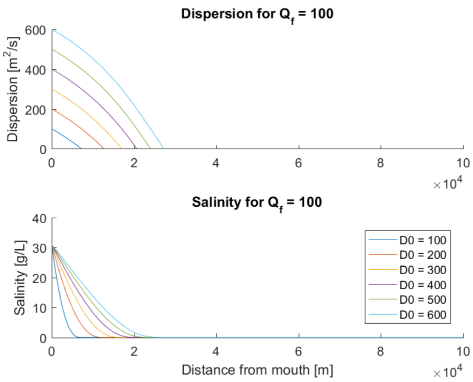


Figure T.9: Dispersion and salinity curves for $Q_f = 100m^3/s$ and different values of D_0

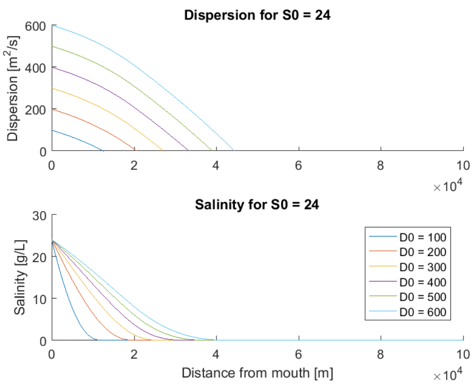


Figure T.10: Dispersion and salinity curves for $S_0 = 24g/L$ and varying values of D_0

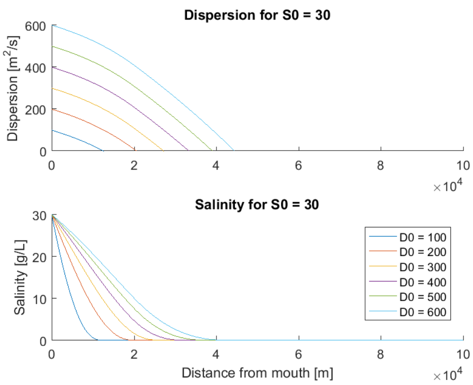


Figure T.11: Dispersion and salinity curves for $S_0 = 30g/L$ and varying values of D_0

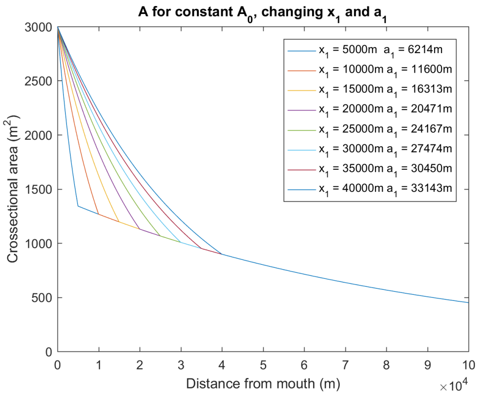


Figure T.12: Profile of the cross sectional area; for a constant cross-sectional area in the mouth, while x_1 and the convergence angle a_1 change.

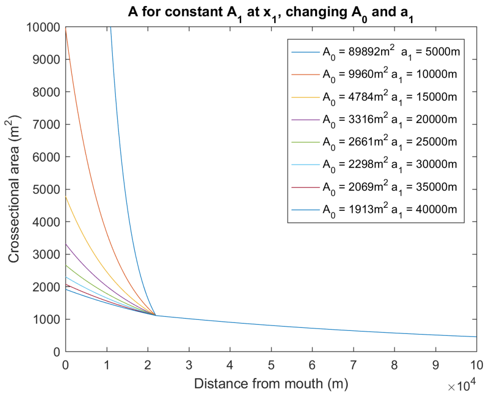


Figure T.13: Profile of the cross sectional area; for a changing cross sectional area in the mouth, while x_1 and the cross sectional area at x_1 are kept constant.

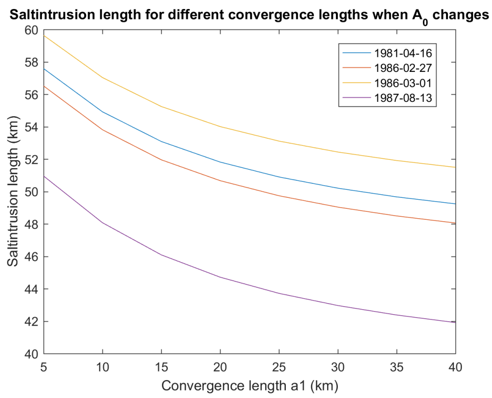


Figure T.14: Salt intrusion lengths for different convergence lengths and a constant cross sectional area in the mouth.

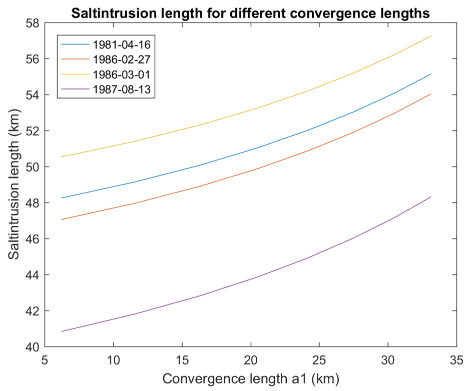


Figure T.15: Salt intrusion lengths for different convergence lengths, a larger convergence length implies a smaller cross sectional area.

Figure T.14 shows the salt intrusion length for different convergence lengths, while the area at the mouth is kept constant. A shorter convergence length will give a smaller salt intrusion length. Figure T.15 appears to show the opposite. However in this figure a smaller convergence length implies a larger cross sectional area in the mouth through which salt water flows into the estuary. The salinity and dispersion curves for the constant cross section in the mouth are shown in figures T.16 to T.23. The same graphs are made for the changing cross section in the mouth, figure T.24 to T.31.

T.5. Conclusions

From the results of the different runs conclusions can be drawn with respect to the reduction of the salt intrusion by the different solutions. Some of the results are promising for the the solutions, but one needs to be cautious with the conclusions. The model is based on some theory and the salt intrusion largely depends on the calibrated K value. Changing bathymetry will also influence this value. Also the dispersion gives additional uncertainty band to the conclusions drawn here.

- Salt intrusion is largely dependent on the dispersion in the mouth. A larger dispersion will give a larger salt intrusion length. The dispersion itself depends on the tidal excursion (and range) and the salinity gradient over the estuary.
- At small fresh water discharges the increase of discharge from upstream will have a significant impact on the salt intrusion length.
- When the convergence length in the mouth decreases while the cross-sectional area in the mouth stays constant the salt intrusion length will decrease. The salt intrusion length might decrease up to 5%,

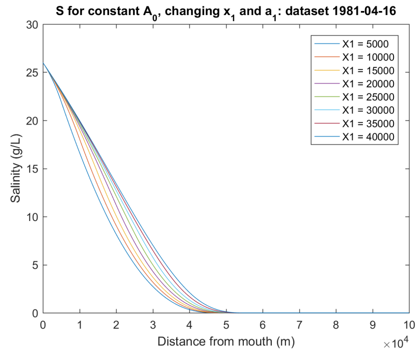


Figure T.16: Salinity curve, A_0 is constant, x_1 and a_1 vary for the data of 1981-04-16

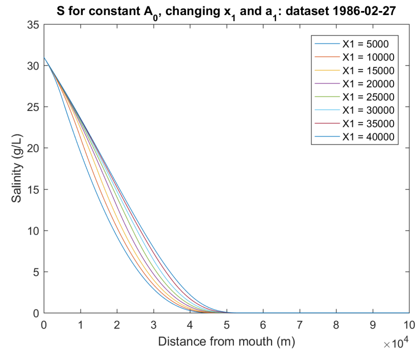


Figure T.17: Salinity curve, A_0 is constant, x_1 and a_1 vary for the data of 1986-02-27

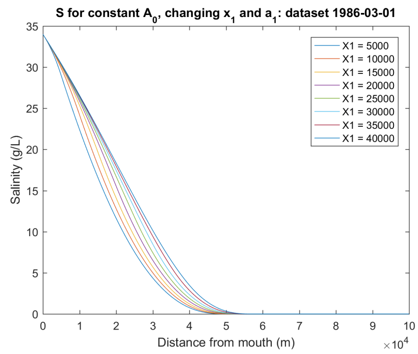


Figure T.18: Salinity curve, A_0 is constant, x_1 and a_1 vary for the data of 1981-03-01

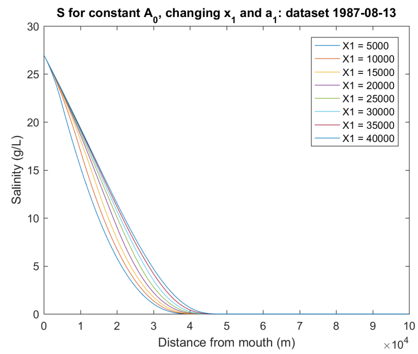


Figure T.19: Salinity curve, A_0 is constant, x_1 and a_1 vary for the data of 1987-08-13

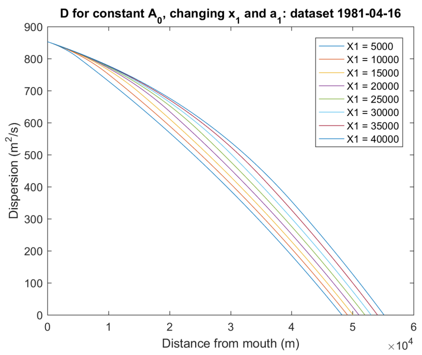


Figure T.20: Dispersion curve, A_0 is constant, x_1 and a_1 vary for the data of 1981-04-16

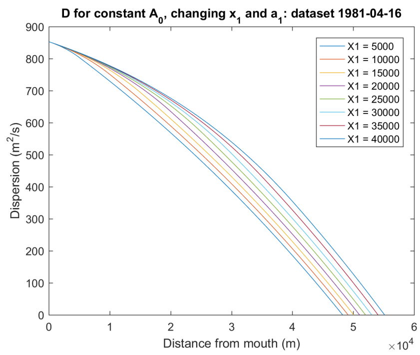


Figure T.21: Dispersion curve, A_0 is constant, x_1 and a_1 vary for the data of 1986-02-27

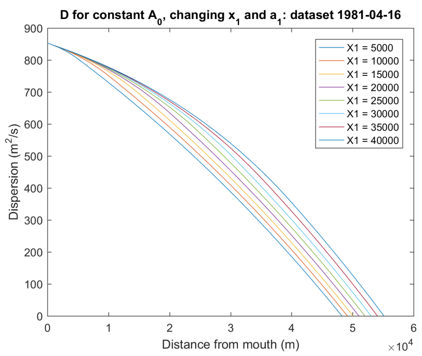


Figure T.22: Dispersion curve, A_0 is constant, x_1 and a_1 vary for the data of 1981-03-01

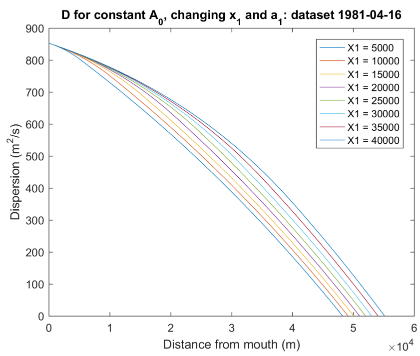


Figure T.23: Dispersion curve, A_0 is constant, x_1 and a_1 vary for the data of 1987-08-13

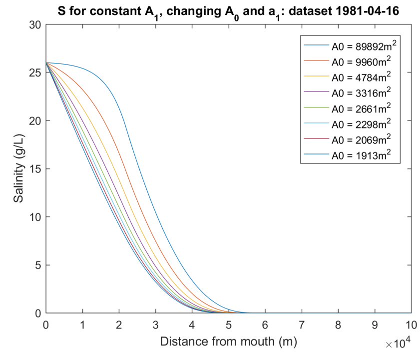


Figure T.24: Salinity curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1981-04-16

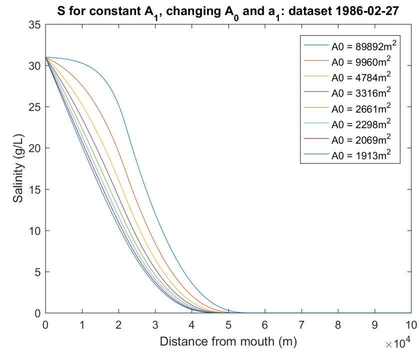


Figure T.25: Salinity curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1986-02-27

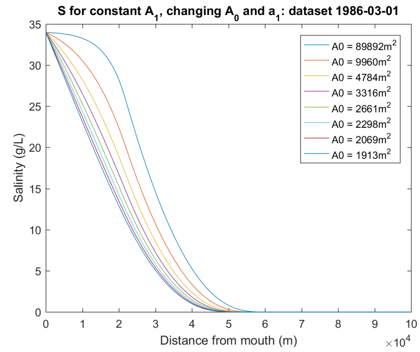


Figure T.26: Salinity curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1981-03-01

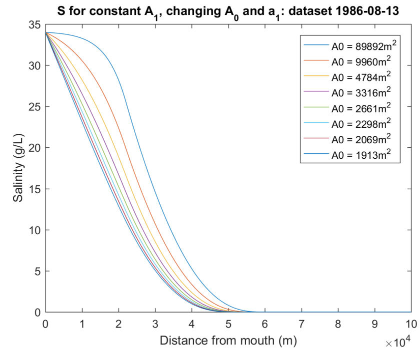


Figure T.27: Salinity curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1987-08-13

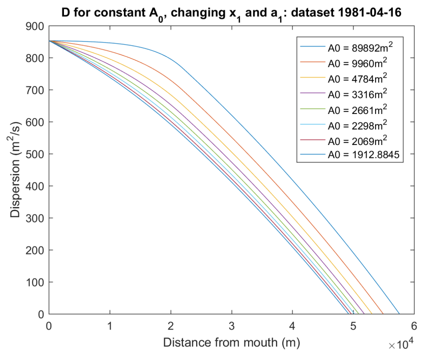


Figure T.28: Dispersion curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1981-04-16

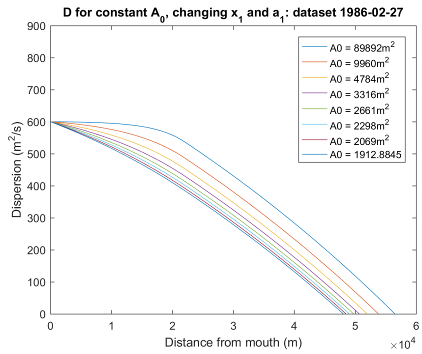


Figure T.29: Dispersion curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1986-02-27

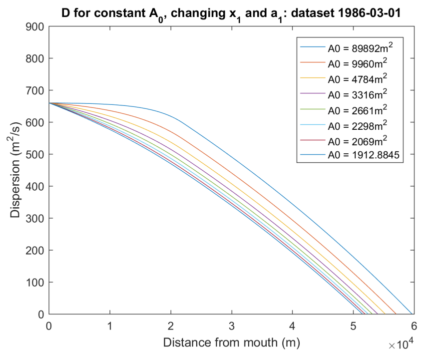


Figure T.30: Dispersion curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1981-03-01

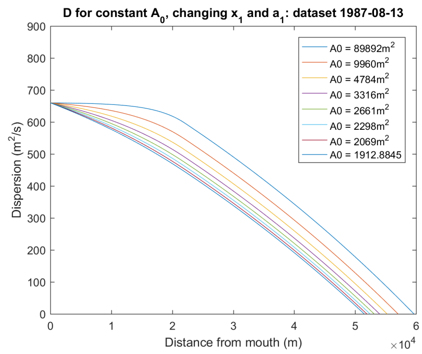


Figure T.31: Dispersion curve, A_1 and x_1 are constant, A_0 and a_1 vary for the data of 1987-08-13 which is not sufficient in case of severe salinity problems in the upstream areas.

