Crisis response for extreme flooding

Using a hydraulic model to support crisis response

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Preface

In this report I proudly present the results of my Bachelor Thesis, “Crisis response for extreme flooding, using a hydraulic model to support crisis response”. Over the past 10 weeks I have worked on my research at Witteveen+Bos within the department of water management, where I joined the group of urban water management and climate adaptation. The weeks have flown by and I look back at an amazing time at the company, interacting with colleagues on and off the work floor and getting a peak of how a large Civil Engineering consultancy operates.

I would like to express my gratitude to my supervisor at Witteveen+Bos, Daniël van den Heuvel, for all the insightful and extensive feedback on all the draft versions that came before this report. Furthermore, I thank him for the quick response time to all my questions and pushing me to get the most out of this research. I would also like to thank Parisa Khorsandi Kuhanestani, my supervisor from the University of Twente. I thank her for the weekly meetings, were I could ask all my questions and got much needed advice whenever I was stuck at a part of my research.

I hope you as a reader will enjoy reading this Thesis report as much as I have enjoyed carrying out my research.

Sincerely,

Thijs Mank
10 July 2023

Summary

In 2011 the worst flooding in Thailand's recent history devastated the central plains of the country, inundating 69 out of 77 provinces with a total area of 4.381 km^2 which is 9,1% of the entire country (Thailand Development Research Institute 2013). Despite the severity of the consequences this flood only registered on the magnitude of roughly an once every 10-20 years event. (Gale and Saunders 2013).

With precipitation events becoming more extreme due to climate change, floods are becoming more severe. This is also the case for the Chao Phraya river basin in central Thailand. The varied hydrology of this river further increases the chance of floods in the region. Despite the risks a lot of people live along the river and this amount is only increasing as developers keep building more homes. Such a new development is planned for a small island in the Chao Phraya river. The developments on this island must be thoroughly protected against floods, especially extreme floods. To achieve this, insight is needed into extreme floods.

This was the first step of the Thesis and the focus was on a T1000 flood event. A hydraulic model was used to gain the lacking insight by simulating extreme flood events in the region of the developments. These model simulations provided an understanding of the severity of extreme floods by determining aspects like water depth, flood extent and flow velocity. The design masterplan of the planned development was implemented in the hydraulic model such that the impact of a T1000 flood on the developments was found. Consequently, sufficient flood protection measures were made for the design masterplan to protect the developments against a extreme flood.

However, despite sufficient protection the impact of an extreme flood calls for an extensive crisis response plan. This was the second step of this Thesis. With a clear picture of the consequences of an extreme flood, a fitting crisis response plan was drafted. This plan was not solely based on the hydraulic model results, but was also supported by literature research about the current flood response in Thailand. This was done to ensure the proposed crisis response plan will actually be implemented and residents will follow it when an extreme flood occurs.

The 2 main strategies that were found to be viable courses of action were staying on the study island or evacuating the island. The benefits and drawbacks of both option were discussed and the best course of action for crisis response in case of a T1000 flood event was found to be surviving the flood on the study island itself. Both literature research and the hydraulic model simulations supported this course of action.

Lastly, the proposed crisis response plan was laid along side the design masterplan of the development for the study island. All the additions and adjustments to the design masterplan required to implement the proposed crisis response strategy were elaborated upon.

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1 Introduction

Humans have been living along river banks for centuries. Rivers were, and still are, a source of fresh water to survive, they are used for transportation, they irrigate farmland and are used for leisure activities. But living near the water also comes with risk of flooding, which is the most common environmental hazard worldwide (Natural Disaster Association 2023).

Currently, floods are becoming more extreme due to climate change which causes more precipitation with higher intensity and rising sea levels. These extreme floods produce devastating consequences for the local environment and population. To gain insight into these floods, hydraulic models can be used. These models simulate the river system and surrounding landscape. Within this landscape a flood can be simulated such that the severity and consequences of a flood can be determined.

These floods can happen anywhere, but some areas like coastal regions, river floodplains, alluvial plains and delta's are most susceptible to flooding. It is essential to have a comprehensive response plan in place for these vulnerable areas. A well thought out crisis response plan can potentially save lives and avoid major economic damage. These plans need to be custom made for a specific area since they are heavenly dependent on the local landscape. Hydraulic models can assist with this, as they are designed for a specific area.

This research looks into the topics of hydraulic modelling and crisis response on a broad scale. However, it also focuses on a specific project. Namely, a development project on an island in Thailand. The following sub-chapters will introduce the exact project and provide the necessary background information. This project has not yet been announced by the contractor, and is therefore confidential. As a result, the contractor will be referred to as "the client" and the particular island as "study island" for the rest of this report.

1.1 Project background

Thailand has a long history of (catastrophic) floods, which often occur within the flood season in the months June-September nationwide (DPPMC 2015). These floods are triggered by long-term rainfall during the rainy season and/or by storm rainfall caused by a typhoon, which occur on average 6 times a year (WorldData 2023). This overload of rainwater results in floods that spread across the central and southern plains of Thailand.

The study island is located in the central plains of Thailand, 60 km to the north of Bangkok. This area is part of the Chao Phraya River Basin, which is a hot spot for flood disasters (AHA Centre 2015). The client has plans to develop the study island. Witteveen+Bos was contracted by the client to investigate and advise on water management aspects of this development project. Specifically, the client has asked Witteveen+Bos to perform the following tasks.

- To review all necessary flood management information, such as climate, topography, hydrology and design flood levels.
- To review and comment on the design of water bodies and structures related to water management, flood protection, water quality and groundwater.
- To assess and present options for typical canal cross sections, the water level control mechanism and navigation structures and flood protection.
- To develop a hydraulic model which can be used to assess the flood protection options and assess any effects on the surrounding areas.
- To advise in a crisis response concept in case of extreme floods or climate hazards.

1.1.1 Project goals and ambitions

The client has big ambitions for this development project. The project is to become a city that boasts living with water and never stops functioning, even during floods. This vision is derived from the living with water concept and entails that despite floods or shortage of water the city should operate without limitations. This means that parts of the island should be allowed to flood without obstructing the functioning of the city.

The client has several focus points for realising its ambitions. One of the focus point for this development project is resilience. The design should be able to respond to climate crisis, including river floods and extreme rainfall. Another focus point of is regeneration, the project should be self sufficient. This means that it should not immediately rely on external help in case of a flood.

1.2 Problem statement

Flooding occurs almost every year in the Chao Phraya river Basin (The World Bank 2012). Therefore, development projects are designed to withstand these floods. However, floods are becoming more extreme, surpassing the design safety level of existing levees and flood defence structures. It is therefore crucial to ensure the project is sufficiently protected against floods. It should also have a crisis response plan in place for floods which are more extreme than the design water levels.

Currently, crisis response plans are made ad-hoc in Thailand due to a lack of insight in extreme floods (return period > T50). It is currently unclear for governmental agencies what an extreme flood looks like in terms of hydrological conditions such as water depth, flow velocities and flood extent. The best reference data is from the 2011 flood in Thailand, which is considered the worst flooding in Thailand's recent history. However, this flood only registered on the magnitude of roughly a once every 10-20 years event (Gale and Saunders 2013).

Without a clear picture of extreme floods, proper crisis response plans cannot be made. Instead the many governmental bureaucracy layers create ad-hoc plans, which can lead to mismanagement of flood protection systems, as happened in 2011. This worsens the overall flood or it leads to measures that locally help reduce flood but in return create bigger problems elsewhere (Meehan 2012).

1.3 Research background

The entire project discussed in the previous chapters is too extensive for this Bachelor Thesis research. Therefore the research will focus on a smaller aspects of the project, namely the crisis response in case of a T1000 flood event. The T1000 flood event was chosen since it is the most extreme scenario that was modelled for the client. A crisis response plan that properly functions for this flood event would also function for lesser flood events like T400 or T100.

The research into crisis response looks into finding the best course of action for the safety of the residents of the study island. This is done in connection with the development plans of the overarching project, as crisis response is effected by the specific design plans for the study island.

The following chapters further discuss the background and direction of the research. First, the knowledge gaps for this research are elaborated upon. Afterwards, the research objective is stated as well as the research questions. Lastly, the research scope is discussed. All of these chapters combined clearly demarcate the content of the research discussed in this report.

1.4 Research gap

Preliminary designs were made for the development of the study island. The aim of the client is for the design to be self sufficient and resilient during floods. To achieve this, the development plans are made based on a design flood level. However, there is a possibility that extreme floods will occur that are bigger then the design flood and this is where a knowledge gap exists. There are 2 main elements in this lack of knowledge:

1. **The hydrological situation when an extreme flood happens.**

The closest reference for a T1000 flood event is historical data from the disastrous floods of 2011. Figure 1 shows the devastating effect this flood had on the study area and surrounding landscape.

Figure 1, The study Island (red arrow), before 2011 flood (left) and after 2011 flood (right)

As figure 1 shows, the entire study area and surrounding landscape were completely inundated. Despite this severe impact, the 2011 floods only have a return period of T20 (Gale and Saunders 2013). As this is the worst flood to date, there is no available insight into important flood characteristics for more extreme floods like a T1000 flood event. The unknown characteristics of extreme floods are: water level, flood duration, flow velocities and flood extent. In order to investigate these characteristics a hydraulic model has been made by Witteveen+Bos. and will provide a clearer insight into the effects of a 1,000 year flood on the area and proposed design for the study island.

2. **A crisis response plan that elaborates on courses of action in case of an extreme flood.**

Although the project will be designed to be resilient against major flooding, the project needs an adequate crisis response plan in case of extreme flood events. The plan should provide a clear strategy in case of flooding that ensures the safety of the local inhabitants as well as visitors of the study island. For this to become a reality, the following knowledge gaps need to be filled:

- Whether residents and visitors can safely remain on the island or have to be evacuated.
- Possible locations to evacuate to.
- The timeframe of the evacuation.
- Mode of transport for the evacuation.
- Key necessities for remaining on the island and how to provide them.
- Shelter locations on the study island.
- Time duration of sheltering on the island, when are residents able to leave.