- While the cross-sectional area in the mouth increases the salt intrusion will increase. While solving salt intrusion problems the cross-sectional area in the mouth should not increase.

U

SOBEK-RE

In order to test the different solutions on the effect on salt intrusion and the hydraulics a numerical model has been used. The numerical model is complementary to the analytical models treated in appendix T and S, the results of the numerical and analytical models serve as proof for the efficiency of the solutions. The chosen model is SOBEK-RE, an one-dimensional time dependent model. SOBEK-RE is the original version of the SOBEK suite and specifically developed for Rivers and Estuaries. This model was chosen because it has a salt intrusion module and the project group already had experience with the model.

In this report first the basics of SOBEK-RE are explained. In the second section discusses the input data for the Tha Chin and the calibration process. The last section elaborates on the results of the principles of the solutions to reduce the salt intrusion. The tested principles are the effect of the Balance Islands, partly blocking the bay and the effect of a gate.

U.1. Introduction

SOBEK solves the one-dimensional mass-balance and momentum-balance equations for water motion. When there are no density differences those are as follows (Deltares, 2012a):

$$\frac{\partial A_t}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{U.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\alpha_B \frac{Q^2}{A_f} + gA_f\frac{\partial h}{\partial x}\right) + \frac{gQ|Q|}{C^2RA_f} \tag{U.2}$$

Where: Q is the discharge in m^3/s, t is the time in s, x is the distance in m, α_B is the Boussinesq coefficient, A_f flow area. in m^2, A_t is the total cross section in m^2, g is the gravitational acceleration in m/s^2, h is the water level in m, C is the Chézy coefficient in $m^{1/2}/s$, R is the hydraulic radius in m and W is the flow width in m.

When salt intrusion is included, the equations without density difference are no longer valid, because the salinity of the water affects the density and density gradients. The advection-diffusion equation for the salinity (equation U.3) has to be added, so density gradients can be calculated and included in the water flow module. The flow and salt intrusion are calculated separately and are coupled with a feedback loop. The flow field that is computed by the flow model is used in the advection-diffusion equation in the salt module, therefore the modules are coupled by the the density and the flow field (Deltares, 2012b).

$$\frac{\partial A_t c_S}{\partial t} + \frac{\partial}{\partial x}\left(Qc_S - A_f D\frac{\partial c_S}{\partial x}\right) = S_S \tag{U.3}$$

Where c_S is the salt concentration in kg/m^3, D is the dispersion coefficient in m^2/s, S_S is the source term for salinity in kg/ms. The advection-diffusion equation calculates the salinity in each grid point at every time step. The flow model has density as input variable, therefore the salinity needs to be translated into water density. SOBEK-RE calculates density of water with the Eckert formula which relates the density to the salinity (c_{sa}) and water temperature (T_w). In the models used in this report a constant water temperature is assumed.

SOBEK-RE has two modules, one for rivers and one for estuaries. In this report the estuary module is used. This module calculates the flow and the salinity through an explicit scheme. This implies that no restrictions on the time and space step are needed in order to have a numerically stable model. However both these values may not be too large in order to be able to calculate the tide properly. In the model some parameters need to be calibrated. Since the bathymetry and the up- and downstream boundaries are known, the friction in the channel and the dispersion for the salt intrusion need to be calibrated in order to obtain a good reference model.

U.2. Input data

The length of the river section that is modelled in SOBEK RE is 250 km, with 0 km at the river mouth and 250 km at the upstream point. From 3 km up to 125 km from the mouth 40 cross sections were provided by the RID, more upstream a constant cross section is used that is derived from Google Earth, width measurements and a depth profile from (RID, 2011), this was almost the same as the last cross section at 125 km. Also the first 3 km of the mouth were estimated by using the known cross sections and width estimations from Google Earth. The most downstream reach is most important for the intrusion of the tide and salinity into the river mouth. In this reach there is (almost) no slope in the bed level, in the upstream reach the slope is around $10^{-}4$, this can be seen in figure D.6 in appendix D.

At the downstream boundary a water level was implemented. These water levels were provided by the RID from 01-01-2009 until 31-07-2014 and were measured in the river mouth and represent the tidal forcing of the system, figures of the measured water levels can be found in appendix G. For the tide and salinity predictions in 2015, a dry year, the downstream tidal data from 2013 and 2014 were used. At the downstream boundary a constant salinity of 31 g/L was used, this is the sea salinity. To account for the freshwater discharge a Thatcher-Harleman time lag was implemented, the duration of the time lag is half a tidal period.

At the upstream boundary the discharge data provided by the RID was used (appendix G). For the calibration of the friction only the discharges from 2009 until 2014 were used. For the calibration of the salinity also the discharges of 2015 were included since this was an extremely dry year. The measured discharges come from the Pho Praya dam and the Song Phi Nong dam which are the main dischargers in the Tha Chin, however along the river there are more points where the discharge is influenced so there is some uncertainty around the used values, they might be a little too high or lower. The salinity at the upstream boundary is 0 g/L.

For the initial conditions water depths were used at 0, 100 and 250 km. The depths are 9, 9 and 6 meters respectively. The initial discharge was 40 m^3/s. For the numerical computation time steps of 1 of 2 hours were taken next to a grid size of 100 m. The times step differences for some of computations. The calibration of the hydrodynamics is done with a time step of 1 hours. This relative short time step is time-consuming but the comparison to the measured water levels which is measured hourly is made easier. The calibration of salt intrusion is performed with a time step of 2 hours. This is because this needs less time and the accuracy of the measured salinity is not very high so a more accurate model is not feasible.

The initial salinity curve that was implemented is a linearly decreasing salinity, with the sea salinity in the mouth and zero at 37 km upstream from the mouth. Those values are determined with the known salinity in the river in combination with the output of the analytical model.

U.3. Calibration

In order to make a model that is representative for the real river some of the parameters need to be calibrated on the measured data.

U.3.1. Discharge

The water levels of measurement station T13, around 145 km upstream (appendix G), are mostly dependent on the discharge from upstream. If the water levels of this station are similar to the outcome of SOBEK, it can be concluded that the discharges implemented in SOBEK comply reasonably well with reality. At some points there are differences between the modelled and measured water levels, this can be explained in two ways. First the highest water level peaks in SOBEK are higher than in the measured data. This may be due to the floods that occur during high discharge, SOBEK does not takes this into account. After those high peaks the water level in SOBEK is also slightly higher than in the measured data, this can be explained by the fact that it takes time to transport all the water during high discharge to the river mouth. During the peak discharges the water flows through the channel as well as over the floodplains and sometimes outside of the river banks. The second explanation is that the measured discharge is data from more upstream. From that point to our area of interest it is possible that more water is distracted from or discharged to the river, this means that the discharge in our area of interest in reality is deviates from the modelled discharge. Figure U.1 gives the measured and modelled water levels at T13 for the best model parameters.

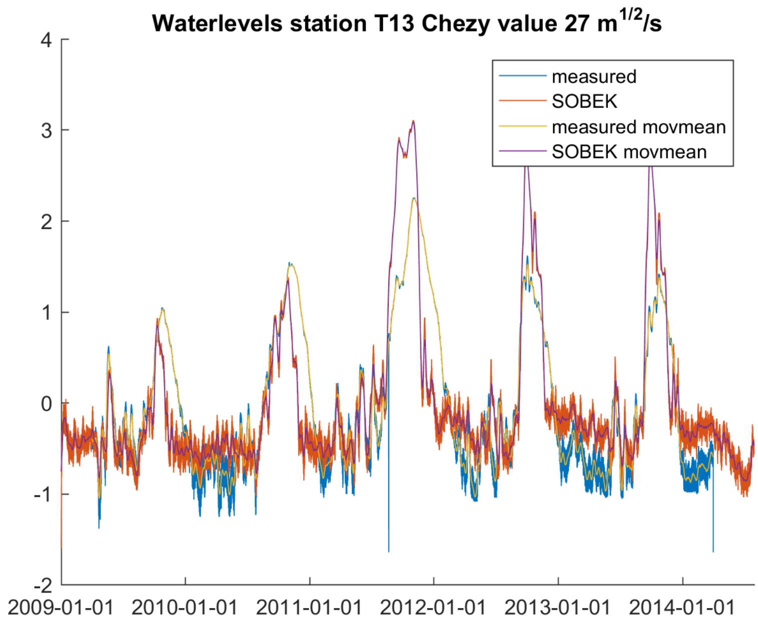


Figure U.1: Measured and Modelled water levels in station T13 for the best parameter set.

U.3.2. Chezy

The Chezy value is the governing parameter that has to be calibrated in order to obtain the best performing hydrodynamics in the model. The Chezy value is calibrated on the water level data of the measuring stations T1, T14 and T13, which are located 88, 58, 145 km from the mouth respectively.

From literature the upper and lower bounds for the Chezy value have been estimated. Savenije (2011) has given a Chezy value of 45 $m^{1/2}/s$. The highest manning factor for a meandering river, n=0.06, gives with an average depth of 6 m a Chezy value of 20 $m^{1/2}/s$. The calibration runs in SOBEK are done with values in this range. The Chezy value is kept constant over the whole river since not enough data is available to validate varying value. Runs have been done for Chezy values of 10, 20, 25, 30 and 45 $m^{1/2}/s$. After a first analysis of the results it was found that the values of 30 and 25 $m^{1/2}/s$ performed best, while for the values of 10 and 45 $m^{1/2}/s$ the model was off. Thus also a value between these values, C=27 $m^{1/2}/s$, has been analyzed.

The performance of the different Chezy values is related to the correlation and the absolute difference between the measured values and the calculated values. The closer the correlation factor is to one the better the performance. When the difference between the measured value and the calculated value is close to zero the model is performing better. The correlation is calculated for the whole dataset, the water levels and the tidal amplitude at each measuring station. This in order to check the influence of the tide and the mean flow separately. Water levels are calculated by taking the running average over 7 days at every time step. The amplitudes are calculated by subtracting that running mean from the total dataset. The results of the different Chezy values per station are shown in table U.1 and figures U.2, U.3 and U.4. The Chezy value of 27 $m^{1/2}/s$ turns out to perform best in the lower part of the estuary. Because we are interested in the salt intrusion in this part and not enough data is available to validate combinations of different Chezy values for the upstream and downstream parts of the river, this value is applied on the whole reach. See figure U.5 and U.6 for the water levels at station T14 and T1 for the best performing Chézy value.

Table U.1: Correlation factors for different Chézy coefficients.

station	Chezy [m^0.5/s]	10	20	25	27	30	35	45	2735
T14	total	0.6368	0.8551	0.8829	0.8848	0.8843	0.8723	0.8414	0.8863
	water level	0.8808	0.8717	0.8618	0.8573	0.8541	0.8394	0.8051	0.8530
	amplitude	0.4943	0.8575	0.9018	0.9115	0.9212	0.9266	0.9216	0.9154
T1	total	0.8050	0.8139	0.8044	0.7947	0.7748	0.7257	0.6146	0.7861
	water level	0.8518	0.8211	0.8132	0.8110	0.8092	0.8017	0.7801	0.8051
	amplitude	0.3999	0.8014	0.8014	0.7922	0.7726	0.7364	0.6652	0.7818
T13	total	0.8509	0.7912	0.7766	0.7729	0.7696	0.7642	0.7499	0.7679
	water level	0.8597	0.7981	0.7828	0.7792	0.7764	0.7738	0.7750	0.7756
	amplitude	0.0094	0.3366	0.4903	0.5202	0.5605	0.5896	0.5853	0.5600

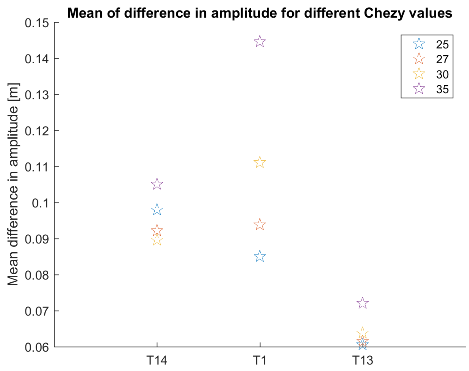


Figure U.2: Absolute difference between the measured and modelled amplitude for different Chezy values.

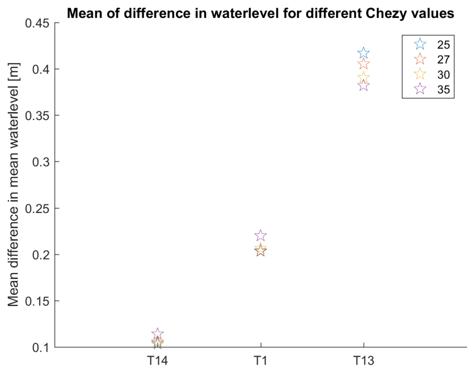


Figure U.3: Absolute difference between the measured and modelled mean water level for different Chezy values.

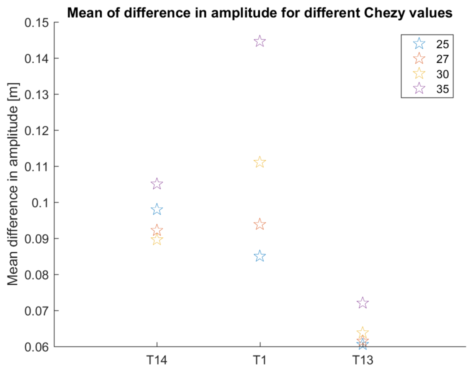


Figure U.4: Absolute difference between the measured and modelled total water level for different Chezy values

U.3.3. Dispersion

For the salt intrusion the dispersion coefficient is the main parameter that influences the salt intrusion length and the concentrations at the different places. In order to predict the influence of different measures on the salt intrusion length this parameter must be calibrated. SOBEK-RE has 4 options to calculate the dispersion coefficient: a spatial or time dependent constant distribution, a linear dependency on the concentration gradient, the Thatcher-Harleman dispersion formula and an empirical dispersion formula. The first option only has 1 parameter to calibrate, the second has two and the last two have 3. Since the measured data set has salinity measurements only during the dry season and a couple of days per month calibrating the model has to be done with little information. For accuracy reasons a constant the dispersion coefficient was tested first. Starting from a dispersion coefficient of 100 m^2/s (lowest possible) and going up with 50 m^2/s each run we obtained a dispersion coefficient of D = 150 m^2/s that performed best, however for the lowest low flows the salt intrusion was a little too low. With a D = 200m^2/s, that could be solved, however this value gave too

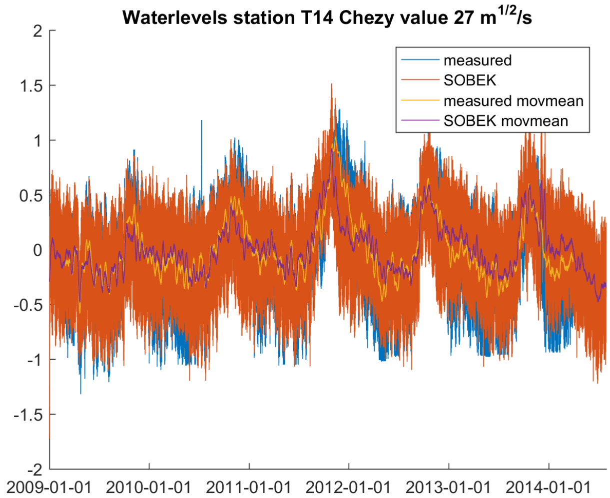


Figure U.5: The measured and modelled water levels at station T14 for the best performing Chézy value, C=27 $m^{1/2}/s$.

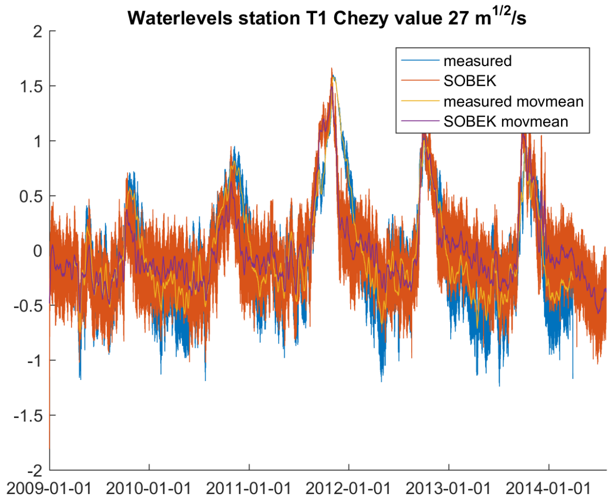


Figure U.6: The measured and modelled water levels at station T14 for the best performing Chézy value, C=27 $m^{1/2}/s$.

large salinity intrusion during high flows.

We also tested the second option for modelling the dispersion coefficient. In that case two coefficients need to be calibrated: f1 and f2. f1 is the background dispersion and f2 is the factor that takes the salinity gradient into the dispersion (equationU.4).

$$D = f_1 + f_2 |\frac{\delta c}{\delta x}| \tag{U.4}$$

In table U.2 the tested combinations of f1 and f2 can be found. The value of the coefficients is chosen based on the best visual fit to the measured data. The background dispersion needs to have a value in order for SOBEK RE to be able to start the calculations. While f2 needs to be large in order to be give the salinity gradient a significant influence on the dispersion. For f1 = 100 and f2 = 50000 the model performs similar to D= 150, higher and lower f2 perform worse.

Figures U.7 to U.12 give the salt intrusion during low flow conditions. Higher dispersion gives an overestimation of the salt intrusion at almost all times. Lower dispersion performs better during high flow but gives a severe underestimation during low flow. Because the time of interest is during the lower flow regimes, the dispersion must perform good during these times. For both D=150 and D=100+ 50000 $\|\frac{\delta c}{\delta x}\|$ the salt intrusion performs equally well, the final value of D is chosen to be D=150 m^2/s.

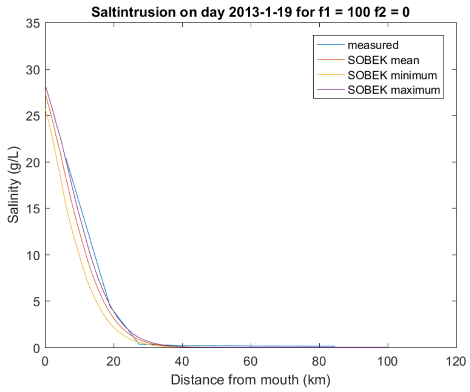


Figure U.7: Salt intrusion on January 19, 2013
for f1 = 100 and f2 0̄

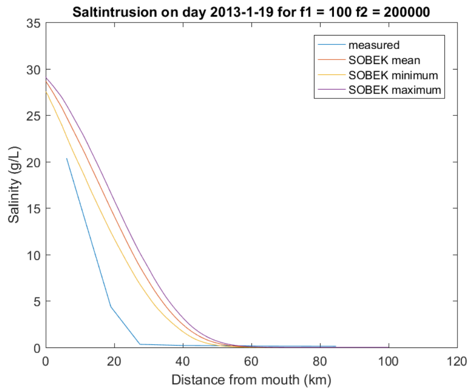


Figure U.8: Salt intrusion on January 19, 2013
for f1 = 100 and f2 = 20000

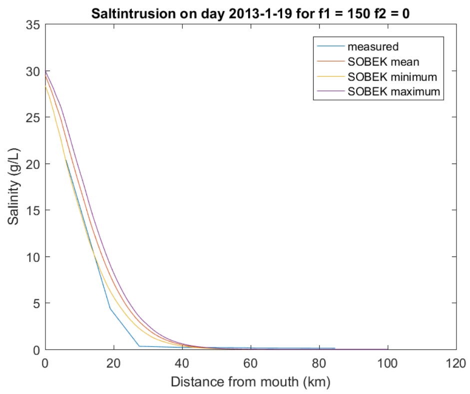


Figure U.9: Salt intrusion on January 19, 2013
for f1 = 150 and f2 = 0

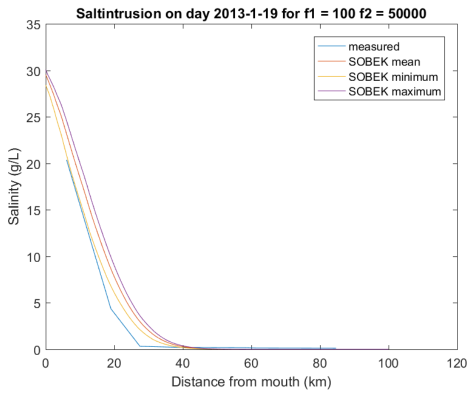


Figure U.10: Salt intrusion on January 19, 2013
for f1 = 100 and f2 = 50000.

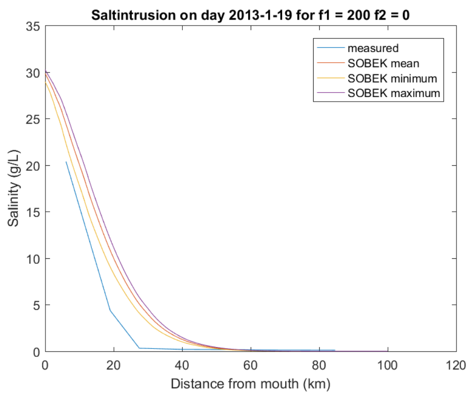


Figure U.11: Salt intrusion on January 19, 2013
for f1 = 200 and f2 = 0

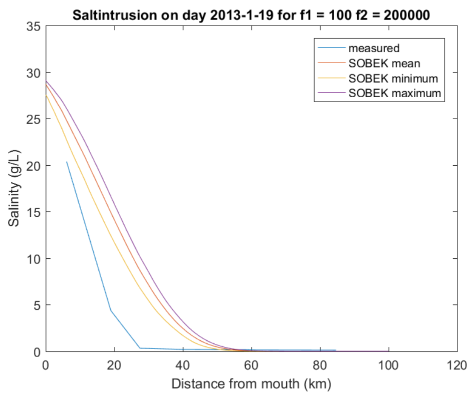


Figure U.12: Salt intrusion on January 19,2013
for f1 = 100 and f2 = 200000

Table U.2: Combinations of f1 and f2 for the calibration of the dispersion.

f1 vs. f2	0 (D const)	20000	50000	100000	200000
100	x	x	**X**	x	x
150	**X**				
200	x				

The found dispersion is quite different than the dispersion used in the analytical model (appendix T). The dispersion is dependent on the timescale of the averaging of the flow. Because the analytical model assumes averaging over the whole tidal period and the SOBEK model averages the flow in the order of the time step, the dispersion in the SOBEK is smaller than in the analytical model.

A note must be made that the dispersion is calibrated on the data from 2012 to 2015, but the simulation time was from 2010 to 2015. The first years have been excluded because of two reasons. First the spin up time of model in the salt module and second the accuracy of the measured data in the first years. A salinity of less than 10 g/L near the mouth in the dry season does not seem realistic.

U.4. Tests of the solutions

With the calibrated models we tested the impact of different solutions in on the salt intrusion length and concentrations. This is done by looking at the first 100 km of the river, because this is the relevant part for the salt intrusion. Two of the proposed salt intrusion reduction measures are based on the theoretical principle that when the tidal amplitude and/or the salinity in the river mouth decrease the salt intrusion also decreases. Different combinations of reduction of the tidal amplitude and the salinity in the mouth are tested. Since dispersion depends on tidal characteristics and the salinity gradient (Savenije, 2012), changing these values will have an effect on the dispersion. Therefore the constant dispersion needs to be adjusted for the new tidal amplitudes and salinity in the mouth. We have tested different combinations of amplitude reduction, salinity reduction and reduction of the dispersion, these can be found in table of runs U.3 .

U.4.1. Changes in tidal amplitude, initial salinity and dispersion

Change in tidal amplitude
In order to test the influence of a change in tidal amplitude on the salt intrusion the tidal forcing was multiplied by 0.5, 0.75, 1.0 and 1.5. So a small reduction and a large reduction and even an increase of tidal amplitude

Change the salinity in the mouth
In the reference model the salinity in the mouth is equal to 30 g/L. In the new cases the salinity in the mouth is reduced to 25 g/L, a medium reduction, and to 20 g/L, a relatively large reduction. These values are chosen to be able to see the effect of a salinity reduction.

Change in Dispersion
The minimum dispersion that SOBEK can run with is 100 m^2/s. Runs are done with values for dispersion between 100, 125,150 and 200 m^2/s. A larger tidal amplitude results in a larger dispersion and a larger salinity gradient gives a larger dispersion.

Combinations
A larger reduction in tidal amplitude will have a stronger effect on the dispersion, so 0.5 is combined with D = 100 m^2/s and 0.7 with D=125 m^2/s. The dispersion is also related to the salinity gradient, a smaller gradient will lead to a lower dispersion . Therefore the dispersion is set on 100 m^2/s and 125 m^2/s when the salinity is respectively 20 g/L and 25 g/L. In addition to those simulations there are also runs performed where only the dispersion or the salinity was changed in order to get a better insight on the influences of those parameters

U.4.2. Changes in the layout of the mouth

A third salt intrusion reduction measure is based on changing the convergence angle near the mouth. In order to be able to do a simulation in SOBEK the model should be changed. The boundary conditions is applied near the mouth, which is the area of interest for this solution. In a numerical model those two should not be at the same place due to the influence of the boundary condition. Therefore this solution cannot be tested in SOBEK with the current settings.

Table U.3: Input values for the different runs to test the effect of the dispersion, tidal amplitude and salinity in the mouth.

Salinity in the mouth [g/l]	Dispersion	Tidal amplification factor
30	100	*0.5
20	100	*0.5
20	150	*0.5
30	125	*0.7
25	125	*0.7
25	150	*0.7
25	150	*1
20	150	*1
25	125	*1
20	100	*1
30	200	*1.5

U.4.3. Salinity barrier

In SOBEK-RE, hydraulic structures can also be modelled with their influence on water levels and flow velocities. To be able to know the effect of a salinity barrier at 12 km upstream of the river, a structure is build at this location in the model. The flow area through this barrier compared to the river cross section is kept the same to avoid any other influences from the barrier. In reality, this will also be a requirement of the final design to minimize environmental impact. SOBEK is run twice with and without a barrier at 12 km to have a good overview of the relative increase in water level over the downstream end.

To analyse the river bank capacity, the maximum river capacity according to the river basin committee (220 m^3/s) has been implemented into SOBEK. The water levels reached at the chosen location of 12 km upstream should fall inside the banks of the river.

The barrier will only be closed during a certain period of a year. To discover when, how often and what the influence is on the salinity, a simulation in SOBEK-RE has been made. Different control systems have been tried to optimize the salinity reduction and closing period.

Control by upstream discharge

First the gate is only controlled by the discharge from upstream. When discharge upstream became too low (to push back the salt), the barrier will be closed. The control script is as follows:

$$\begin{cases} \text{close} & \text{if } Q_{at240km} < Q_{dicht240} \\ \text{open} & \text{if } Q_{at240km} > Q_{dicht240} \end{cases} \tag{U.5}$$

This control scheme is tested for $Q_{dicht240} = 20\ m^3/s$, $Q_{dicht240} = 30\ m^3/s$ and $Q_{dicht,240} = 40\ m^3/s$.

Control by down- and upstream discharge

An additional run is made were closing the gate was also depended on the incoming tide. Which was done by the discharge at 5 km. This is done to reduce closing time when it is possibly not needed that the gate is closed. The control script is as follows:

$$\begin{cases} \text{close} & \text{if } Q_{at240km} < Q_{dicht,240} \;\&\; Q_{at5km} < Q_{dicht,5} \\ \text{open} & \text{if } Q_{at240km} > Q_{dicht,240} \;\&\; Q_{at5km} > Q_{dicht,5} \\ & \text{orif } Q_{at240km} > Q_{dicht,240} \end{cases} \tag{U.6}$$

The first statement makes sure that the gate will be closed when the discharge from upstream is low and the tide propagates into the river. The discharge is not set at zero because it is better if the salinity in front of the gate is already a little bit lower, so when the gate is opened the difference in salinity is smaller. The next statement makes sure the gate opens when the tide propagates out of the river. The last statement will open the gate when the discharge from upstream is high enough. This control scheme has been tested with $Q_{dicht,240} = 30\ m^3/s$ and $Q_{dicht,5} = 50\ m^3/s$, flow directions are taken positive in the downstream direction.

Control by upstream discharge and upstream water level
To control the water level upstream and not let this water pile up upstream of the barrier, another control function was implemented to partially open the gates when the water level became too high. The control script is as follows:

$$\begin{cases} \text{close} & \text{if } Q_{at\,240\,km} < Q_{dicht,240} \;\&\; H_{at\,12.1\,km} < H_{open\,partially,12.1\,km} \\ \text{open} & \text{if } Q_{at\,240\,km} > Q_{dicht,240} \;\&\; H_{at\,12.1\,km} < H_{open\,partially,12.1\,km} \\ \text{open gate 1 m above bed level} & \text{if } Q_{at\,240\,km} > Q_{dicht,240} \;\&\; H_{at\,12.1\,km} > H_{open\,partially,12.1\,km} \\ & \text{orif} Q_{at\,240\,km} < Q_{dicht,240} \;\&\; H_{at\,12.1\,km} > H_{open\,partially} \end{cases} \tag{U.7}$$

This control scheme has been tested with $Q_{dicht,240} = 30\ m^3/s$ and $H_{open\,partially,12.1\,km} = 2\ m$

Weir
At last a simple weir with a varying crest level was put to the test. In this case only the crest level could be adjusted and this crest height had a minimum height of 5 m above the bed (MSL -4 m) in the model. Adjusting the crest level to MSL + 2 m to close the weir when the discharge is too low, it could be ensured a higher water level than MSL + 2m could not be reached. In this way, the weir would overflow at the right moment not letting saline water in but letting fresh water out.

U.5. Results and conclusions

In this section all the results of the different runs will be discussed and conclusions regarding those results will be drawn.

U.5.1. Changes in Tidal amplitude, initial salinity and dispersion

Figures U.13 till U.24 show the results of the changed tidal amplitude, salinity in the mouth and dispersion. From these figures the following can be concluded:

- Reducing the tidal amplitude has only a small effect on the reduction of the salt intrusion length.
- Every reduction works the best for the wet season in relative change in salinity.
- In all runs the the line the intrusion length is shifted in its entirety with an almost constant. distance. The absolute change in intrusion length is almost equal at all times.
- D0 has the biggest influence in reduction of the intrusion length.
- Even in the best case the threshold of 2 g/L at 30 km is exceeded. But less often and for a shorter period than in current situation.
- The best case has a reduction of 30 to 40 % in intrusion length.
- Because the model uses a constant dispersion over the whole reach the salinity in the upstream parts has a small overestimation, resulting in larger intrusion lengths for the 0.01 g/L line.

U.5.2. Changes in the layout of the mouth

Since this solution could not be tested, no conclusion on the effectiveness of salt intrusion reduction can be drawn.

U.5.3. Salinity barrier

To relate the effect of the barrier on the hydraulics to the initial situation the tidal amplitude and the water levels in the situation without the barrier are shown in U.25 and U.26.