1.5 Research Objective

Combining the problem context and the knowledge gaps that exist in the research field, the research objective is determined. The major knowledge gaps for this project are the lacking insight in the hydraulic conditions of Chao Phraya river in case of extreme flooding. Furthermore, the lack of a crisis response plan in case such flooding occurs. Specifically for the development project, and therefore this Thesis, the research objective is two-fold and as follows:

To investigate the hydrological characteristics during extreme floods up to T1000 in and around the study area. Furthermore, to provide recommended course of action to the client in case of extreme flooding of the study island.

1.6 Research questions

To reach the research objective, several questions need to be answered. For this Thesis there are 2 main questions. Each of these main question is further divided into sub questions. The first main question of this research is:

1. **What is the impact of a T1,000 flood on the hydraulic conditions around the study island?**

To provide an answer to this question a few sub questions need to be answered first. These question are:

- *What is the maximum water level in the Chao Phraya river around the study island in a T1,000 flood event?*
- *How long does the flooding last and how does the water level in the Chao Phraya river change over time during a flood?*
- *Is the Chao Phraya river still navigable in case of a T1,000 flood?*
- *What is the flood extent in case of a T1,000 flood around the study island?*

The second main research question for this Thesis is:

2. What is the course of action to ensure the safety of people on The study island during a T1,000 flood event and how should the design masterplan be adapted to make this possible?

To give an answer to this question a few sub questions need to be answered first. These question are:

- *After which time period is it possible to leave the study island safely?*
- *What are possible locations to evacuate to outside of the study island?*
- *What is required to stay on the study island safely for the duration of a T1,000 flood event?*

1.7 Research scope

The research is bound by a time constraint of 10 weeks, therefore some limitations to the scope of this research are present. These constraints are listed below and demarcate the research such that it fits within the time constraint.

- The hydraulic model needed to find water level during a major flood in the Chao Praya river will be completely made by Witteveen+Bos. In this study, only the model outcomes will be used. No additions or alterations will be made to the model supplied by Witteveen+Bos.
- Only a T1,000 flood will be investigated. Although crisis response plans need to be in place for smaller floods as well, The focus of this research is only on a plan for a T1,000 flood.
- Even though a large area will be inundated after a major flood, the focus lies on the residents and visitors of the study island. The surroundings of the study area are not taken into account.
- It is assumed that the development of the study island will be realised without any major deviations from the design masterplan mentioned in chapter 2.3.

1.8 Reading guide

The previous (sub-)chapters provided background information about the specific project that this research is linked to. The structure of the remaining of this report is the following:

- Chapter 2 discusses the study area in more detail, discussing the study island and the characteristics of the Chao Phraya river.
- Chapter 3 describes the theoretical framework that forms the basis of this research, including the key concepts for this research.
- Chapter 4 describes the methodology that was used to complete this research.
- Chapter 5 contains the results from the hydraulic model study.
- Chapter 6 discusses crisis response, the current situation in Thailand, possible courses of action and the advice for this specific project.
- Chapter 7 contains a discussion about the outcomes of the research, the answers to the research questions as well as recommendations for future research.
- Chapter 8 summarises all other chapters, listing major steps and conclusions drawn for this research.

2 Description of study area

This chapter discusses the study area of the project. The location and physical characteristics of the study island are elaborated. Furthermore, the hydrology and characteristics of the Chao Phraya river are discussed.

2.1 Study area

The study area of this study (the study island) is shown in figure 2.

Figure 2, The study Island

The study Island has a size of 96 hectares. The island is hardly developed; there are only several dwellings along the shoreline while the centre of the island is filled with grass fields. The area of the planned development covers about 64 hectares of the island, as can be seen in figure 2. The island is located in an alluvial plain in the lower reaches of the Chao Phraya river, which flows form central Thailand to the gulf of Thailand. The entire Chao Phraya basin is shown in figure 3.

Figure 3, Chao Phraya river basin

Figure 4 shows the ground elevation level of the study island and its immediate surroundings.

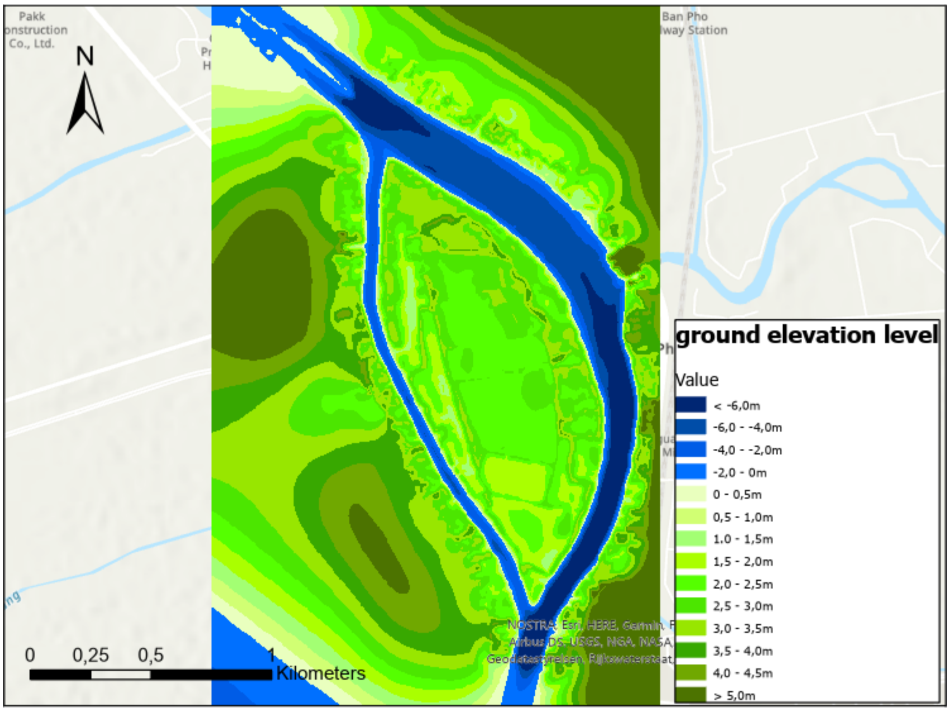

Figure 4, ground elevation levels study island

The study island has a range of different elevation levels. The northern tip and east side of the island along the main river branch have the highest elevation levels, between 1m and 3m +MSL, of the island. The west side of the island along the smaller and shallower river branch varies in elevation between 0m and 1.5m +MSL. The major centre part of the island has an elevation of 2.0m to 2.5m +MSL.

2.2 River hydrology and characteristics

Chao Phraya river is the main river of Thailand and with a length of 365 km and a basin of 160,079 km^2 (Encyclopedia Britannica 2019). The river provides water for settlements along its shores as well as irrigation water for rice fields. It also serves as a transportation artery within the city of Bangkok. The river is characterized by the monsoon season which causes the water levels of the river to fluctuate over the year. Figure 5 shows the average water levels of the Chao Phraya river as a function of time for the period 2004-2022 at gauging station C.35. Figure 6 shows all relevant gauging stations along the Chao Phraya river.

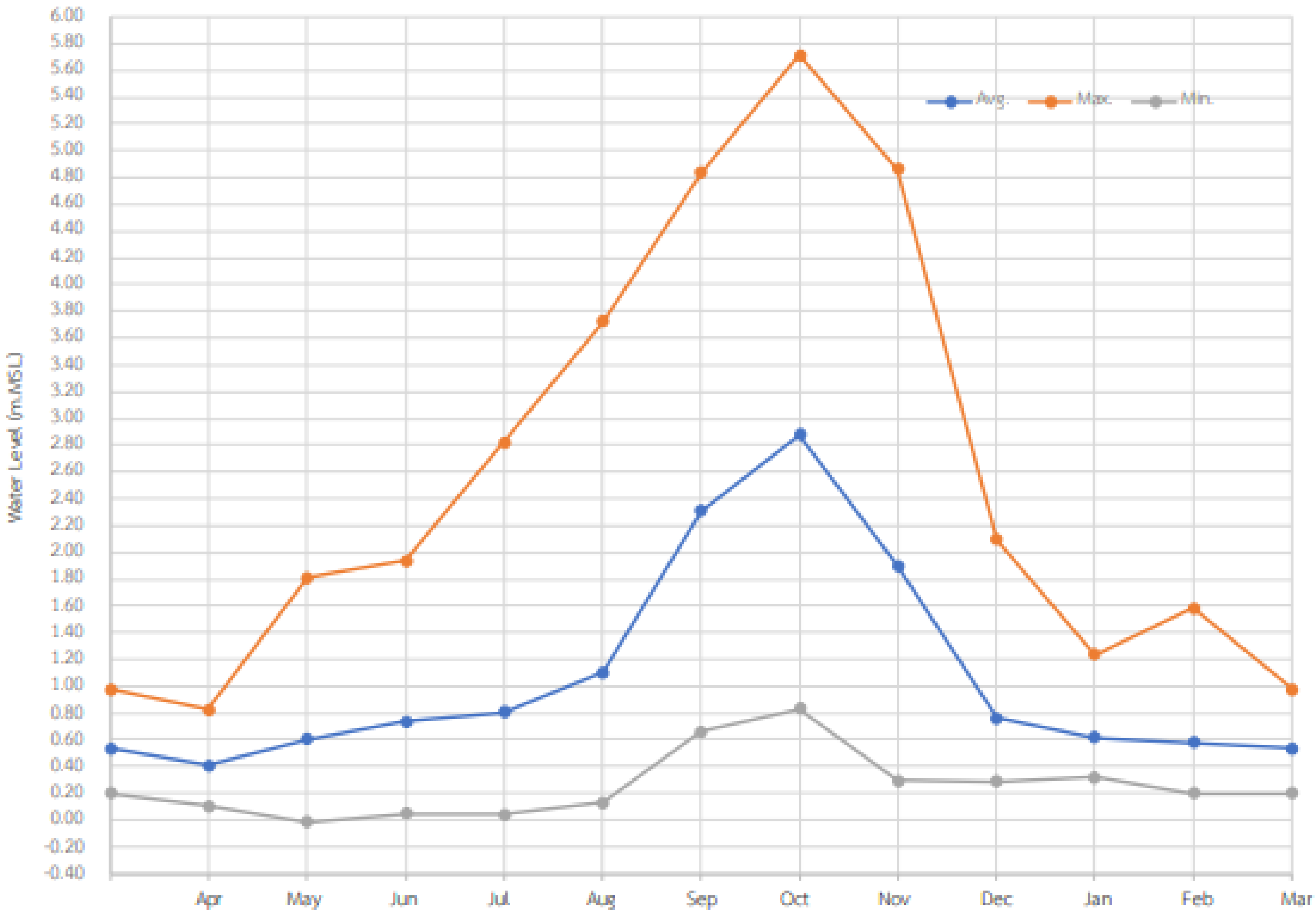

Figure 5, Average Monthly Water Level in the Chao Phraya River (2004-2022) at gauging station C.35