As can be seen in figure U.25, he relative increase is 7% and equals 12 cm which results in a water level of MSL +1.92 . The minimum water level is deviating more with 13% equal to 22 cm which results in a minimum water level of MSL –1.92 m. Figure U.26 a time plot is made of the water levels at 12 km upstream. The maximum water level reached is assumed to be the river bank capacity. This resulted in a maximum water level at 12 km of MSL + 1.95 m

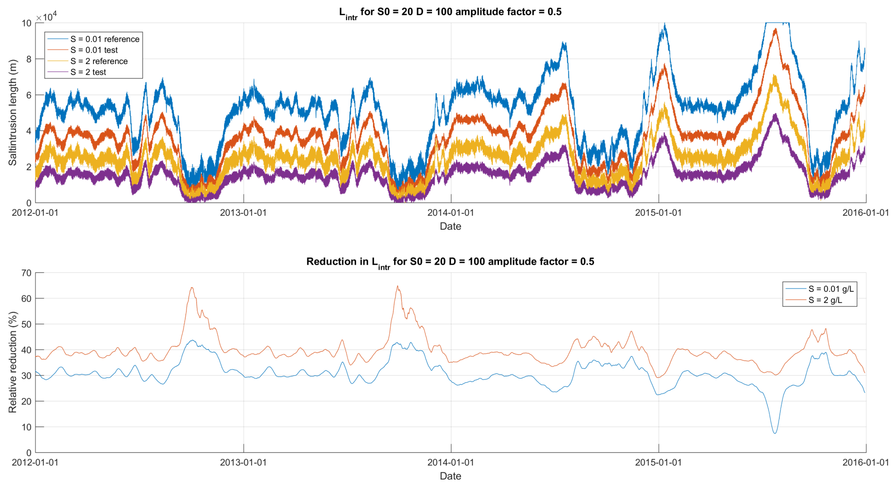


Figure U.13: The salt intrusion length and the intrusion length of 2 g/L

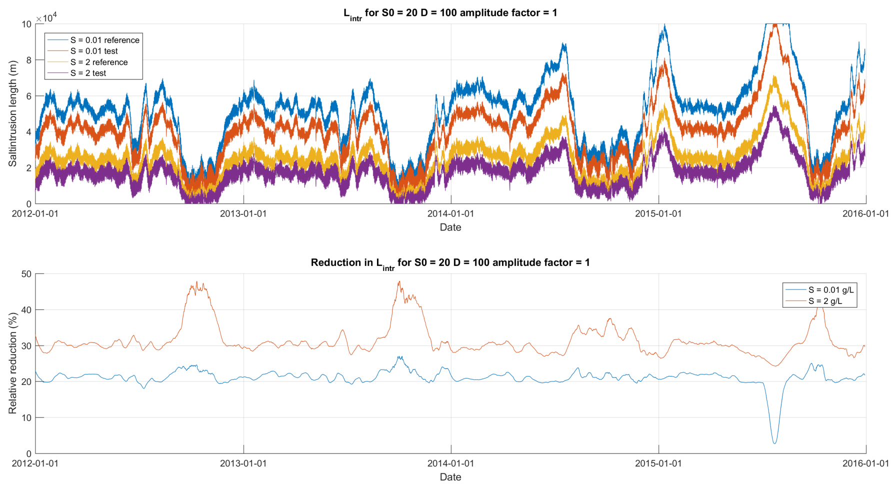


Figure U.14: The salt intrusion length and the intrusion length of 2 g/L

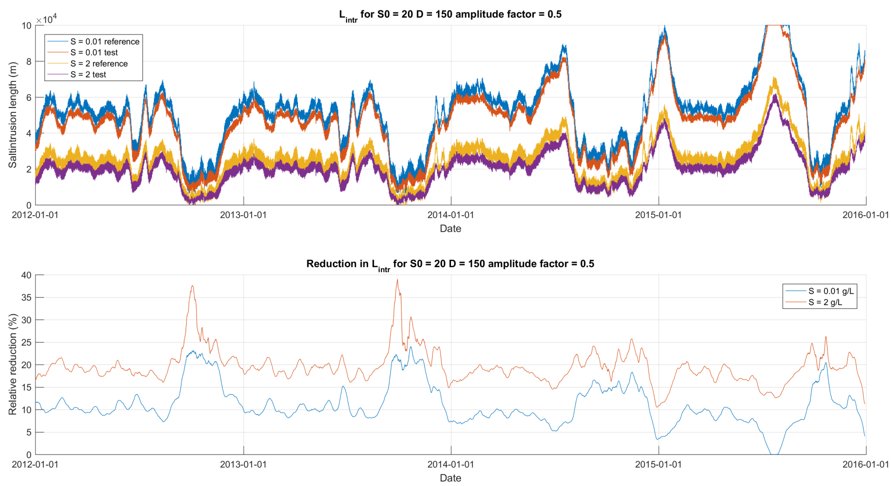


Figure U.15: The salt intrusion length and the intrusion length of 2 g/L for

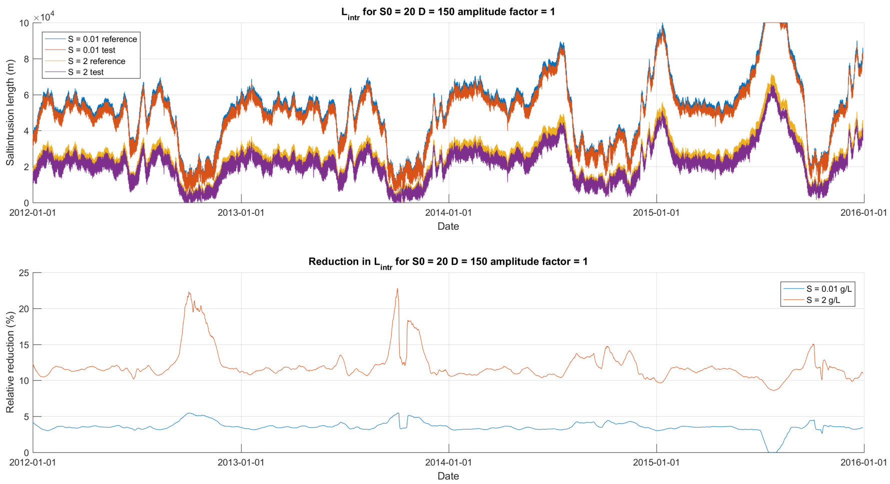


Figure U.16: The salt intrusion length and the intrusion length of 2 g/L for

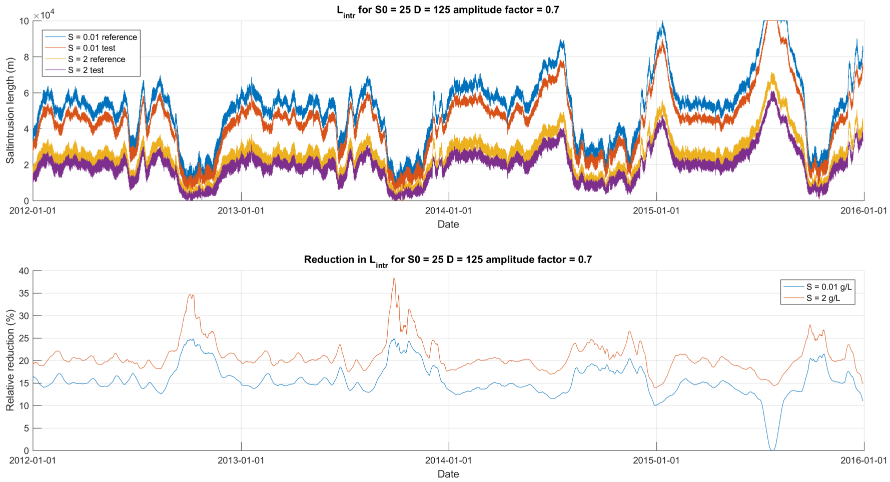


Figure U.17: The salt intrusion length and the intrusion length of 2 g/L for

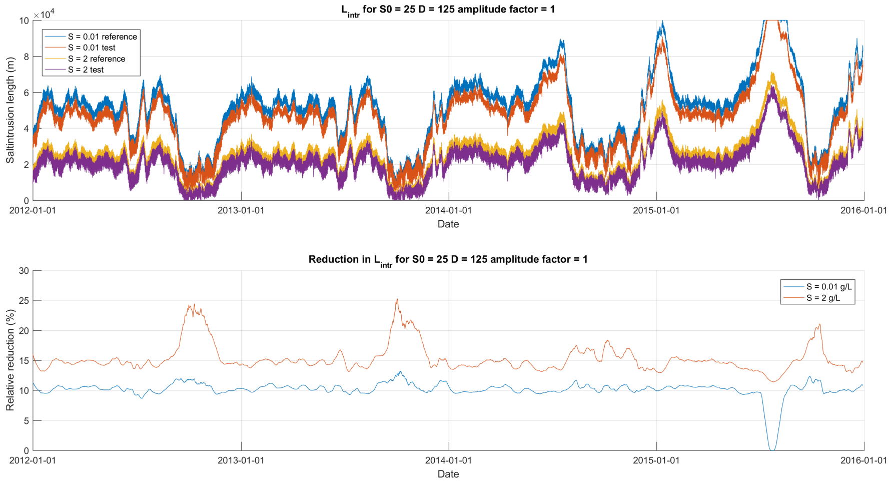


Figure U.18: The salt intrusion length and the intrusion length of 2 g/L for

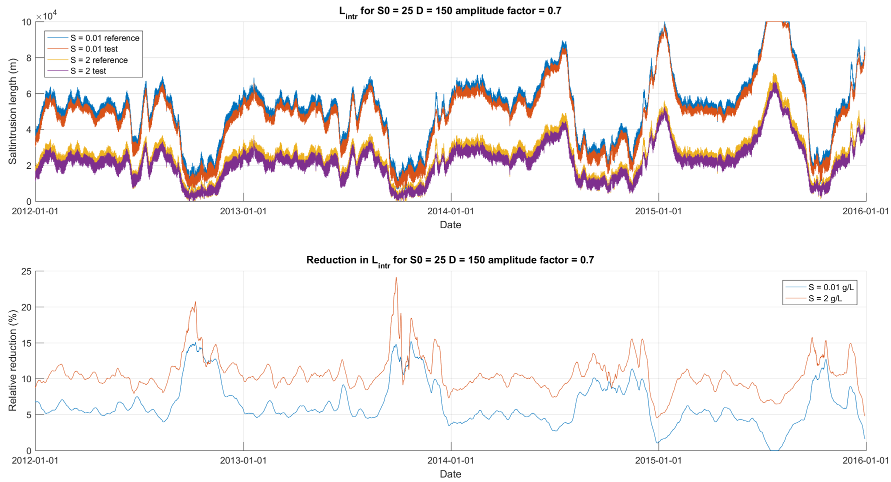


Figure U.19: The salt intrusion length and the intrusion length of 2 g/L for

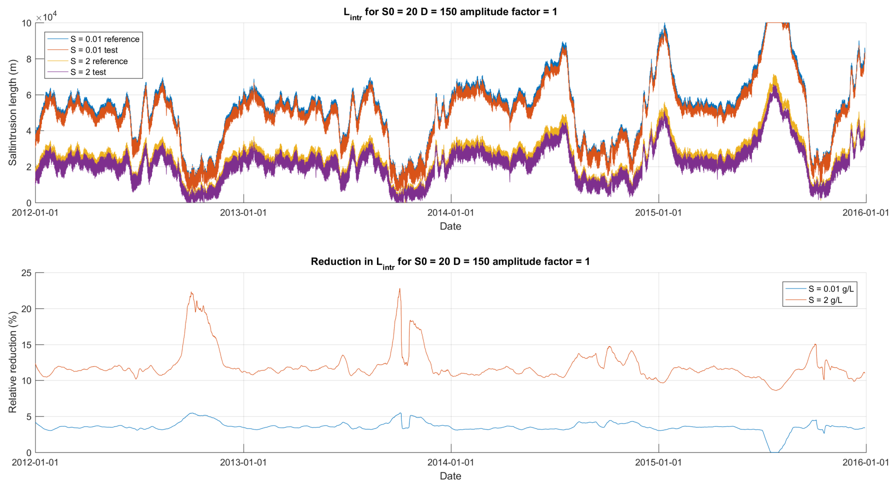


Figure U.20: The salt intrusion length and the intrusion length of 2 g/L for

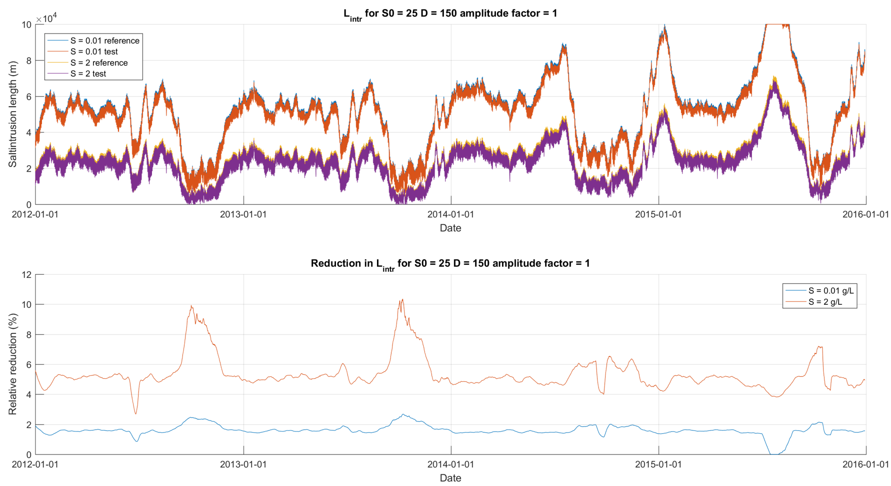


Figure U.21: The salt intrusion length and the intrusion length of 2 g/L for

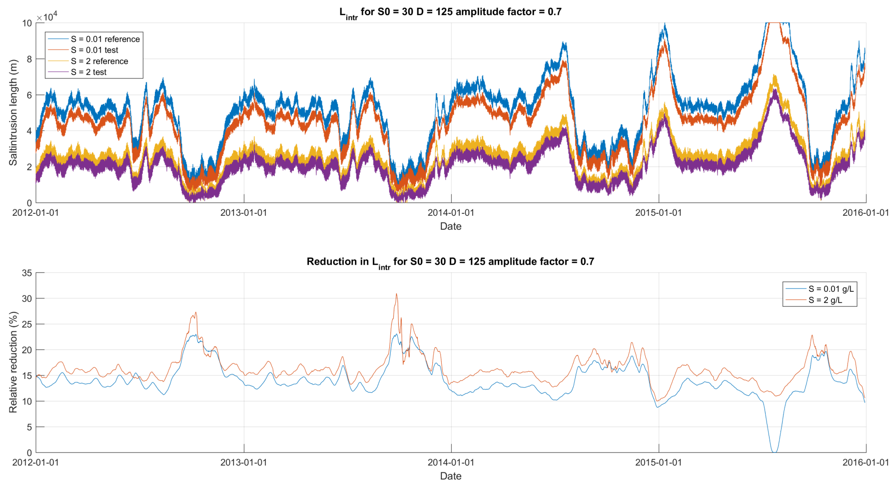


Figure U.22: The salt intrusion length and the intrusion length of 2 g/L for

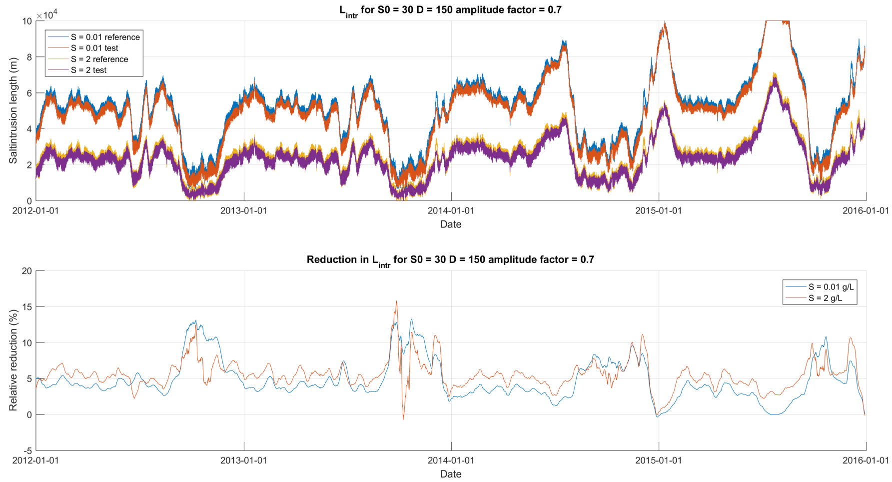


Figure U.23: The salt intrusion length and the intrusion length of 2 g/L for

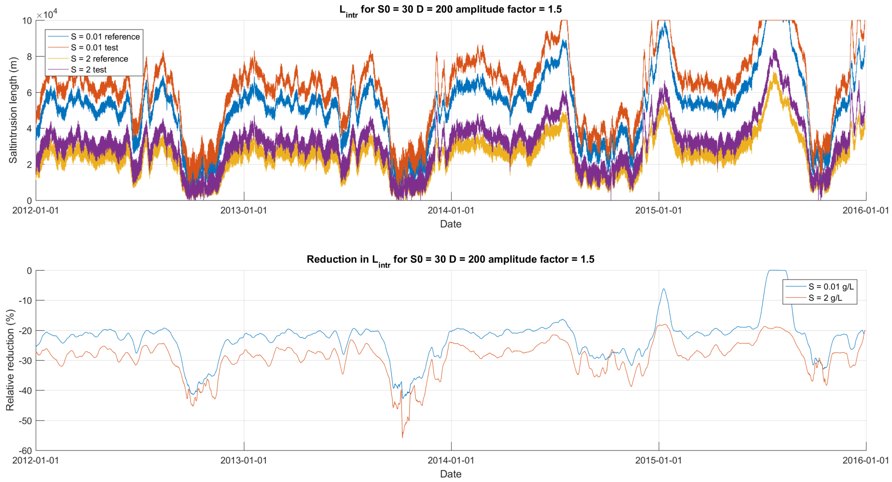


Figure U.24: The salt intrusion length and the intrusion length of 2 g/L for

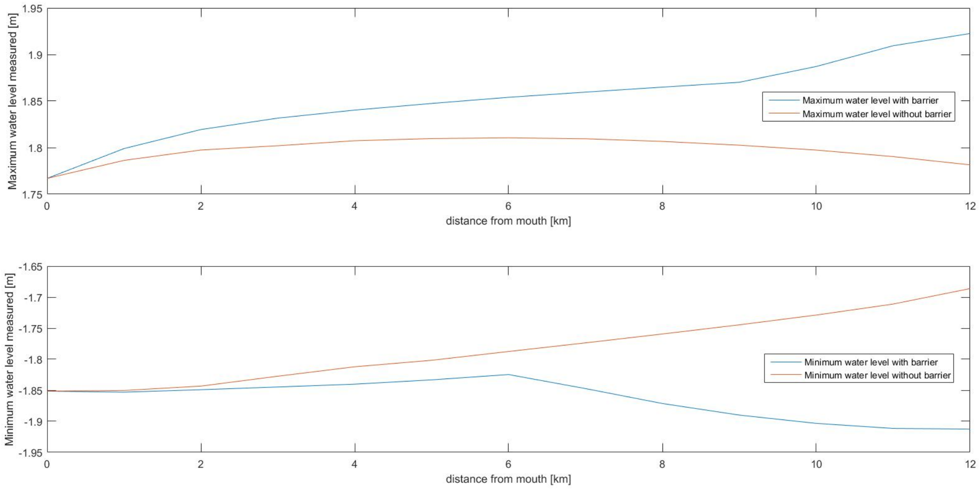


Figure U.25: Maximum and minimum water level up to 12 km in the mouth with and without the barrier. (SOBEK results)

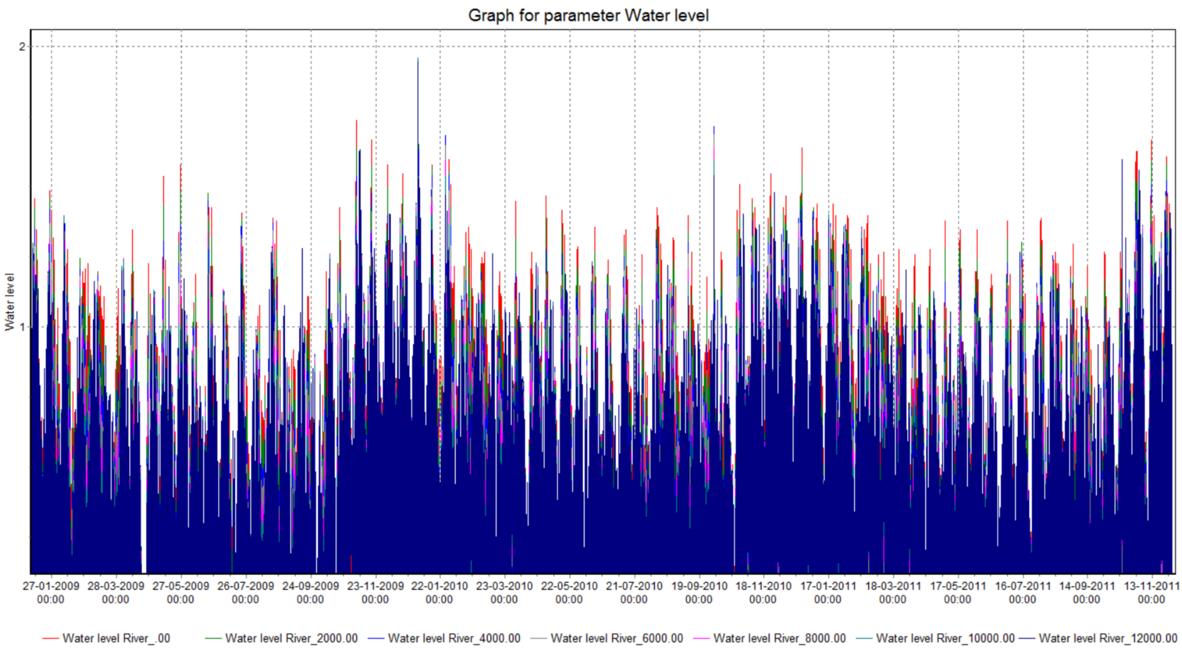


Figure U.26: Current water levels above MSL at the proposed pace of the barrier.

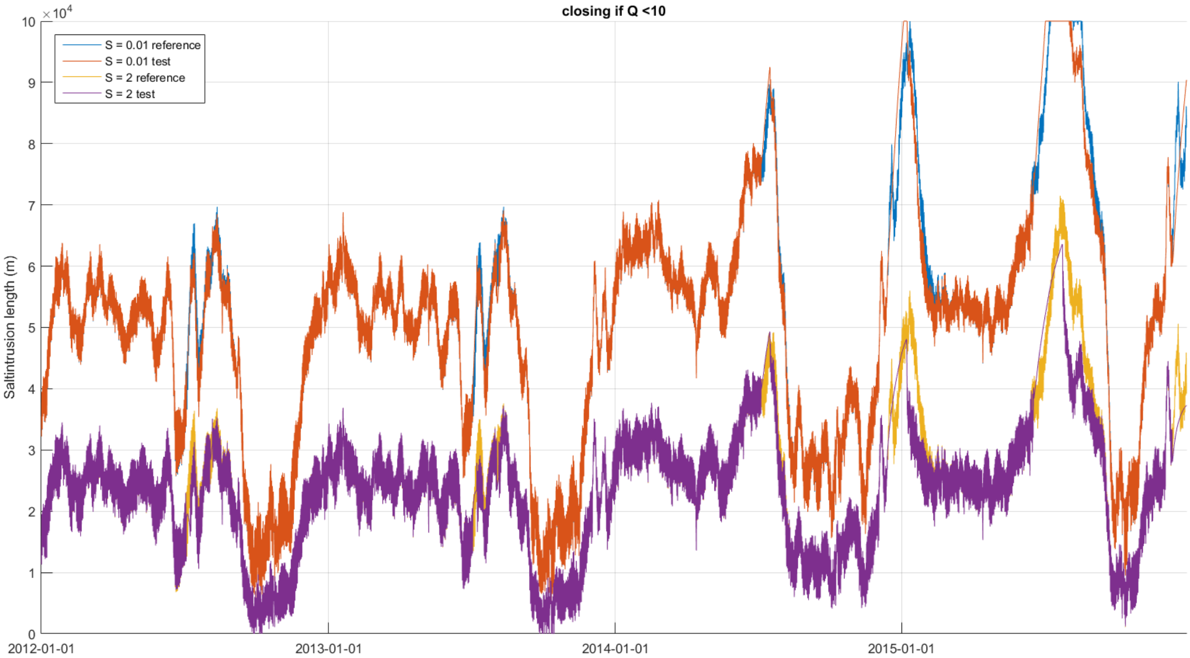


Figure U.27: The salt intrusion length and the intrusion length of 2 g/L for the control scheme: upstream discharge discharge with the trigger at $Q = 10\,m^3/s$.

Control by upstream discharge