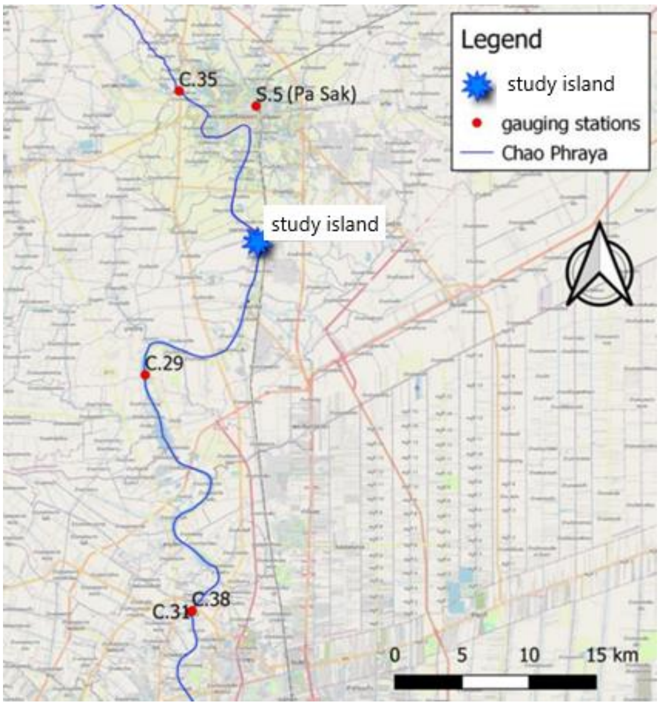

Figure 6, gauging stations along the Chao Phraya river

The data in figure 5 was gathered at the closest gauging station upstream of the study island, gauging station C.35 shown in figure 6. Figure 5 shows that the maximum water level ranges between approximately 1.0 and 5.5m +MSL. The main part of the study island as shown in figure 4 lies between approximately 2.0 and 2.5m +MSL, which almost guarantees flooding during the rainy season.

Furthermore, figure 5 depicts the varied nature of the chao Phraya river. The shape of the average, maximum and minimum water level clearly show the effects of the rainy season (May-October) and dry season(November- April). The variation of the water level is often multiple meters, which is an challenge for the study island. This is because the island should be protected against high water levels but should also keep functioning during droughts. For instance, vessels navigating to and from the island need sufficient draught during drought.

Next to variation during the year, there is also significant variation between a dry year with drought and wet years with floods. The orange line (maximum water level) depicts the situation in case of extreme precipitation. Especially during the rainy season the water levels are exceptionally high reaching up to 5.80m +MSL, which ensures large scale inundation. The grey line (minimum water level) shows the other side of the spectrum, namely drought. During the rainy season the water rises to a meagre 0.80m +MSL and the rest of the year water levels are even lower. This impacts water provision to the study island and surrounding farmland.

However, not only the extreme years cause problems. The blue line in figure 5 indicates that even for an average year the water level varies between 0.40 and 2.70m +MSL. This also entails that even during an average year parts of the study island will flood for several months, since 2.70m +MSL exceeds the ground elevation level of parts of the study island (figure 4). Because of the varied nature of the river both drought and flooding can occur it is essential to take this into account when making plans for the development project on the study island. The island has to be operational and reachable with high and low water levels.

2.3 Design masterplan

To achieve the ambitions of the client (chapter 1.1.1) a design masterplan has been made following the philosophy of living with water. The design uses different land elevation levels for parts of the development project as can be seen in figure 7.

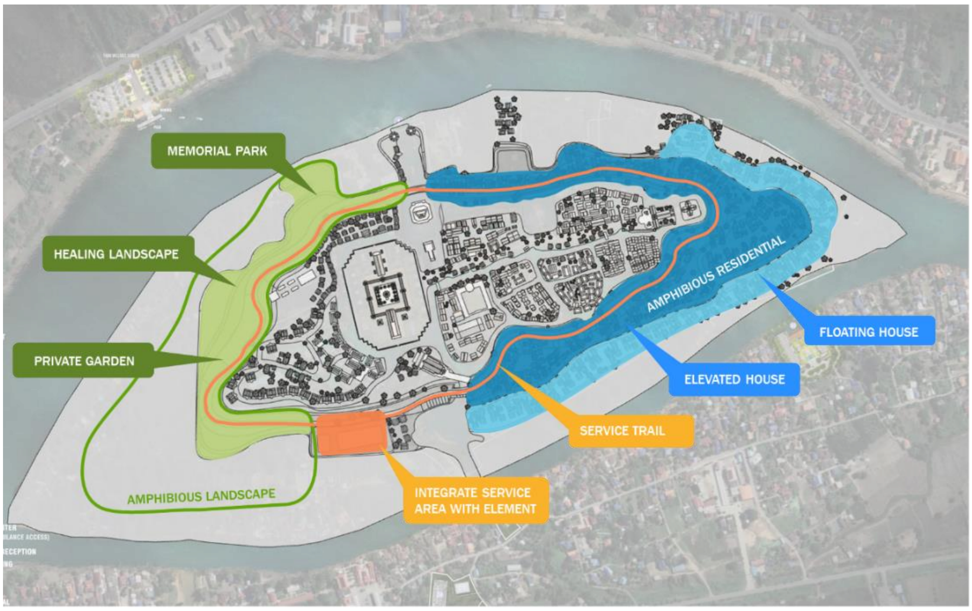

Figure 7, Design masterplan the study Island

Figure 8 shows a 3D version of the design masterplan, including the planned location for all houses, commercial buildings and temple.

Figure 8, 3D version of the design masterplan

Figure 8 clearly shows the internal water system that separates the different districts and temple in the central non-flood zone. This central area is surrounded by a dyke, depicted with dark green in figure 8.

The main aspects of the design shown in figure 7 and 8 are:

- The central area is filled with commercial buildings as well as a temple. These buildings are never allowed to flood, so the central no-flood zone area is protected by a dyke (orange line in figure 7). The dyke's crest height is set at 6.20m +MSL to offer protection during extreme floods.
- Surrounding the central area are residential areas with varying levels of elevation, between 2.5 and 3.5m +MSL. These areas are allowed to periodically flood, as part of the living with water concept.
- All buildings in the periodic flood zones (blue area in figure 7) have floor levels of 6m +MSL to protect people and property form flooding. This is achieved by building either elevated- or floating houses. Although the buildings themselves remain safe, the ground level will flood.
- The inner water system is separated from the outer (river) water system by a lock. The lock enables vessels to overcome any differences in water level between the inner water system and the Chao Phraya river.

A safe elevation level of 6.20m +MSL for all the buildings was chosen based on historical data gathered at a measuring station upstream of the island. The choice of this safety level of 6.20m +MSL is further supported by the fact that industrial estates in the vicinity have increased their flood protection measures to similar standards, as can be seen in figure 9.

Figure 9, flood protection levels of industrial estates

3 Theoretical framework

Hydraulic models are one of the key concepts within the essential theory for this research. Therefore, the basics of the hydraulic model used for this research will be described below. On top of that, key concepts regarding crisis response are discussed in this chapter. All this information combined forms the theoretical framework needed to understand this Thesis research.

3.1 Hydraulic models

Hydraulic modelling is a form of physical modelling used for replicating flow and fluid-transport processes in diverse natural flow systems (Ettema, Arndt en Wahl 2000). Hydraulic models are virtual representations of a study area created from river cross sections, elevation maps and land use data. After the study area is build different scenarios like a T2, T10 or T1,000 flood can be investigated by specifying a certain discharge, so how much water flows through the study area. The hydraulic model then simulates how the water travels from the upstream boundary towards the downstream boundary of the study area. The hydraulic model provides insight into water depths, water flow, flow velocities and water retention time.

There are multiple types of hydraulic models used in the field of hydraulic engineering. There are 1 dimensional (1D), 2 dimensional (2D) or combined 1D-2D hydraulic models. Each type has its strengths and weaknesses and which type is the best choice depends on the study area and goals/aims of a project. In general, 1D modelling takes less effort to develop and calibrate and has a lower computational time (Brunner 2021). The trade off is that 1D works best in “simple” situations where flow maintains primarily uni-directional flow patterns and water flows within well-defined channel/overbank systems (Goodell 2016). For more sophisticated study areas where flow will go continuously in multiple directions, 2D potentially provides better results but at the cost of longer computational time.

Following developments in software for hydraulic models, an increasing number of projects now apply a combined 1D-2D approach. With this method the clearly demarcated riverbanks within a study area can be modelled in 1D and the surrounding area outside of the embankments is modelled in 2D. D-HYDRO is a modelling software that makes use of this approach and this software will also be used for this Thesis. The specific set-up of the D-HYDRO model is given in chapter 4.

3.2 Crisis response

Early warning systems

Crisis response starts with early warning systems, which are the first to notice that a potential crisis is coming. These systems allow residents and authorities to properly prepare for a disaster. International standards state that in the case of flooding, alerts should be issued at least 120 hours in advance (Thai PBS World's General Desk 2022). This ensures that there is sufficient time to prepare for a flood. Unfortunately, this 120 hours standard is often not the case in Thailand. These alerts are often based on measured water levels at gauging stations upstream. If water level values exceed a critical value an alert is issued to the population downstream. It is also possible to send out alerts based on weather forecasts. If water levels are high and heavy rain is expected then an alert can be send out pre-emptively to warm people of possible flooding. However, if this is done to soon and the weather changes a warning only causes panic among the population.

Evacuation

After the early warning systems have set the crisis response in motion, multiple process start to unfold both before and during a crisis. The most important process is the potential evacuation of property and residents within the disaster area. After a warning is given and people have a idea of the magnitude of the flood they have several options for what to do with their property and themselves. On of these options is to move to relatives in higher elevated areas, however this is not always possible. Another option is to evacuate to a public shelter, this is most often a big public building like a school or hospital that is build to better withstand floods then the houses of residents in the area. The last option is to stay in their own house. In Thailand, locals have become quite adapt at getting through floods in their own homes. The choice of one of these options depends on multiple factors such as health and well-being of the residents, income, magnitude of the flood and time until the flood arrives.

Information

During all the steps mentioned above, form early warnings to evacuation procedures, the provision of information is crucial. Governmental institutions should provide clear and timely communication to residents. The basic principle behind this is in most countries disaster warning levels. In Thailand, there are 5 disaster warning levels that the government uses to communicate the severity of a disaster (Center for Excellence in Disaster Management and Humanitarian Assistance 2022). Next to that, updates about the location and speed at which the flood spreads must be shared with the public. This can be done via news channels or text messages send by the government.

There is also information sharing between residents. This happens mostly via social media, where people share what is happening in their own area. This information is then used by others to based their evacuation plans on. A downside to this is that information shared through social media can be confusing and contradictory (Thai PBS World's General Desk 2022).

4 Methodology

This chapter describes the methodological approach that was used to answer the 2 main research questions. The methodology will be discussed for both research questions individually in the sections below. First, figure 10 shows a flow chart that provides a clear overview of the general steps that were taken. Afterwards, the methods that were applied to answer the questions are discussed more in depth.

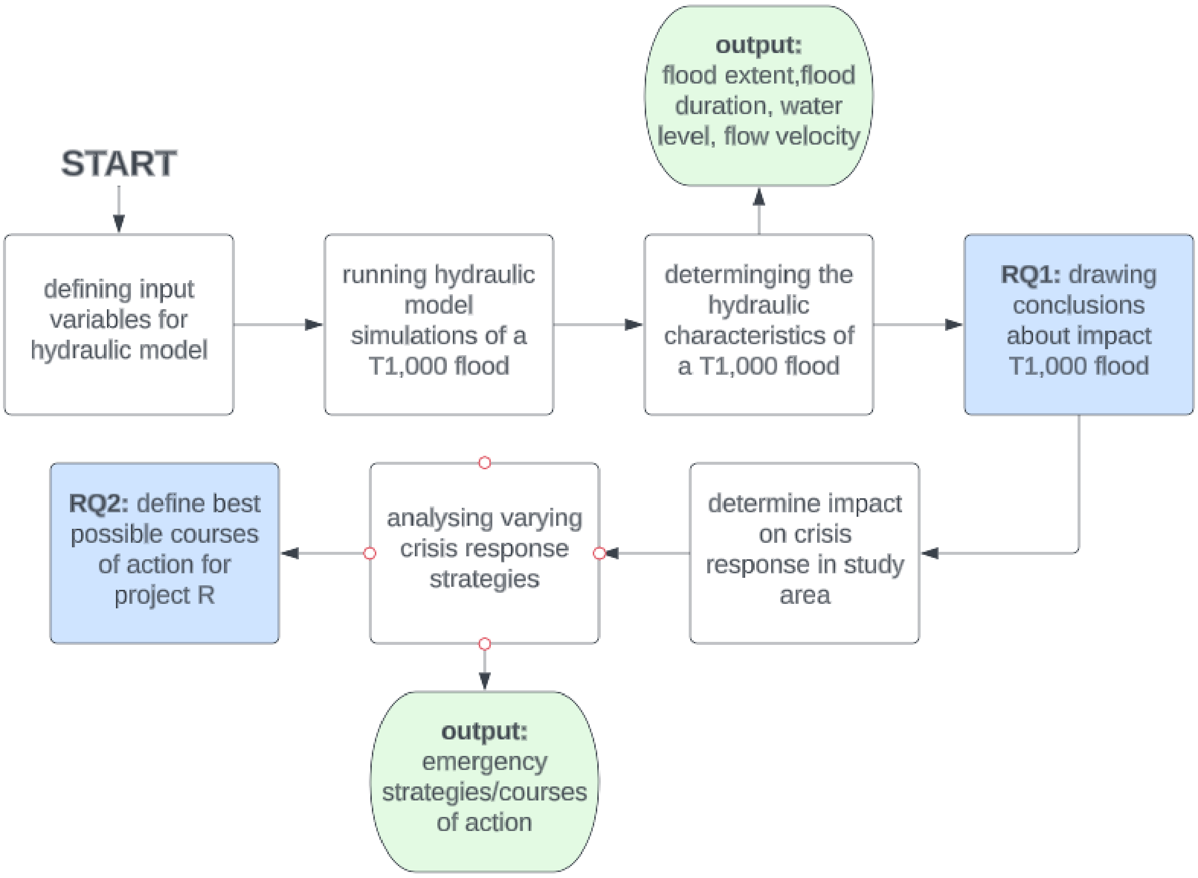

Figure 10, Schematic of methodology

4.1 Research question 1

The first research question, *What is the impact of a T1,000 flood on the hydrological conditions around The study island?,* was answered by using 2 different methods. The first was simulating different scenarios in the hydraulic model made by Witteveen+Bos. The hydraulic model was made with the D-HYDRO software, which has been developed by Deltares. The model uses a combined 1D-2D approach, modelling some of the study area in 1D and other parts in 2D. This ensures detailed results with a reasonable computation time. In this instances the computation time was approximately 6 hours per simulation.

The D-HYDRO model needs several inputs to simulate different scenarios. The main inputs of the model are: roughness of different parts of the river, cross sections of the river and discharge data from gauging stations along the Chao Phraya river. The scope of the hydraulic model can be seen in figure 11.

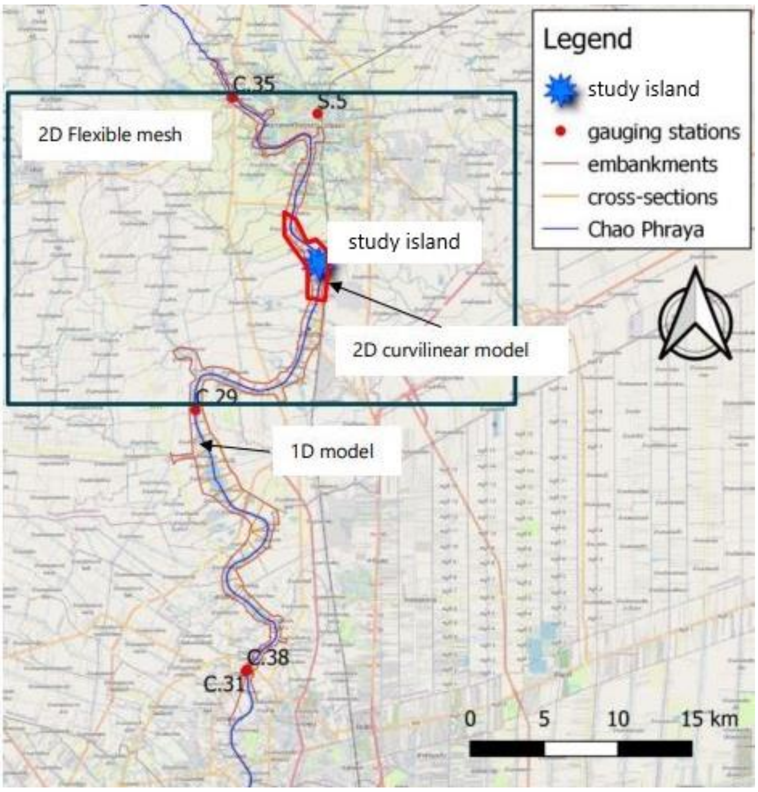

Figure 11, Scope of the hydraulic model made by Witteveen+Bos

The scope of the model includes the area between gauging station C.35 and C.31/C.28. The area within the river embankments was modelled in 1D. Another section of the study area outside the river embankments was modelled in a 2D flexible mesh. The model was calibrated using the roughness of the summer bed of the river. This variable was varied and the model outputs were then compared to measuring data from gauging stations C.29, C.31 and C.35.

Multiple simulations were conducted in D-Hydro for T1, T2, T10, T25, T100, T400 and T1000 flood events. In all these cases the current situation was simulated (reference scenario) and a simulation including the design masterplan (MP3) shown in figures 7 and 8. All the simulations apart form the reference scenario took into account climate change. On top of that, the effect of a side channel that is currently being dug was also taken into account by adjusting the input discharge of the model.

The simulations resulted in multiple outputs. These outputs are: water levels, flood extent and flow velocities. From the data the maximum outputs of the flood characteristics were derived. These were then used to determine the impact of the T1000 flood on crisis response.

Water levels and flow velocities were used to determine if evacuating the island was a possibility. The actual water depths and flow velocities were gained form the model simulations. With expert judgement and literature sources thresholds were determined for both water depth and flow velocity. If the outputs exceeded these thresholds evacuation attempts would be limited and only possible with additional constraints. Locations to possibly evacuate to were determined with the flood extent and water levels. Flood duration and water levels were used to determine how long and how severely the flood would disrupt residents' lives.