From figures U.27, U.28 and U.29 it can be concluded that closing the gate is really efficient when the discharge from upstream is too low. From three different discharges, 30 m^3/s gave the best results; Just before the salinity of 2 g/L starts to intrude further than 30 km the intrusion length drops, because of the closure of the gate. If a lower discharge is chosen, the required salinity will not be reached. The intrusion length of 0.01 g/L is larger than before. This can be explained by the dispersion, which is too high in the upstream reaches. In this SOBEK model the dispersion is fixed to 150 m^2/s but in reality this will differ along the river branch. Next to this, when the gate closes there is a certain salinity in the river, due to dispersion this will be more spread in time. When the gate is closed for a longer period, the 0.01 g/L intrusion length will increase. Due to the constant dispersion which is slightly too high this effect will be more in SOBEK than in reality. For the trigger at 10 m^3/s the gate will be closed 7 % of the time, for 20 m^3/s this goes up to 17 % and for 30 m^3/s it will be closed 41% of the time.

Control by upstream and downstream discharge

With the chosen discharge of 30 m^3/s, the barrier is constantly closed. A second run also introduced an opening trigger to open the barrier when it was not needed to close it. In this case, the closure of the gate is also dependent on the tidal discharge (in or outflow), this reduces the time the gate is closed to 9 % of the time per year. The results can be seen in figure U.30. From this figure it can be concluded that there is no significant decrease in salinity concentrations. Sometimes the salinity even increases. This can be explained by the large difference in the salinity between the downstream side and the upstream side of the gate. The salinity upstream of the gate will increase rapidly when the gate is opened due to this large difference. Which sometimes brings the unwanted concentration even further upstream than in the reference case.

Control by upstream discharge and upstream water level

Results from this run are promising and are shown in figures U.31 and U.32. While $Q_{dicht,240} = 30 m^3/s$, this the salinity is reduction is sufficient, on average the gate is closed 35 % of the year. The results show the same form as in the first run with a discharge of 30 m^3/s upstream. However, small differences in salinity concentration can be seen in parts where the barrier is normally closed for the longest period. In these periods, the upstream water level is kept constant by opening the gate for a short period. This reduces the closing period from 41 to about 35 %.

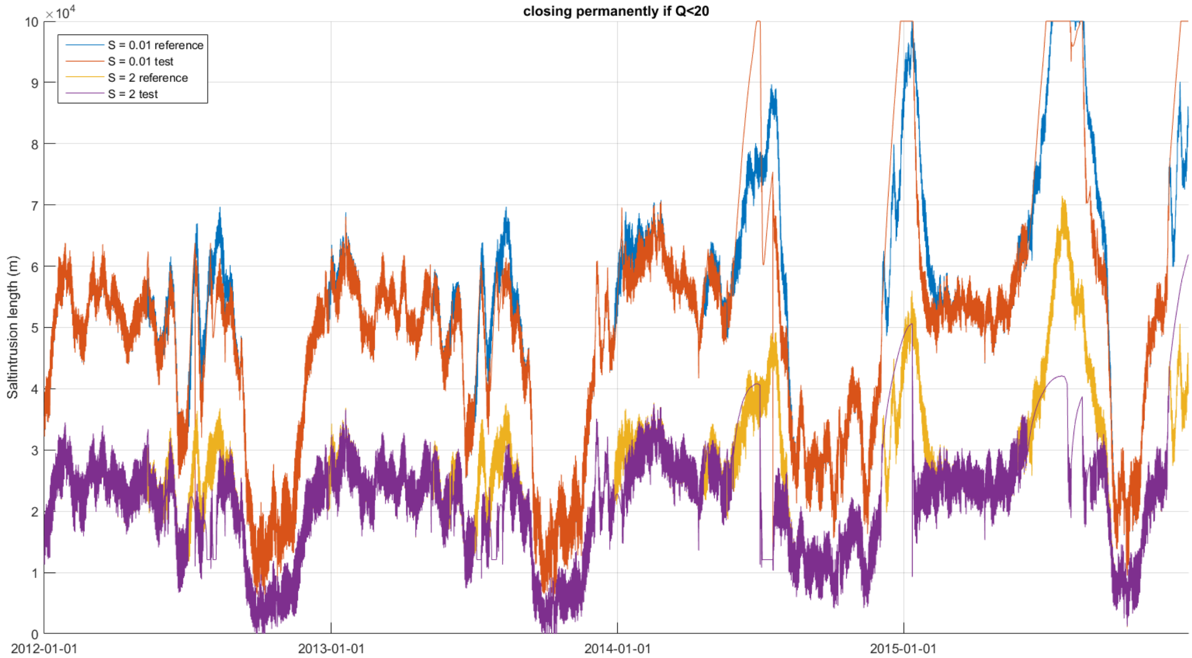


Figure U.28: The salt intrusion length and the intrusion length of 2 g/L for the control scheme: upstream discharge discharge with the trigger at $Q = 20\,m^3/s$

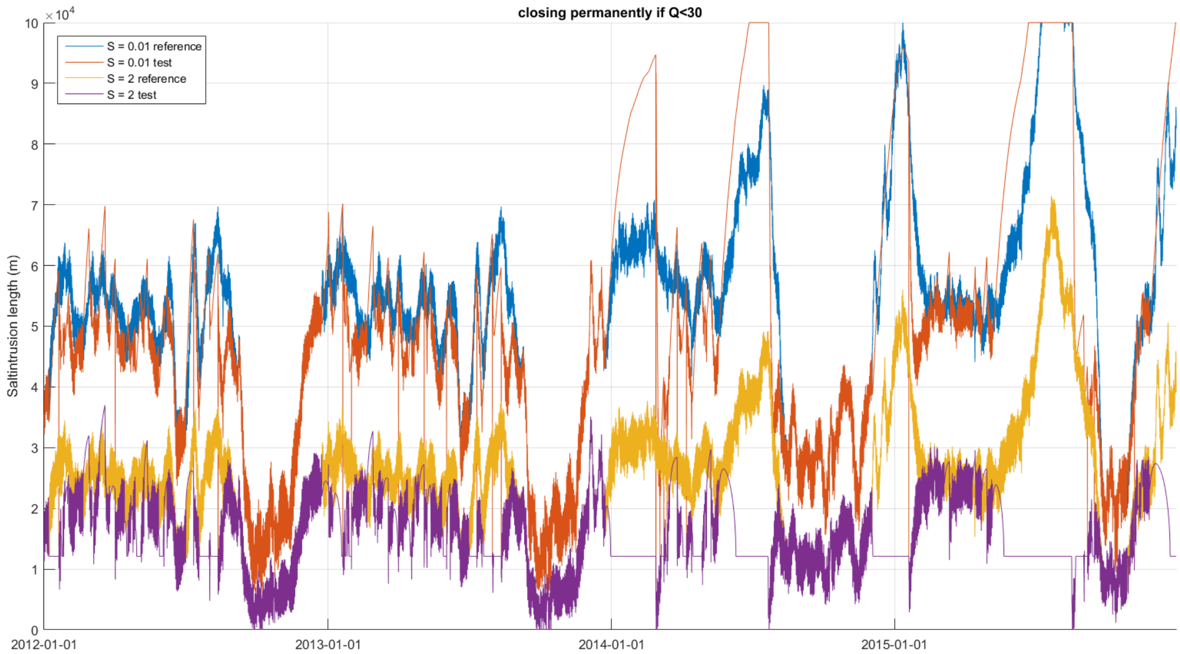


Figure U.29: The salt intrusion length and the intrusion length of 2 g/L for the control scheme: upstream discharge discharge with the trigger at $Q = 30\,m^3/s$