The second method to answer the first research question was looking at historical data of extreme floods in the area. The data obtained form this method served as an extension to the hydraulic model output. This method does have some drawbacks, data is limited since T1,000 floods are a rare occurrence. Furthermore, data was often only available in a single measurement and not per time interval during a flood event. Despite the drawbacks historical data was still used since, not all sub-questions could be answered with just the hydraulic model results. Specifically determining the flood extent was not possible since the model scope as shown in figure 11 is limited and therefore cannot show the complete flood extent. Historical data of extreme floods covered for this and showed the flood extent outside of the model scope. An example of this is the areal photo shown in figure 8, which shows the extent of the extreme flood in 2011 in and outside the scope of the hydraulic model.

To conclude, the hydraulic model approach provided accurate and precise data on many hydraulic characteristics of an extreme flood, but is limited in scope. The historic data method doesn't have a scope limitation but the obtained data was not as exact and extensive as hydraulic model outputs. By combining both approaches accurate data for the direct vicinity of The study island was obtained and conclusions about the area outside of the model scope were made.

4.2 Research question 2

The second research question, *What is the course of action to ensure the safety of people on the study island during a T1,000 flood event and how should the design masterplan be adapted to make this possible?,* applies a different methodology then the first research question. However, the results from the method applied in the first research question were used to answer the sub-questions of the second research question. For all sub-questions data from the hydraulic model is needed, so the methodology for research question 2 starts by answering research question 1, as is shown in figure 10.

With the hydrological conditions known, different methods were applied at each sub-question in order to answer the second research question. To answer the first sub-question "*After which time period is it possible to leave the study island safely?"* the navigability of the river was determined. There are currently no bridges to the island, so the main way for residents to leave by themselves is by boat. Finding out when this is possible was investigated based on the flow velocities obtained form the hydraulic model. On top of that, it is important to know if there is a lot of debris in the river after a flood, which was determined with literature research.

For the second sub-question "*What are possible locations to evacuate to outside of the study island?"* maps of the flood level and -extent were made. With these maps in mind the next step was to determined what the range of possible evacuation is. As mentioned earlier the primary mode of transport to evacuate is by boat, which limits the range of evacuation. Once a suitable range was chosen the next step was to identify possible location to evacuate to. These location were identified based on multiple factors, such as distance from the study island, capacity, available facilities and elevation level.

For the last sub-question, "*What is required to stay on the study island safely for a prolonged period of time?",* the first step was to determine what kind of supplies and facilities are needed for people to stay on the study island during a flood. This was investigated based on literature and existing crisis response plans of similar projects. After this it was determined how many people are expected to stay on the island during a flood. This information was obtained based on the housing capacity of the developments and the amount of residents and workers on the island during one day.

The next step was to determine the amount of time people need to stay on the study island. This was done with the flood duration obtained from the hydraulic model. The value found with this approach was the maximal time. However, depending on the answer to sub-question 1 this time might be shorter since people might be able to leave before the end of the flood.

Once the relevant supplies, amount of people on the island and time period was chosen, the amount of supplies could be estimated. With this final estimation all the information has been obtained for the last step of this sub-question, namely making proposals for the design to accommodate people staying on the island or aid in evacuation during a flood. This proposal includes locations to shelter people, storage for fuel and food, power generators and other facilities.

To further improve the soundness of the conclusions drawn from the literature research an expert was contacted as an credible local source of information. The expert in question was Dr. Seree Supratid, Director of the Climate Change and Disaster Center (CCDC) and professor at Rangsit university. All questions and answers from Dr Seree are listed in appendix A.

5 Hydraulic model Results

After all the scenarios had been simulated in the calibrated hydraulic model, the data was collected and analysed. All the main results for a T1000 flood are discussed in this chapter. Multiple figures of the model outputs are shown in this chapter, but not all. Additional figures as well as the model calibration results can be found in appendix B.

5.1 Water depth

Figure 11 shows the Maximum water depth at the different measuring points in the model for different return periods.

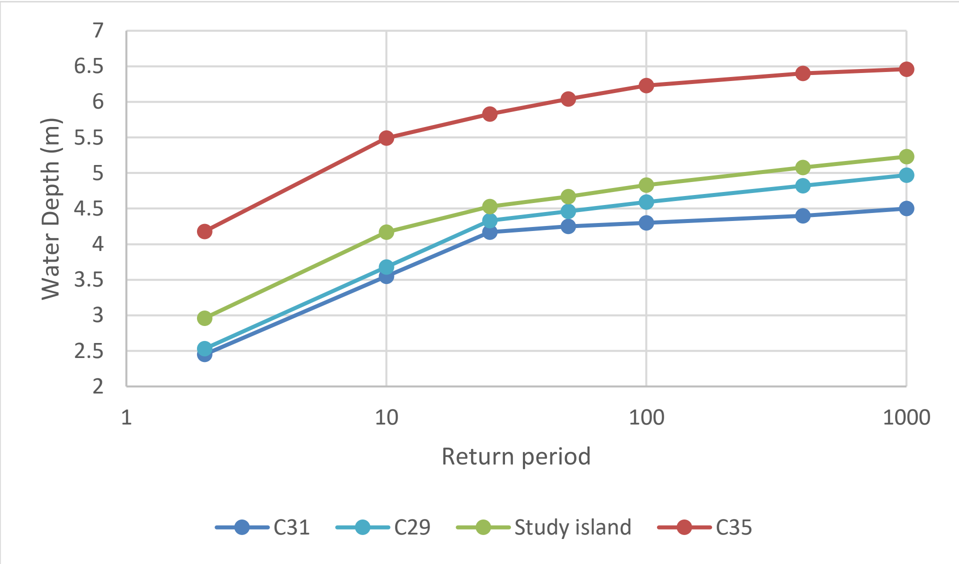

Figure 12, return period vs water depth in the Chao Phraya river

Figure 12 shows that the maximum water level around the study island in case of a T1000 flood is 5.23m +MSL. It also indicates that between higher return periods the increase in water level becomes less significant compared to the increase between lower return periods. The reason for this is that at higher return periods the whole surrounding area is inundated, therefore a much bigger volume of water is needed to make the water level rise.

Figure 13 and 14 show the maximum water depths in case of a T1000 flood event for the reference scenario and with the implemented design masterplan respectively.

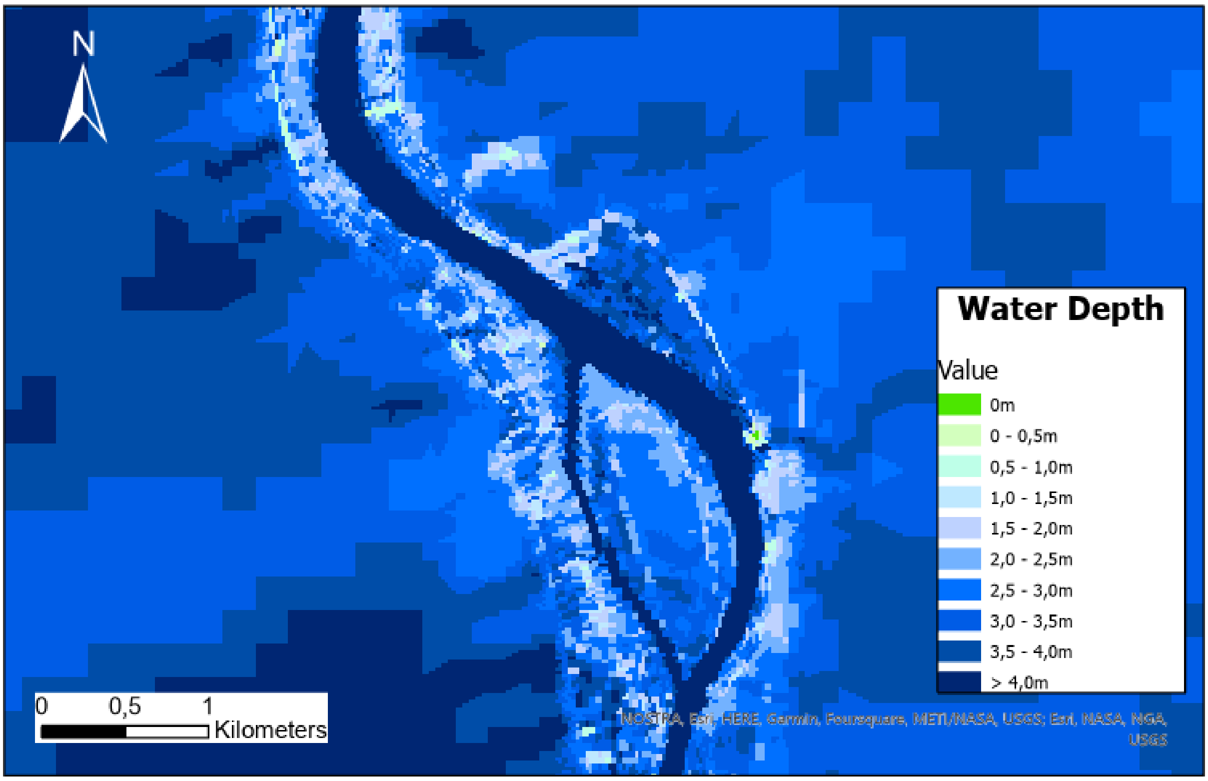

Figure 13, T1000 flood event reference situation scale 1:34.000

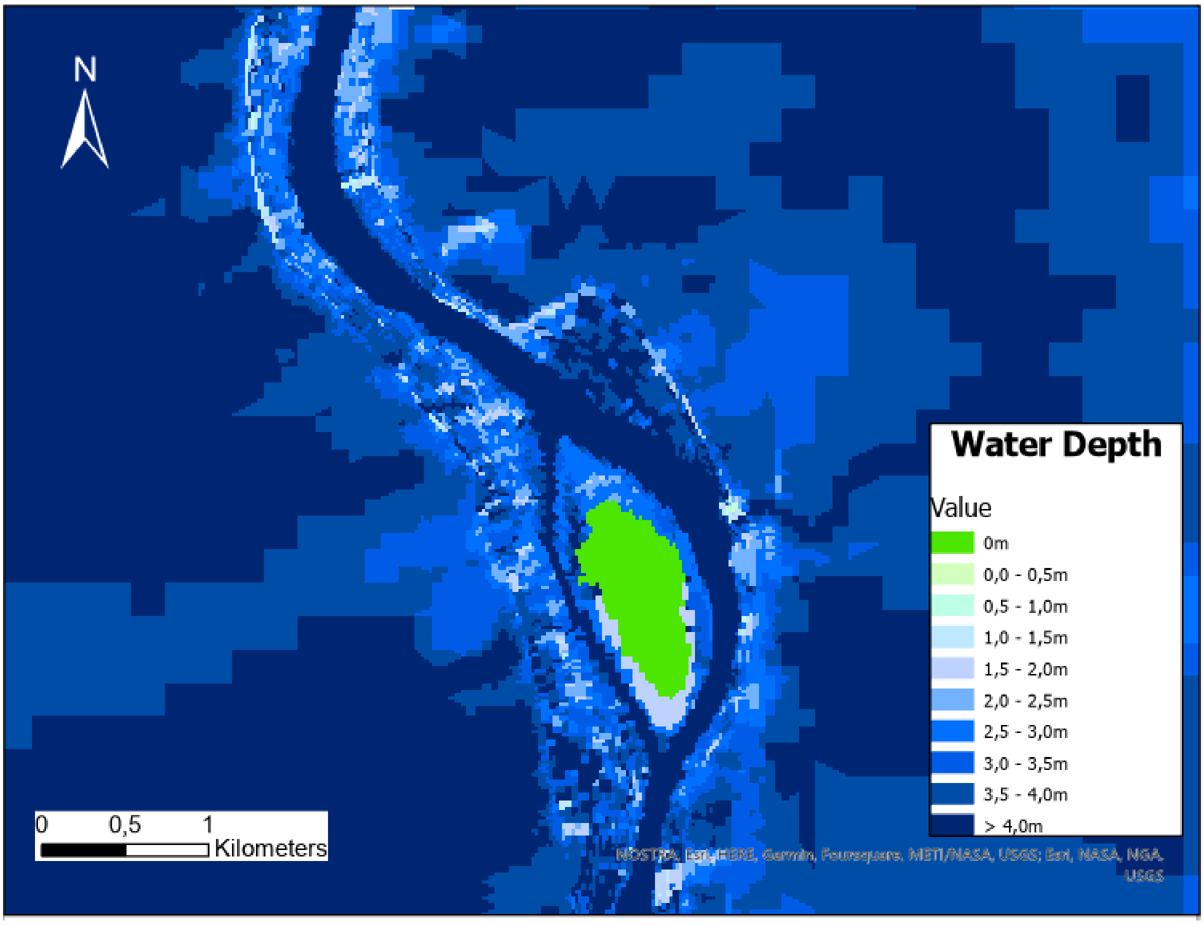

Figure 14, T1000 flood event design masterplan iteration 3 (MP3) scale 1:34.000

Figure 13 shows that if a T1000 flood were to happen now, the entire island and its surroundings will be completely inundated with at least half a meter of water. Some areas will even have over 4 meters of inundation. Figure 14 shows that once the design masterplan for the study island is implemented, there will be some dry area if a T1000 flood happens. Parts of the island will still flood, but this has been taken into account in the design plan. These areas make up the amphibious zone (blue area in figure 7). While the ground level floods, buildings will be safe because of higher elevation or because the buildings are floating.

Figure 14 also shows that the developments on the study island make the inundation in the surrounding landscape worse. A much bigger area is inundated with 4+ meters of water in the MP3 scenario compared to the reference scenario. This major difference in water depth can largely be explained by climate change, which is taken into account in the MP3 scenario but not in the reference scenario.

In the direct vicinity adjacent of the study island the flooding is much less for the MP3 scenario compared to the reference scenario. Figure 14 clearly shows a large area of 1.5 to 2.0m water depth south of the core area. In contrast, figure 13 shows a water depth of at least 3.0m in the same area. As mentioned in chapter 1.7, the focus of this research is the residents and visitors of the study island. For them the developments are beneficial, as it creates non-inundated ground and reduces the water depth around the centre island in case of a T1000 flood event.

Both figures give a clear insight into the flood extent of a T1000 flood event. Unfortunately, they are still limited to the area within the model scope. For the area outside this scope satellite images like figure 1 give more insight into the flood extent. Figure 15 shows the 2011 flood extent in the entire delta that the study island is located in.

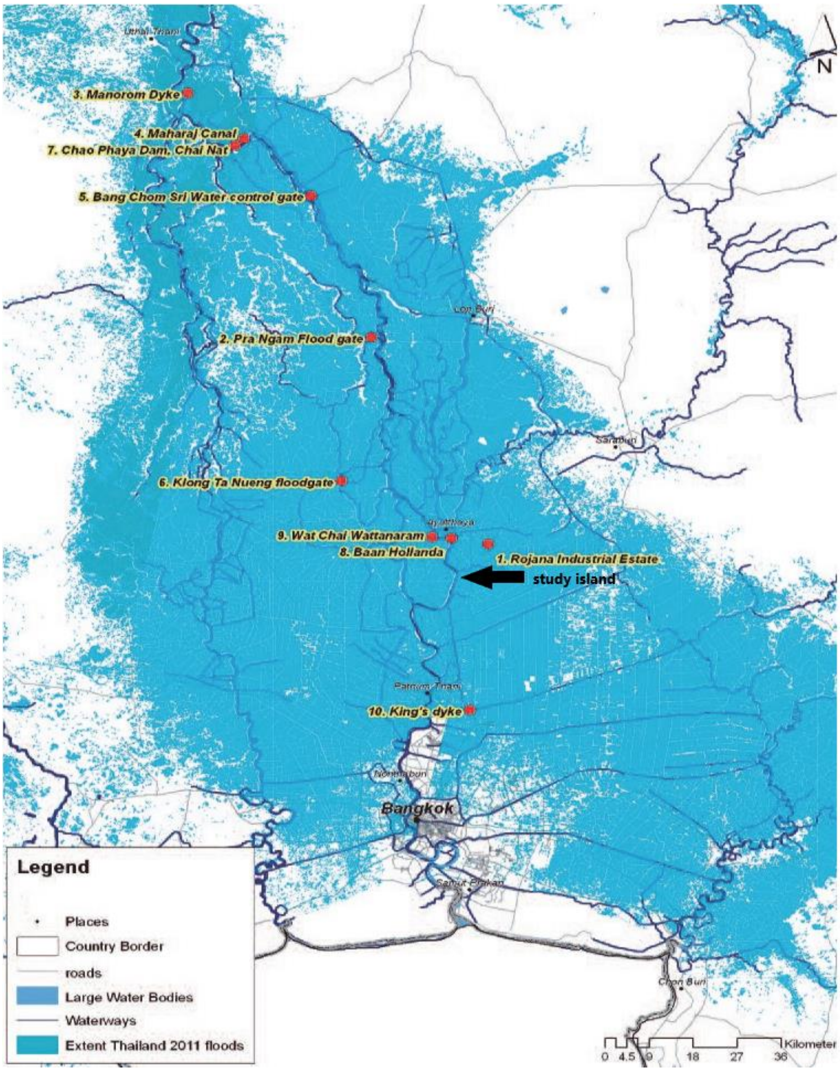

Figure 15, extent of the 2011 floods (T20) source: (Marks 2016)

As figure 15 shows, during extreme flood events the entire delta becomes inundated. The figure shows the flood extent of (only) a T20 flood (Gale and Saunders 2013), so a T1000 flood event would cause an even larger area to be inundated.

5.2 Flow velocity

Next to water depth another aspect of floods is the flow velocity of the water. Figure 16 and 17 show the flow velocity for a T1000 flood event for bot the reference- and MP3 scenario.

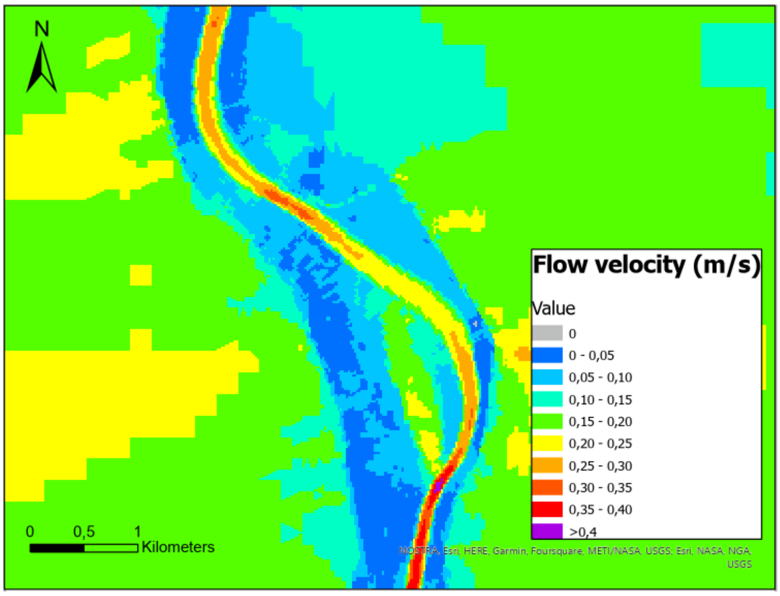

Figure 16, flow velocity T1000 reference scenario

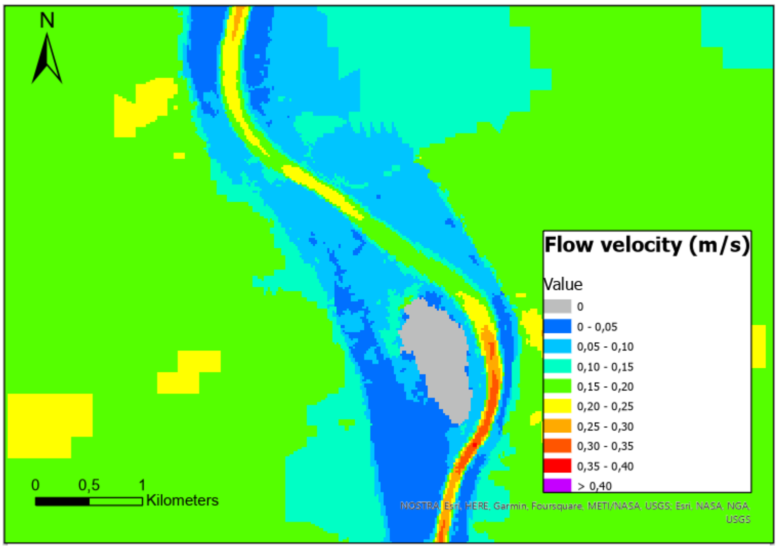

Figure 17, flow velocity T1000 MP3 scenario

Both figures show that the flow velocity in the main channel of the river is relatively high while the side channel to the west of the island has a much lower velocity. To put the magnitude of the velocity into perspective, a rip current which can overpower the average swimmer typically has speeds of 0.30 to 0.60 m/s (National Ocean Service 2023). Therefore it is only possible to use boats propelled by a motor to safely navigate the river. Using a row boat or swimming in these flow velocities is far to dangerous to be attempted.