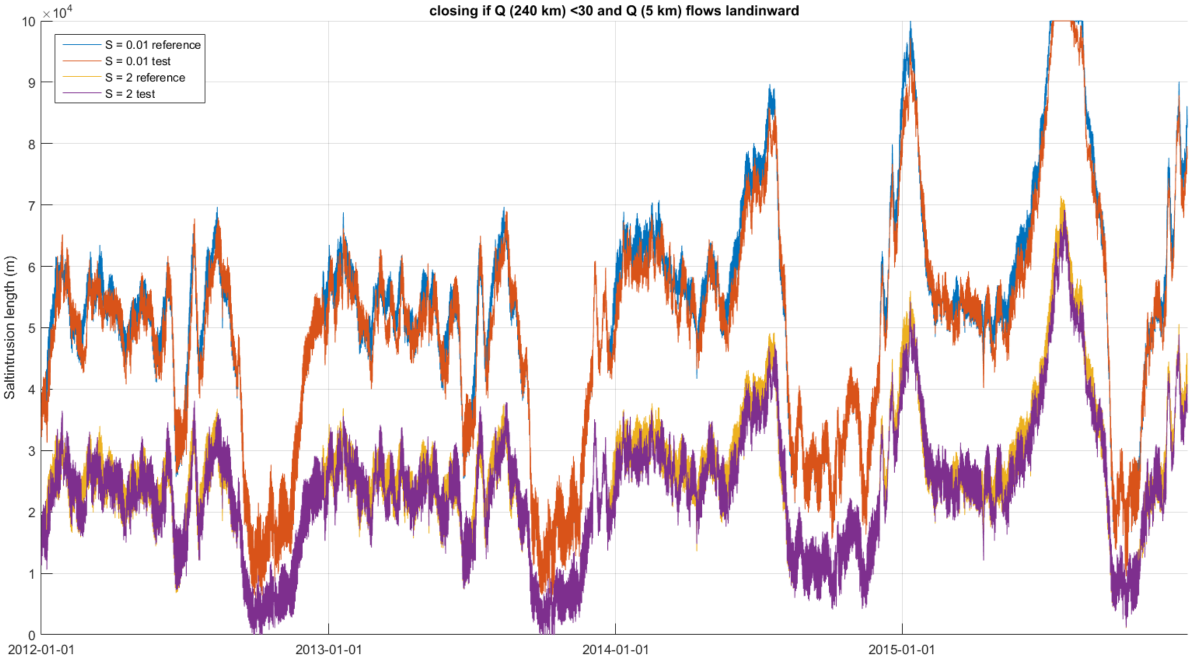


Figure U.30: The salt intrusion length and the intrusion length of 2 g/L for the control scheme: upstream discharge and downstream discharge.

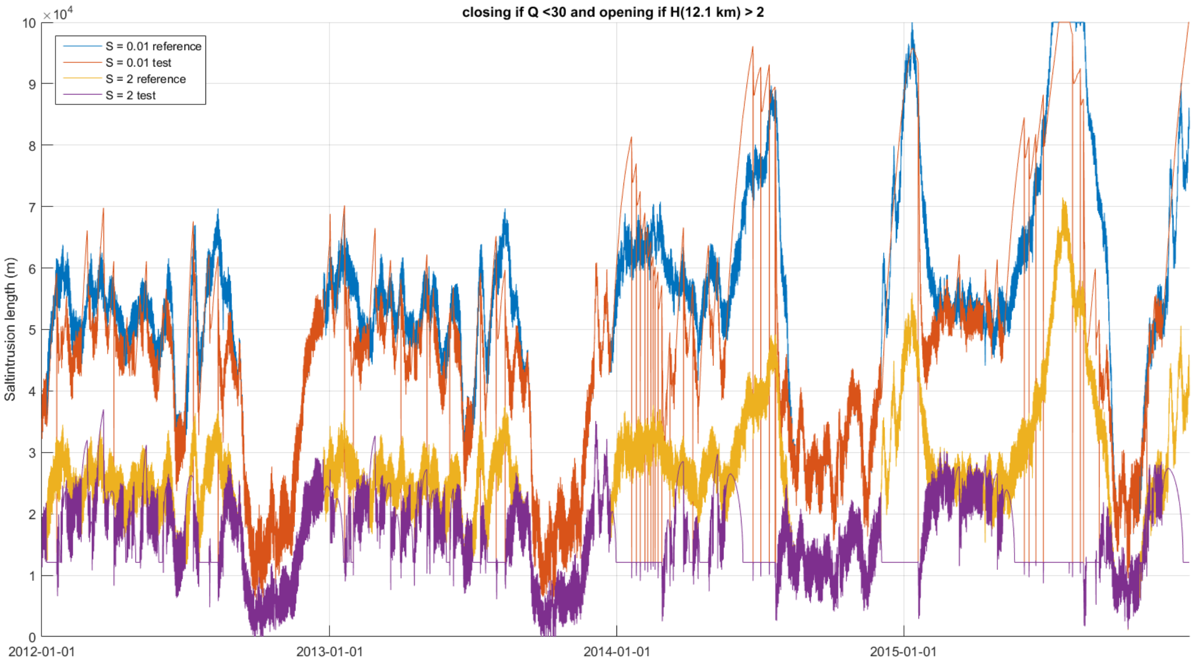


Figure U.31: The salt intrusion length and the intrusion length of 2 g/L for the control scheme: upstream discharge and upstream water level

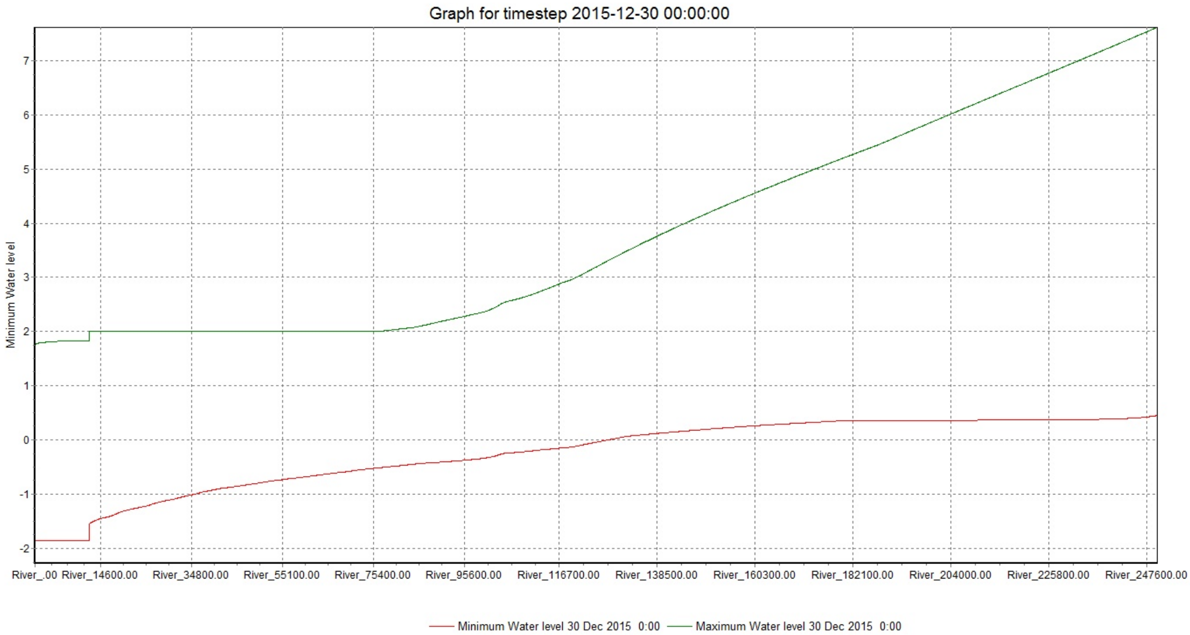


Figure U.32: The water levels for the control scheme: upstream discharge and upstream water level

Weir

Result of the weir are presented in figure U.33. With a sill height of -4 m relative to MSL the is able to reduce the salinity sufficiently. The weir will be closed 26 % of the time. Unfortunately, lower values of the sill height cannot be modelled. Further research is required to further analyse this control option.

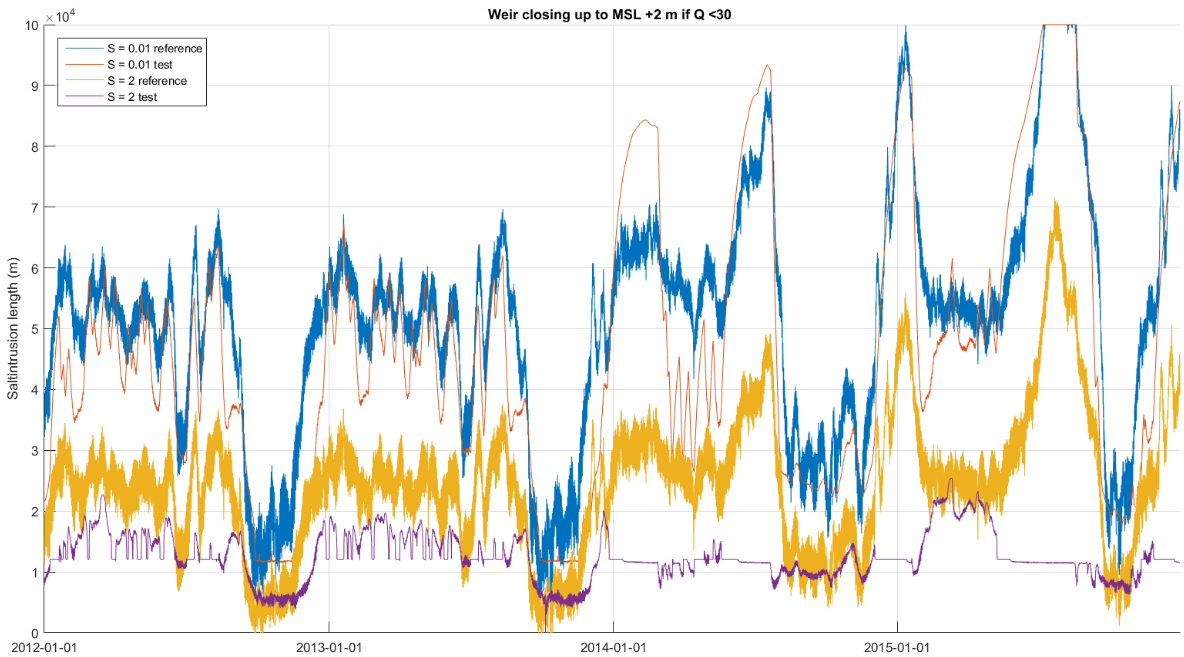


Figure U.33: The salt intrusion length and the intrusion length of 2 g/L with the weir

V

Minutes of meetings in Thailand

V.1. Meeting with the RID, 30 Augustus

Location: the RID, Bangkok.
Present: Chaiwat, Somkiat, Tha Chin project group, 2 Thai students (Thong and Eve).

About the salt intrusion problem:

At the river basin (about 200 km from the river mouth), a gate is used to control the salt intrusion. When salt water penetrates the river, the gate is opened to increase the water flow and thus push back the salt water. This works well, except for the dry season. The water flow is too low then and the basin hasn't got enough water to effectively push back the salt water. Thus the river becomes salt and the water not useable. This problem is the worst in April and May.

The water in the river is used for domestic use (about everywhere), and by farmers for irrigating their fields (starting about 30 km upstream). This is done by directly pumping water out of canals that are connected to the river. These canals often (not always) have a lock where the canal connects to the river. Some of the biggest locks are controlled by the RID, but most locks are controlled by locals. We also asked if there was any industry using the water. The RID answered that there was some industry, but they remained vague. We don't know what the size or water use of these parties are.

Reference project

A project similar to this exists, in the Bang Pakong River. The RID has put a control structure there to prevent salt intrusion, but problems occurred with landslides at the structure's feet. It turned out that they had not checked the tidal resonance and had placed the structure at about the worst place with regard to tidal resonance. This project can be used as a reference for us – the feasibility study was requested.

A city exists nearby the river mouth, with fishing and trading ships navigating the river. The salt water is no problem here. The salt water has to be stopped starting at 10 km upstream. At 30 km upstream, a station exists in the river that measures salt levels. This is used (by the RID we presume) to control the gate 200 km upstream.

The RID believes a water discharge of 18 (or was it 80?) m^3/s is needed to prevent salt water intruding the river. They told us river cross sections are available. We further asked for data on salinity levels, discharge levels, tide levels, water usage and land usage data, as well as sediment data.

We told the RID something about possible solutions. We agreed that we would start working on the project and when we have made real progress, we would schedule some kind of mid-term meeting.

Some questions that remained for us

Is the problem really only about the open water becoming salt? Are groundwater salinity and land subsidence not also problems?

Is the problem a shortage of freshwater or a surplus of saltwater? In other words: if we could block all the salt water, would enough freshwater remain to cope with during the dry season?

Is the RID really the only party that's fully involved in the river?

What is the real amount of industry that's connected to the river? And what is there impact on the river system?

V.2. Meeting with the Tha Chin River basin committee, 12 September

Location: a hotel in the Suphan Buri province
Present: Tha Chin River basin committee, Han, Inge, Willem and four Thai students.

Immediately upon arrival we were guided to the room where the committee (about 40 people) was seated. We got a table near the side. The meeting started around the same time.

Broad summary of the committee meeting.

We were given a report made for the meeting that included all information and the contents of the meeting. Six main topics were discussed: watersupply and demand; waterdemand for agriculture; watermanagement for inundation; management of waterquality; mitigation of the forests; general technology (e.g. information systems).

The meeting mostly beheld exchanging information, short summaries of last years' performances and budgets for this year. There's a long detailed budget explanation. The risk of floods/inundation of Bangkok, the weather forecasts (how dry this year will be), attending to locals to try lessen their water use and fishery are all discussed. It is stated that local farmers should be involved in the next meeting. Someone says that next year some departments' efficiency should rise and that they should file a report of their activities and budget spending.

In general, the team got the impression that no decisions were made, nor were there any discussions about anything regarding the river. Nor was any long term plan or vision discussed. The meeting was almost only about comparing this year to last year, and about budgets. It was an exchange of information, not a meeting where policies were made.