Furthermore, the figures show that the flow velocity of the water is higher in the reference scenario compared to the MP3 scenario. Generally a higher water depth, which is the case in the MP3 scenario as figure 14 shows, means a stronger current. The flow velocity might be lower since the flood extent in the MPS scenario is larger so the water spread over a larger area, lowering flow velocity.

6 Crisis response Results

This chapter presents the results of research done for the crisis response of the study island in case of a severe flood. The proposed crisis response plan for the study island must fit within the overall structure of Thailand's emergency response. Therefore, the current structure of crisis response in Thailand is discussed first. Next, possible courses of action for residents of the study island are determined. Lastly, the best course of action for crisis response is given and the implications this has on the design masterplan are elaborated.

6.1 Current situation

The organisational structure of Thailand's Disaster response is shown in figure 18. The main organisation is the Department of Disaster Prevention and Mitigation with 18 provincial directors coordination emergency response in the 18 regions of Thailand. These regions are further split into areas in the care of a local director who dictates the specific emergency response plan within the area, following guidelines set by the higher levels of the organisation.

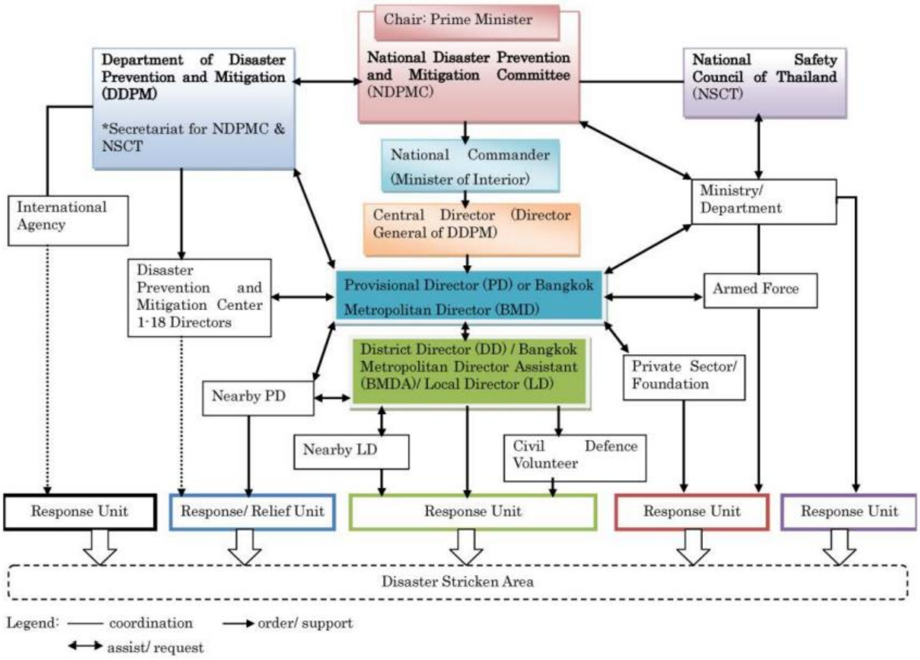

Figure 18, Disaster management System (AHA Centre 2015)

Unfortunately, there are some caveats in the current disaster response structure of Thailand. The first is the lack of an accurate Flood early warning system (FEWS). There is currently no functioning FEWS system for the Chao Phraya river (Supratid 2023). This causes agencies like the National Disaster Warning Center to rely on secondary data, like citing reports from the weather bureau (Thai PBS World's General Desk 2022). The data collected in this way rarely specifies crucial information like the flood level, flood duration and locations in danger of flooding.

The second weakness in the system is communicating the limited amount of information with the population. Alerts and information are often directed to other governmental organisations and executives, but not often shared directly with the population. Thailand does not have a wireless emergency alert system, like NL-alert in the Netherlands or IT-alert in Italy. Instead flood warnings are disseminated 3 to 5 days in advance on the main communication channel of the government, which is their website. However, this is only the case for fluvial floods. For pluvial floods there is no warning system, regional rainfall forecasts from the Thai Meteorological Department are the only source of information for the public (Supratid 2023).

The lack of clear communication and a FEWS results in alerts and warnings reaching the population to late, or not at all. Inhabitants often decide for themselves how to respond to a flood, evacuate or stay behind. There are public shelters included in evacuation plans for residents to go to. These are bigger buildings on higher ground or with multiple stories, like schools or temples.

However, shelters are not popular since they lack privacy and Thais are worried their belongings will be stolen (Krongthaeo, et al. 2023). Since evacuation ordered by the government is not mandatory, many choose to stay behind and guard their belongings. Even if they are forced to leave their homes due to the severity of the flood, they will set up tents along non-flooded roads in the vicinity of their homes and even leave a person at their house as a guard (Supratid 2023).

Traveling from their evacuation location to their homes is possible but in case of extreme floods only for bigger, family sized motorised boats. The river is still navigable and there are no major obstruction from debris, although it is not risk free and accidents still occur. Family sized boats are also used to buy drinking water and food at local shops or at a public service point that provides survival rations.

6.2 Possible courses of action for extreme floods

Due to the current structure of crisis response in Thailand, residents are left with two general options in case of a flood. They can either stay at their house or evacuate to a nearby shelter. In the case of the study island this means there are 2 possible courses of action, remaining on the island or evacuate to a shelter or other temporary refuge on the mainland.

6.2.1 Evacuation

With this course of action residents evacuate to shelter outside the study island, either an official shelter appointed by the government or an improvised shelter/a house of friends and family. Both evacuation options are time sensitive, since evacuation preferably starts ahead of the flood before roads and other infrastructure becomes unusable. Evacuation should therefore start at least a day in advance of a flood, so infrastructure is still intact. Furthermore, the emergency communication in Thailand often takes a long time to reach all residents. Evacuation to a shelter can start up later then moving to a higher elevated area, since shelters are often closer by.

If evacuation is initiated at sufficient time ahead of the flood, residents can cross the river by boat to the mainland and then use the roads to drive to a safe location. If the surrounding area is already inundated, limited evacuation is still possible. Figures 16 and 17 indicate that traveling across the water is only achievable in bigger motor propelled boats. The flow velocity in the main channel of the river is to high to safely row or swim across. Also outside of the river banks the water has a high flow velocity which makes motor boats the only option for long distance travel. There is no problem of large debris in the river but accidents normally do happen (Supratid 2023) so there is always some risk in delayed evacuation.

Evacuating to friends or family in a non-inundated area, can be too far away since the study island is located in a very flat plain with larger higher elevated areas far away. The closest dry land for residents of the study island (in a T20 flood event) would be at least 40km away to the east (figure 15), where the delta stops and the mountainous region begins. But in a T1000 flood event this might be even further away.

Furthermore, not all residents have friends or family living in an higher elevated area. Another option is to go to Bangkok, which is kept dry by sandbag walls and has highly elevated buildings that have non-inundated floor levels. However, the densely populated city becomes even more cramped with people from all over the delta fleeing to the city, so there might not be enough space.

An alternative to non-inundated areas are public shelters, which are often located in inundated areas. Figure 19 shows a map of possible public shelters in the vicinity of the study island.

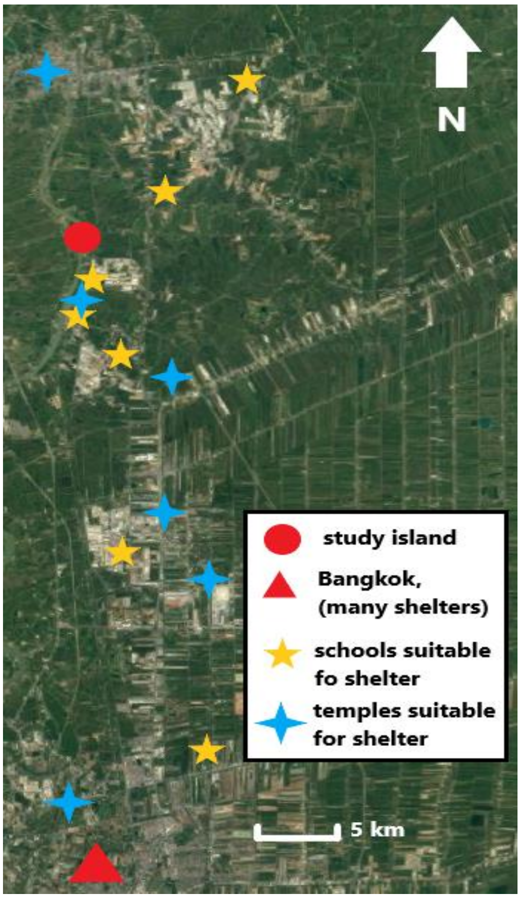

Figure 19, possible shelter locations

As figure 19 shows, public shelters are closer then traveling to friends and family. Buildings chosen to serve as a shelter are more common, since shelter buildings are mostly schools or temples. There are many more of these shelters then shown in figure 19. These buildings are either build on a heighten foundation or have at least 2 floor levels (Supratid 2023). This ensure that despite being located in inundated area, they can still shelter residents.