Meeting four committee members

These are two river experts and two department officials (at least one from Water Resources). Their major problem we first discuss is water pollution. There's too much dissolved oxygen and the biochemical hygiene is bad. There's too much chemical pollution (N, P and K-salts and pesticides) from farmers. Salt water is only for farmers and domestic users a problem, and only in the river water (not also in the groundwater). They tell us about shrimp farmers, who apparently transport seawater and dump it in shallow wells to grow shrimps, after which the water is dumped in the river. This practice has just been prohibited everywhere but because of that could still be in practice. It's unknown to us where they are located.

They claim that the water discharge is about 100 m^3/s. They claim that the total river capacity is 220 m^3/s(thus the discharge number should be reasonable). They also claim that in Changwat Nakhon Pathom (the second province from the river mouth) a discharge of 50 m^3/s is needed to stop salt intrusion.

After this, they talk about fruit farming and rice farming. They claim that salt water is bad for the rice fields but good for fruit farming (!). They explain that most rice fields are more upstream the river, in an area where salinity levels are already below the critical value, while most fruit farms are more downstream the river. Therefore, they state that salt intrusion is no problem for the river. We ask them to explain this. They first tell that shrimp farmers in Suphan Buri are the only problems and that local farmers complain about them at the governor, not about salt intrusion at the RID. After that they say that also in the dry season the water supply to push back salt is enough, thanks to the Tasarn – Bangpla canal. This is a canal that connects the Tha Chin and the Maeklong River, through which the Tha Chin River can get extra water supplied by the Maeklong River. These water supplies combined are enough to push back salt water during the dry season.

We say we have data about the Pho Praya water gate that indicates a discharge below 50 m^3/s. They say that at those moments the Maeklong River is used. They say the RID has data about the Maeklong water discharge.

We ask about the roles of the RID and the DWR. They say that the scope of the DWR is water management, planning and construction outside the irrigation areas. In the Tha Chin, RID has the most responsibility and is the most active in watermanagement. So they kind of do the same but in different areas (for partly different users).

We go on about the salt intrusion and the expert (firmly) states again that this is no problem. We tell about our salinity data but they say that these data is probably wrong, e.g. that the dimensions are not in g/L but in

mg/L (or ppm instead of ppt). He also says he thinks the RID's sample is taken at high tide, instead of at low tide. They claim that "The problem is only in the mouth, in the first province of the river. The water is salt but it's drinkable." On the other side, he also claimed that a salinity level in the river mouth of 33 ppt.

Finally, we ask them to give their opinions about some possible design options. They are firmly against a water gate. The Thai had two bad experiences (Ban Pakong and another) and they say that a water gate would cause much protests from NGO's and from local communities. When we talk about changing the tidal amplitude through adjusting the estuary, they don't exactly seem to understand what we mean. But they do say that people won't be willing to move.

When we ask about shutting of the bay through a dam, they claim that won't be possible because of huge protests. A partly dam like in Jakarta seems feasible for them. An environmental impact assessment should be made though, they claim. We ask them if they have any other problems. Water shortage from the river basins, especially last year, is mentioned. We ask them if there is any solution for that, if they have tried anything. They say that raising community awareness about water use and monitoring water use could help. They say that farmers get up to four crops per year, partly because the irrigation system is the best in Suphan Buri. In other words: the water use is very high. When there's a water shortage, the first priority is pushing back salt water (and thus providing less water for use).

Our own conclusions of the meeting:

- Their (DWR? Suphan Buri RID?) priorities differ from the Bangkok's RID. The latter party wants to have as much water available as possible, to everyone. These people claim that the water use (of the farmers) and water pollution are the problems.
- Their story about the salt data appears odd to us.
- The same is true for their story about using salt water to grow fruit.
- We can with some certainty claim what the problem is. There's no salt problem per se. The RID just wants to have more water available, which would cause salt intrusion problems in the current situation.

V.3. Field visit including meeting, 27 September

This trip can be divided in three parts. Visitors were the Tha Chin River project team and Kong Chaiyasarn, a Thai student who drove the car.

Visiting the river mouth

The first location of the visit was the river mouth. We went to the pier closest to the river mouth. Our first note was the amount of traffic on the river. A lot of big (50-100 m in length) fishing ships and some gas tank ships were occupying the river, waiting. We also saw Mangrove forests at the banks, planted as a government project to strengthen the river bed, in order to prevent landslides. We did not see any local fisheries.

We talked to a woman living at the pier. She told us that most of the people in the area work in the fishing industry. A lot of fishing-related places (e.g. markets, processing places and piers where fish was collected from sea) exist in this area. We ask her about fishing in the river and she explains that people used to catch shrimps in the river before, but that shrimps are now gone (probably because pollution problems). Only very small shrimps continue to live near the river mouth. Fish and/or shrimp farming does not exist in this area – the local economy mostly depends on fishing at sea. We also saw some gas companies nearby on the way to the pier.

Visiting the river upstream of the bridge

We want to see the amount of traffic after the first big bridge in the river, because we think sea traffic won't pass this bridge. We therefore visit Wat Pa Tha Sai Putthabucha, just on the upstream side of the bridge. We see that the traffic on the river now only consists of inland barges. We talk to the head monk of the Wat. He tells us that there used to be a lot of farming in this area. Then industry (factories) arose in the area and this caused the pollution levels to rise significantly. This in turn made farming activities dissolve. He also tells us that the dump of waste water by factories happens at night, which makes it undetected by government officials monitoring pollution.

Visiting the Khlong Chinda RID sub district office

On the way to the office we see a continuous stream of cultivated farm fields with layouts of water canals in them. Kong tells us that in the distribution canals, boats with mounted pumps are used to pump up water from the irrigation canal to the fields.

We arrive at the Khlong Chinda sub office of the RID and have a meeting with the director and with a farmer representing the orchid farmers. They tell us about last year's problem, when they faced a big water shortage which caused the seawater to penetrate the river too far. The salinity levels destroyed parts of the crops. They tell us all farmers in the area are affected by water shortage problems. We ask them about water supply control and they tell us that in times of shortage the RID advises farmers to grow lower volumes of crops, but that at that time most of the crops are already planted. They also tell us orchid farmers are prioritized in water supply, because orchids is a high-value crop.

We ask about problems with salt. They tell us that some fruits (mango a little, coconut quite well) can resist saline water, but that in general salt water is not at all desired. Salt water would flow into the soil, which would harm the plants. The salt problems occur from January up to June. We ask them whether pollution is a problem and they say that Chinda is appointed as green area, which means no factories are allowed to set up. Therefore, they don't have any pollution problems. This however conflicts with the statements made by the experts at the basin committee, which talked about dissolved oxygen and chemical pollution.

They talk about their measures against salt water and tell that they lacked salt measuring devices before. Because of that, last year they accidentally let salt water flow in their irrigation system, which caused orchids to die. This combined with the severe draughts the last years, they are now implementing a new water management plan. This consists of a new dam currently under construction at the Khlong Chinda very nearby the Tha Chin River, that will be used to have better control over the water inflow and additionally serves as extra retention against floods. A second source of water from the Tha Chin, more upstream, will be diversed to the Chinda area to provide extra water supply. They have constructed a basin in Chinda to store a surplus of water to be used later in the (dry) season. Also, they developed better communication with the Port Department, which can warn the RID about high tide levels. The Chinda water system holds a lot of small gates, as in the rest of the Tha Chin basin. Up to now, these gates mostly served the orchids farmers, as they were given priority. However, they tell us that the new system is design to benefit all users in the Chinda region. If this system of extra gate(s) and water storage(s) works properly, their intention is to implement it at other regions too.

Our conclusions:

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- Heavy ship traffic only occurs in the first 10 km of the river.
- Our knowledge up so far about farming, fishing and water pollution near the river mouth is confirmed.
- The local RID already is working on a solution to prevent salt intrusion.
- The local RID's claims about water pollution conflicts with statements made by the experts at the river basin committee meeting

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V.4. Meeting with the Department of Water Resources, 30 September

Location: Crisis Centre, Department of Water Resources, Bangkok.
Present: Rachadaporn Suphanpong, Foreign Relations Officer at DWR, Pipat Ruang-nam, director of Crisis Centre of DWR, Pantipa Sudthapanya of the Dutch Embassy, Han, Willem.

Note: names of places have been scribbled down quickly and phonetically and thus might not be correct.

We arrive at the crisis control centre, 11th floor, which also looks like a crisis control centre. The director shows us a big report with data. P.398 shows a map with telemetry station points. P. 385 shows a list of water quality information.

The director starts talking about the main problem according to him. First, he tells that the Maeklong delta is not connected (hydrologically) to the Tha Chin delta since it's not part of the Chao Phraya-delta. Management of the two river systems is separate. He again states that in the Tha Chin 8 ministries and 19 departments are involved. The main problem is water quality and pollution. Especially the Nahn province and river basin, but more places were named. He tells about ongoing deforestation activities far upstream. He tells deforestation always starts with the use of chemicals. These chemicals flow into the water system, together with the bottles in which they were contained. At present, about 2000 used chemical bottles arrive in the Sirikit reservoir each day. He tells that all the fish in Song Phi Nong (Suphan Buri province) have died from chemicals 2 months ago. From the Sirikit reservoir, chemicals flow downstream the whole river of course. The port at the river mouth has a lot of fishing activities and ships (over 4000 ships). These ships spill oil. This oil flows both in the Gulf as in the river (due to the tide).

Sedimentation problems also occur. The river has an almost flat slope, limiting sediment transport. At the river mouth, sediment is aggregating in the shape of a half circle. The bank thus formed helps preventing salt intrusion in the dry season, but at the same time limits the run-off of oil spills and pollution.

The middle part of the river basin has a lot of paddy fields, which grow about 5 crops each 2 years. They use a lot of fertilizers, which cause a algae bloom, which lowers the amounts of dissolved oxygen (DO) in the water. This makes way for a new ecological problem. There's a fish species that live in the deep sea and come to Nakhom Pathon to breed (and to feed of the fertilization? Maybe he meant the fertilization makes the plankton food for the fish). The plankton boom lowers the amounts of DO, which in turn kills the fish coming there.

He also tells about a heavily industrialized area in Nakhon Pathom: 50 factories that are located in a 1 km part of the river. During the dry season, pollution dump from the factories can easily be measured and thus detected. During the wet season this is however not the case. Therefore during the first two weeks of the wet season, there's a big peak in water pollution levels.

East of the river mouth in Luang Pradang?, there are over 5000 small canals, all with gates in them. This makes it possible for this area to manage salt levels, since (he claims) each canal / part has enough fresh water to push back salt water penetrating the river at the mouth. However, because of the industrial boom, land prices have risen. Because of that, canals are filled in order to create more land and higher profits. This stops the canals functioning as a salt water blockage. He claims to have direct evidence of this, from measuring station TTC09. Additionally, the remaining water stagnates, which again causes DO levels to drop. He also tells about land flooding in this area, because the remaining canals don't have enough capacity to work as a retention area anymore. He said originally, this area was planned as a retention area for flooding (among other uses of course).

Another problem is that during the 2011 floods, straight canals have been excavated to side track meandering river parts. These still exist, without gates in them. As a result, water now also flows in more easily, thus making salt penetration easier. These new canals are less deep than the existing river, so water flowing out during low tide can't go through these canals. This makes that salt water flows out slower than in. Because of this, salt water stays in the meandering river parts, accumulating. Later on, he tells that the problem of the side track channels can easily be solved, by just blocking the first channel.This block should not have to be complex - he told us simple wooden planks could already be enough.

Bridges also pose a problem: the skirts of the columns (which stand in the river) aren't in line with the river flow and because of this sediment is blocked. This sediment accumulates in front of the bridge, making the sides of the river under the bridge more shallow. This again blocks salt water from flowing out of the river during low tide.

Side (irrigation) canals are also less deep than the main river. Sediment is transported in the canals to the faster-flowing river. At the edge of the canal to the river, sediment accumulates because of turbulence at the outlet of the canal. This again blocks salt water in the canals to flow back to the river and the sea. Because of this, salt water penetrates the ground up to 15 meters depth. The salt water is located between the surface groundwater and the aquifer, which is protected by a clay layer. Because the upper groundwater layer is still fresh, farmers don't experience problems with it. Because of river morphology, the river layout changes of course. This leaves 'left-overs' of old sandy river beds. These (mostly) underground permeable sand layers connect to the river to create these salt water layers. In other words: they store salt water. During the dry season, because of the low river water levels the salt water returns back in the river water, making it saline. He thinks this problem is very hard to solve.

He tells about the DWR's functions:

- water resource development & water conservation
- water board: it makes policy, takes policy measures and they develop plans for every other agency involved in water.

He tells us he is waiting for the new Water Act, because this says other agencies should first send their water plans to the DWR. If the DWR doesn't approve, there will be a budget stop. At the moment, the basin committee makes project plans, but these don't contain real action plans. The Water Act would give DWR the power to force the committee and others to also make action plans.

He thinks a control structure near the mouth would work. This should function in two parts, so at high tide, the upper part can be opened, allowing fresh water to flow out, while the down part is closed, blocking salt water to flow in. At low tide, both parts would be opened. He also tells he would like to re-dug the canals east of the river mouth. But because locals don't know the problems, they won't cooperate.

He then tells about a salt making factory (or factories?) in the Luang Pradang area, using salt fields. In combination with the decreased amount of canals, salt density becomes higher than ever, which kills the mangrove trees at the river mouth. This in turn kills all the other life around them. He told about dying dolphins and turtles which were recently on the news. The dying mangroves don't cause coastal erosion though. This is because of the sea water flows in the Gulf of Thailand.

He continues about sea water flows. These come from the west and follow the shores of the bay. Meanwhile, they collect all kinds of garbage from the sea, from as far as Malaysia and Indonesia, and dispose it at Pattaya. Attempts to collect this garbage caused dolphins to get stuck in the nets and therefore have been ceased.

He thinks the key for solving the problems in the river is: people - partnership. Really involving locals and letting them solve the problem themselves, instead of mere participation without any actual influence of locals. He would like to have just one big operation plan, which can be worked out step by step. Therefore he wants to integrate each party and each plan into one system. He stresses the importance of involving local people, because the community of the Tha Chin is very strong, compared to other river basins. Therefore, locals should be partners in solving problems.

We asked if he could use the help of the We Love Tha Chin-NGO. He says that contact persons of the NGO change every year. In contrast, he wants a long term approach with a long term attitude. This makes working with these party (and other parties as well) difficult for him. To achieve long term commitment from locals, he thinks you should first show them concrete proof and examples of the problems, than make them committed, and then let people solve the problems themselves, with some knowledge you gave them.

We asked his opinion about the plan currently underway in Chinda. He thinks this is a good example, because people (locals) will learn from this, especially if more regions would do this and water shortage problems would occur. He hopes that this would draw people from different parts together, discuss these problems, and with some help, learn how to solve them. This would really create a resilient water management system in his opinion. A system with committed people who know how the system works and how to solve problems it has. Local cooperation is key to success he thinks.

He thinks therefore locals should be given a means to communicate and discuss water management and each other's activities. For example, meetings could be held. Secondly, he thinks the people should be given the right knowledge. Then, these people could take responsibility in water management, and because the water problems really become their own problems, long term commitment is secured. He tells about a reference project of his own in the Moon River basin, where he approached one guy, who approached others and in such a way a complete management community was created. Water management thus started with one man managing the water, and other locals approaching this man and becoming part of the management system.

He said he thinks the start-up of these kind of projects is waiting for the new Water Act, because this will give the DWR to coordinate and prioritise them. He speaks of a 20-year action plan made and enforced by the DWR on a national scale. Local river basin committees could then fill in the local details and execute the plan in their area (N.B. at the moment, it's the other way round: the basin committees make shopping lists, which the government has to execute).

At the end, we asked his opinion on some possible solutions. When asked about increasing friction, he starts talking about the problems with water hyacinths. At the dam in Chainat, hyacinths accumulate and flow into the Tha Chin-side of the river, because this side has a lower barrage (gate). At parts in for example Nakon Pathom, everything gets filled with water hyacinths, causing multiple problems. First: the hyacinths block sunlight to the water, resulting in the death of plants under water. Secondly, water evaporation through the hyacinths goes 5 times faster than normal surface evaporation, making for far higher amounts of water loss. The roots of the hyacinths are on average 60 cm long, the hyacinths themselves are about 20 to 60 cm wide. The plants create extra friction, which causes fresh water velocity to drop to 3 times as low as normal, almost to 0 m/s. The plants grow very fast (twice as big in 10 days), faster than they die. Ten plants entering the river upstream grow into 2 ha of plants downstream. Additionally, their roots sink when they die and so create plant waste mud. This settles at the mouth, causing a sort of bank in the shape of half a circle, blocking salt water flowing out during low tide (as mentioned before). To make a long story short: increasing friction won't help, because there is already too much friction. Tackling the water hyacinth problem will have to be done at its source, far upstream, for example at Kang Phen Phet or Yom.

Changing the convergence angle would make the fresh water penetrate the sea further he thinks. This would influence the sea flow coming from the west and therefore influence the other two rivers (Chao Phraya and Bang Pakong). He thinks a 'dotted line' solution, using for example bamboo sticks as barriers, would be better. This would enable existing mangrove trees and fish to continue living. Eventually, the bamboo sticks would be closed up by growing plants / trees. When concrete would be used to build a barrier, the outflow of water would of course be faster. This would increase bed erosion, which would eventually lead to coastal erosion and land slides at the coast next to the river mouth.

He thinks balance islands would cause problems during rain floods. He thinks it will be hard to convince the local community that flood problems would not occur.

He heard of building a barrier in sea to close off (parts of) the Gulf before. He thinks closing of the river would be very good for the surface water quality. However, he thinks the consequential lack of tide will influence groundwater levels. This because when the tide is gone, water inflow from the source into the underground sand beds and outflow of water from the beds to the sea will not be controllable. Outflowing groundwater would cause land subsidence. In another situation, they've already experienced land subsidence at a rate of 7 cm/year. That's one of the reasons they don't conduct big groundwater projects, but only projects on a local scale.

Building a partly barrier would ensure the proper amount of water outflow. However, he thinks within 2 years the basin in front of the river mouth would be completely filled with mostly plant waste mud (a sedimentation problem). Then we said about thus also addressing the plant problem, and he agreed. At the end, Rachadaporn told us we could contact her if we need extra information and / or if we want another meeting. She said they were interested in our final report.

V.5. mid-term meeting with RID, 12 October.

Present: Chaiwat, Somkiat, Tha Chin project group

We started with a presentation, and asked Dokter Somkiat about his opinion

Balance Island

- They are not really enthusiastic about the islands because they do not understand this solution
- Floods: The lay out of the islands must also be tested on the outflow conditions in the rainy season.
- Fishermen: need to be well informed. Say that if implemented right, large fishing ships can pass and that because of the positive consequences (salt reduction) and right use of the island in improving the local ecosystem, even local fishing will be possible again in the future.
- Collaboration with the Harbour Department needed
- Doubts about the influence of current sediment banks laying in the river mouth
- Doubts about the feasibility in Thailand

conclusions we made:

- We have to tell about the possible reduction of the intrusion length, but this is hard to model
- We can not model this, a lot of more research is needed
- They need proof for it in order to believe in this solution

Change convergence length morphology/bathymetry in the mouth

- Not many remarks

- Sounds maybe too easy
- Based on theory
- Doubts about the river mouth sedimentation (N.B. we think this will not be a problem).

Salt stairs

- Is it even possible in this area (very flat slope)
- Needs maintenance (a lot)
- The whole gulf is really shallow so hard to implement
- They think sediment will settle on the steps and make the stair-shape flat.
- Salt stairs will probably not work, because the measure might only work during high discharges and the problem is during low discharge.

Dam in the Bay of Bangkok

- local fisherman, nature, environmental problems might be too extensive
- Protest
- Costs
- Huge impact on a lot of people
- Would not pass the EIA
- Similar idea, did not know the amount of sea level rise
- Hard to change people (habits, culture, way of life)
- Dr. Somkiat recommends not to do this as it has already been proposed and has been put off due to many protest
- There have been two studies already, both caused a lot of protest.

Partly dam in the Bay of Bangkok

- Extensive modelling needed (just an idea, to make to first might be more feasible)
- Sedimentation problems
- EIA, to be done
- More positive reaction (than the completely barrier) because he believed impact to be lower

Barrier in the river

- Storage in the mouth, possible? There is not much space left over there. Using the Kaem ling structures in the dry season is not possible since the water is too polluted. Farmers and other users do not want that polluted water on their lands.
- River mouth, hard to implement, 10 km upstream if we make sure the increase of the amplitude is as low as possible. Banks in the lower part
- Easy operation needed
- Be aware of the location because of the tide
- Be aware of pollution
- Hard to build in the river mouth because of large width. Also fishery ships will be blocked if gate is closed.

Questions

- For the salinity the only clear demand is that 2g/l is not exceeded at the station at 30 km upstream: if this can be met at all times it is ok.
- Khlong Chinda: Good solution, let people solve it locally. But when this solution is implemented in more parts in the basin this will not solve the problem. Salinity level at 30 km upstream still needs to be lower than 2 g/l. If more communities will implement this, there might not be enough water left in the river to meet that condition.

Conclusions after the meeting

- Kaem ling cannot be used for diverting water in the dry season, since the water coming from upstream is too polluted.
- We really have to design with impact in mind. Their biggest concern is the amount of people and nature affected by a solution.
- For the gate solution it is our task to come up with an ‘ideal’ location considering: increase of tidal amplitude, shipping, costs, people etc.
- If a solution is presented. We need to present the requirements that come with this solution as well. An example: if we reduce salt concentrations it should be kept at this concentration. Management schemes about minimal discharges to reduce salt levels have to be implemented with strict execution

W

Brainstorm

Bibliography

AMNH. Mangroves: the roots of the sea, 2004. URL http://www.amnh.org/explore/science-bulletins/bio/documentaries/mangroves-the-roots-of-the-sea/mangrove-threats-and-solutions/. retrieved: 9-22-2016.

Monton Anongponyoskun. *Application of numerical model on the water circulation and suspended solid dispersion in the Upper Gulf of Thailand.* Thesis, Kasetsart University, 2007. URL http://doi.nrct.go.th//ListDoi/listDetail?Resolve_DOI=10.14457/KU.the.2007.330.

BankokPost. Damned if you do, damned if you don't. *Bangkok Post*, 2016.

J. A. Battjes. Vloeistofmechanica, 2002. TU Delft lecture notes. Course: CT2100.

J. de Kort and S.C. van Rooij. Balance island: Numerieke modellering van effecten van balance island op zoutindringing. Report, Grontmij Nederland B.V., 2013.

Waterloopkundig Laboratorium Delft. Zoutbufferput ijmuiden: Samenvatting orienterend onderzoek. Report, Waterloopkundig Laboratorium Delft, 1968.

Deltares. Technical reference, flow: Sobek-re, 2012a.

Deltares. Technical reference, salt: Sobek-re, 2012b.

DoF, 2016. URL http://www4.fisheries.go.th/. retrieved: 9-22-2016, Department of Fisheries Thailand.

DutchWatersector. Delta alliance young professionals awarding ceremony at the rio plus 20, 2012. URL http://www.dutchwatersector.com/news-events/news/3013-delta-alliance-young-professionals-awarding-ceremony-at-the-rio-plus-20.html. retrieved: 9-22-2016.

I. Faridah-Hanum, A. Latiff, K.R. Hakeem, and m. Ozturk. *Ecosystems of Asia: Status, Challenges and Management Strategies.* Springer Science+Business Media, New York, 2014. ISBN 978-1-4614-8581-0. doi: 10.1007/978-1-4614-8582-7.

S. Feld, S. Prajamwong, and S. Sherman. Proposed integrated land and water resources management system (ilwrms) for the bang pakong river basin: lessons from a user needs assessment. *Journal of Water Supply Research and Technology-Aqua*, 52(6):435–442, 2003. ISSN 0003-7214. URL <GotoISI>://WOS:000185910800005.

Y. Friocourt, K. Kuijper, and N Leung. Factsheet: Saltintrusion, 2014.

S. Graas and H. H. G. Savenije. Salt intrusion in the pungue estuary, mozambique: effect of sand banks as a natural temporary salt intrusion barrier. *Hydrol. Earth Syst. Sci. Discuss.*, 2008:2523–2542, 2008. ISSN 1812-2116. doi: 10.5194/hessd-5-2523-2008. URL http://www.hydrol-earth-syst-sci-discuss.net/5/2523/2008/.

George Green et al. On the motion of waves in a variable canal of small depth and width. *Transactions of the Cambridge Philosophical Society*, 6:457–462, 1837.

David P. Hamilton, Terence Chan, Malcolm S. Robb, Chari B. Pattiaratchi, and Michael Herzfeld. The hydrology of the upper swan river estuary with focus on an artificial destratifaction trial. *Hydrological Processes*, 15(13):2465–2480, 2001. doi: 10.1002/hyp.298.

IFAD, 2016. URL https://www.ifad.org/topic/gef/operations/. retrieved: 9-23-2016.

IUCN. Thailand's new marine and coastal resources management act: engaging coastal communities in conservation, 2015. URL https://www.iucn.org/content/thailand%E2%80%99s-new-marine-and-coastal-resources-management-act-engaging-coastal-communities. retrieved: 10-4-2016.

JICA. The detailed design study on the bang pakong diversion dam project: detailed design report. Report, Japan international cooperstion agency Royal Irrigation Department, 1993.

Th. v.d. Kaaij, H.F.P. van den Boogaard, C. Kuijper, C.J. Sloff, and J.W. van Zetten. Herstel van de trapjeslijn in de niewe waterweg en de nieuwe maas (fase 2): vervolgstudie naar de effecten op de zoutinidringing. Report, Deltares, 2010.

Lerdsak Kamkongsak and Margie Law. Laying waste to the land: Thailand's khong-chi-mun irrigation project. *Watershed*, 6(3):11, 2001.

Prachoen Khonthet. We love tha chin river society, nakhonpathom: Learning for our beloved river: Hia applications in tha chin river, 2007.

LAUNCH, 2016. URL http://www.launch.org/innovators/mark-tonkin. retrieved: 9-23-2016.

Weir Westgarth Ltd. Msf desalination plant at jebel ali g station, dubai, 1994. URL https://en.wikipedia.org/wiki/Multi-stage_flash_distillation#/media/File:Multi_Stage_Flash_Desalination_Plant_at_Jebel_Ali_G_Station.jpg.

E. Manowong and S.O. Ogunlana. The roles of non-governmental organizations in development projects: experiences from thailand, 2004.

MarineDep, 2016. URL http://www.md.go.th/en/. retrieved: 9-22-2016, Marine Department Thailand.

F. Molle, T. Srijantr, and P. Promchote. The bang pakong river basin committee : analysis and summary of experience. Report, Institut de recherche pour le développement Food and Agriculture Organization of the United Nations, January 2009.

NCICD. Masterplan: National capital integrated coastal develepment, 2014.

P. Ndimele, C. Kumolu-Johnson, and M. Anetekhai. The invasive aquatic macrophyte, water hyacinth Eichhornia crassipes (Mart.) Solm-Laubach: Pontedericeae: problems and prospects. *Research Journal of Environmental Science and Technology*, 5(6):509–520, 2011.

Tien Hai Nguyen. Mangrove forest management: lessons from thailand, 2015. URL http://blog.worldagroforestry.org/index.php/2015/09/29/mangrove-forest-management-lessons-from-thailand/. retrieved: 10-6-2016.

NLDEmbassy. The water sector in thailand, 2016. Embassy of the Kingdom of the Netherlands in Bangkok.

PCD, 2016. URL http://www.pcd.go.th/. retrieved: 9-22-2016, Pollution Control Department Thailand.

J. Phaksopa and P. Sojisuporn. Storm surge in the gulf of thailand generated by typhoon linda in 1997 using princeton ocean model (pom), 2003.

A. Pickaver and D. Sadacharan. The benefits of inter-linking coastal and river management. Report, EUCC - The Coastal Union, 2007.

David Prandle. *Estuaries: dynamics, mixing, sedimentation and morphology.* 2009.

T. Raadgever, S. Smith, E. Quataert, B. van Bueren, A. Giardino, A. Nolte, M. van der Groep, E. Moens, and T. Ysebaert. Balance island: an international feasibility study in bangladesh and vietnam. Report, Grontmij, Imares, Deltares, Water architect van Bueren, water.nl, Netherlands Enterprise Agency, 2016.

RID. The tha chin river basin, 2011. Original in Thai.

RID. Salinity data, 2016. http://water.rid.go.th/hwm/swq/sediment/river/river2.html, retrieved: 9-7-2016.

H.H.G Savenije. Salinity and tides in alluvial estuaries, 2nd completely revised edition: salinityandtides.com, 2012. URL `salinityandtides.com`.

H.H.G. Savenije and E.J.M. Veling. Relation between tidal damping and wave celerity in estuaries. *Journal of Geophysical Research: Oceans*, 110(C4), 2005. doi: 10.1029/2004JC002278.

Pramot Sojisuporn, Chalermrat Sangmanee, and Gullaya Wattayakorn. Recent estimate of sea-level rise in the gulf of thailand. *MAEJO INTERNATIONAL JOURNAL OF SCIENCE AND TECHNOLOGY*, 7:106–113, 2013.

Taichi Tebakari. Seminar presentation on bhuminbol and sirikit dam, 2016. Presentation at the KMUTT.

Yu Terashima. Dams in the philippines and in thailand: Social and environmental impacts of natural resourses development projects, 2011.

TMD, 2016. URL `http://www.tmd.go.th/en/climate.php?FileID=7/`. retrieved: 9-10-2016, Thai Meteorological Department.

L. Tolk, A. Tuinhof, T. te Winkel, K. Matin Ahmed, and M. Bolton. Underground fresh water storage: a practical solution to increase water security in saline deltas. Report, Acacia water, 2014. URL `http://www.thewaterchannel.tv/images/undergroundfreshwaterstorage.pdf`.

UNEP. Water hyacinth - can its aggressive invasion be controlled?, 2013.

L.C. Van Rijn. Tidal phenomena in the scheldt estuary. *Report, Deltares*, 2010.

S. van Rooij, E. Verduin, M. van Kersten, H. Hoogendoorn, B. van Bueren, and E. Kuijs. Balance island, 2012.

Suphat Vongvisessomjai, Phairot Chatanantavet, and Patchanok Srivihok. Interaction of tide and salinity barrier: Limitation of numerical model. *Songklanakarin Journal of Science and Technology*, 30(4), 2008.

WallStreetJournal. Court delays thailand's flood control projects. *Wall Street Journal*, 2013.

WaterloopkundigLaboratoriumDelft. Reproductie zouttoestand getijrivieren viii: Invloed luchtbellen gordijn op zoutpenetratie, 1971.

Tennille Winter, D.J. Pannell, and Laura McCann. The economics of desalination and its potential application in australia, sea working paper 01/02, 2006.

H Winterwerp. Lecture notes: Sediment dynamics, 2016. TU Delft course CIE4308.

WorldBank. Climate change impact and adaptation study for bangkok metropolitan region : final report. Report, World Bank, 2009. URL `http://documents.worldbank.org/curated/en/834261468025503285/Climate-change-impact-and-adaptation-study-for-Bangkok-metropolitan-region-final-report`.

WWAP. *Chao Phraya River Basin, Thailand*. UNESCO - United Nations World Water Assessement Programme, 2003.