Despite an abundance of shelters, the willingness to evacuate to a public shelter is low among residents. From the current way residents respond to flood events it is clear that they favour staying near their property since they are worried about their belongings. Next to low willingness of residents, evacuation is also not in line with the ambition of the client to be self sufficient during a flood.

6.2.2 Stay on the study island

The alternative course of action to evacuation is to remain on the island during a T1000 flood event. The hydraulic model shows that the design masterplan (figures 7 and 8) creates an area that is not inundated in case of a T1000 flood (figure 14). So staying on the study island is a valid option. However, several things have to be taken into account before staying on the island is a realistic course of action. These are basic necessities such as a storage room for food, emergency drinking water supply, waste (water) treatment, healthcare and a power supply.

6.2.2.1 Shelter

The first necessity is that there are shelters present on the island, so the buildings on the island must be qualified to serve as shelters. Shelter buildings are generally made of concrete, elevated on strong pillars with a deep foundation and often have metal shutters against wind, rain and debris (UNEP-DHI CENTRE 2018). Most buildings on the island are constructed according to these standards, or can be adopted to fit the criteria. The buildings in the centre area of the study island are in a non-inundated zone, so they can serve as shelters. Since the houses in the amphibious zone still have non-inundated floor levels and flow velocities are maximal 0.10m/s (figure 17), they can also be used for shelter. Combining the buildings in these 2 areas provides sufficient space to shelter every resident of the island.

6.2.2.2 Power supply

The second necessity is a power supply, providing electricity to the shelter buildings on the island. Next to power for houses, electricity is also needed for other essential facilities on the island. For instance, the clinic that provides healthcare needs electricity to function. A power supply can be arranged in different ways. The simplest way is to use generators that turn fuel into electric power, provided there is enough fuel stored on the island.

Alternatively a sustainable energy source can be used, like solar panels. Solar panels can be mounted on the roofs of houses and will keep generating energy during a flood event. But this method is depended on the weather and might not be able to meet the demand for the whole flood duration. Consequently, using sustainable energy also requires a storage facility to stored energy ahead of a flood event.

6.2.2.3 Food & Water

Another basic necessity are supplies, like food and water. These can be stockpile before the flood in a storage facility on the island. Focus should be on food that does not spoil quickly, such as rice and canned goods. For the storage of water large tanks can be used and residents can collect water from the tanks to bring back to their shelter.

6.2.2.4 Transportation

The client aims to be self sufficient during a flood event and therefore supplies will be stored on the island. However, the flood duration of extreme floods spans multiple months, the 2011 floods (T20) lasted about 2.5 months (Supratid 2023). Therefore, going off island for supplies is inevitable. Making a storage space for food lasting 2.5 months is unrealistic with the limited space available on the study island.

As stated in chapter 6.1, drinking water and food can be brought in from outside the island, as well as other resources like fuel and medical supplies. Since the river is still navigable during a flood event motor boats can be used to transport supplies to and from the island. Boats can make many trips a day to gather food, water and fuel if storage on the island is running low.

Alternatively a helicopter can be used, however this entails that a landing zone is present at both the supply point and delivery point on the study island. Furthermore, this method of transportation is expensive and less efficient then motor boats. In specific cases a helicopter is better suited for transport. For instance, if a resident is badly injured and has to be treated at a hospital. Using a boat takes a longer time and might worsen injuries.

6.3 Proposed crisis response plan

After evaluating all the gathered Information, the best course of action for a crisis response plan is to stay on the study island and there are a couple of reasons for this. First of all, there are some limitations with the alternative course of action, namely evacuating the island. Finding non-inundated area to evacuate to is difficult since the surrounding area is also completely inundated. Furthermore, the flow velocity of the river puts some restrains and risk on evacuation as a course of action. On top of that, based on the current response of residents to a flood event it is clear that residents are not eager to evacuate away from their homes.

Therefore, staying on the island seems like the better course of action. However, this has several implications for the design masterplan. Some adjustments have to be made to ensure all the necessities mentioned in chapter 6.2 are present on the study island.

For the shelters, buildings need to adhere to certain standards, like deep foundations and made from robust materials. This can easily be taken into account during the construction phase of the development plans. Other aspects like metal shutters can be installed later, once the buildings have been build. For the houses in the amphibious zone, especially the floating houses, it is more difficult to apply these building standards. However , it is still achievable if these standards are though of at the beginning of the developments.

For a (emergency) power supply on the island the two options are either a sustainable source or making use of generators that run on fuel. Either method requires an underground cable network to distribute power from a central service building to the houses and facilities on the island. Both methods would imply a storage facility as well. In the case of generators to store fuel, which creates a contamination risk and/or fire hazard.

In the case of solar panels battery capacity storage is needed, since solar panels provide power inconsistently and might not generate sufficient power to meet demand during a flood. So, additional electricity must be supplies that was generated before the flood event. Due to the safety risks associated with fuel storage and ambitions of the client to be resilient and sustainable, using solar panels as a power supply is the better option for this project.

In order to store food and water a storage facility needs to be built on the study island. With the limited space available on the island and the flood duration of at least 2.5 months it is impossible to store enough food to last the entire flood event. However, a food reserve that can provide all residents with minimal meals to survive for at least one week should be present on the island at al times.

one week is chosen here as a worse case scenario, if for instance supplies form outside of the island are completely cut off or if the dyke around the central part of the island is breached and the island cannot be used as a shelter anymore. In these scenarios it will take some time to evacuate all residents off island.

To refill food supplies and water supplies from the mainland the best mode of transportation is a motor boat. So, a docking place must be built on the study island for these boats, preferably near the storage facility. The lock on the island can compensate for the different water levels of the inner and outer (river) water system so motorboats can travel to and from the island.

Next to boats, a helicopter might be needed for certain situation. To facilitate this a landing zone must be present somewhere on the study Island. When some parts of the study island are inundated this limits the available options for this landing zone. The best location for a landing zone is on the flat plateau surrounding the temple in the centre of the study island (figure 8).

With all these adjustments and additions to the design masterplan the study island should be sufficiently prepared for a T1000 flood event. However, in the nature of disasters, something can go wrong. In the case of this project, damages might occur to the dyke surrounding the central area of the study island, to the lock connecting the inner and outer water system or to houses in the amphibious zone.

If the dyke is breached the central area will also be subject to several meters of inundation, since the elevation of this area is 3m +MSL while the surrounding water level will be around 6m +MSL. Consequently, the study island loses almost all of its shelter capacity. This also happens if multiple houses in the amphibius zone are damaged. If the lock becomes unusable it will block the refilling of supplies from the mainland. All these situations take away one or multiple necessities for staying on the island during a flood event. Once staying on the island is not an option anymore, the next course of action despite the drawbacks is to start evacuating the island.

7 Discussion & recommendations

While this research has been conducted as thoroughly as possible, there was a time limit of 10 weeks. So there are still some discussion points regarding the hydraulic model and crisis response research as well as recommendations for future research. Despite the time constraint, valid outcomes were found which contributed to answers for all the research questions. All of the above will be discussed in this chapter.

The first research question was: ***'What is the impact of a T1,000 flood on the hydraulic conditions around the study island?'*** To answer this question several sub questions were answered first, using the methodology described in chapter 4.

With the hydraulic model the maximum water level of the Chao Phraya river was found to be 5.23m +MSL (T1,000). The model also gave insight into the water levels of the surrounding landscape. Furthermore, model outputs of the flow velocity showed that the river is navigable during a T1000 flood event, but only with motor propelled boats, as the current is to strong for rowing or swimming. Next to the model output this was also supported by literature and the fact that residents currently use boats for transportation during floods.

After the completion of the model, water depths and flow velocities were quickly found. Using a hydraulic model to obtain these results is a solid method, which is why these models are used a lot in the work field. The hydraulic model functions fully as a tool to support crisis response plans. However, for this project there is still some room for improvement since the design masterplan that has been simulated in the hydraulic model is not fully accurate. When the plan is implemented the ground of the island will form a slope, with its highest elevation being the dyke around the central area and then going down until it reaches the shoreline. This creates the flood and non-flood zones of the development project.

However, in the hydraulic model this slope does not exist. Instead, the different elevation levels are structured like steps/terraces. So you have a flat surface for a certain elevation level, then a straight drop to the next lower elevation level. This can impact the flow of the river, and therefore the hydraulic model results. Future research can preform the simulations again but with a improved implementation of the design masterplan. By performing the simulations again different result will be obtained which might contradict the conclusions drawn in this research.

Literature research provided an additional insight into the flood duration. A local expert and literature sources showed that the floods in the study area last for a long time. A T20 flood event in 2011 caused inundation for 2.5 months and a T10 flood event about 1.5 months (Supratid 2023). So a T1000 flood will probably result in an even longer period of inundation.

On top of that, literature research gave insight into the flood extent of extreme floods. The hydraulic model clearly showed that within its scope the entire landscape will be inundated for a T1000 flood event. However, the scope of the model limits the area of clear and accurate data of the flood extent. Therefore, the literature research of past floods added more details for the area outside the model scope by looking at satellite images of historic extreme floods.

Unfortunately, These images are not available for floods the size of T1000 flood events, as they have not yet occurred in the study area. This makes crisis response plans that opt for evacuation more risky, resulting in sheltering on the island to more easily look like the better option. Future research can look into this problem by expanding the scope of the hydraulic model used in this study. However, expanding the model can come with some downsides. The model can cover to big of a scope such that runtimes are days long or the required storage is to much for most computer systems. When considering this option researchers must clearly think about if the benefits outweigh the costs.

The lack of existing insight into T1000 flood events begs the question if it is even worth it to look at such extreme cases. The 2011 floods (T20) already inundated the entire delta which is already an extreme situation for crisis response. So, T1000 produces even more devastating consequences and protecting a single island according to these standards is hard to defend when the surrounding hinterland and landscape is held to a much lower standard. Of course the crisis response plan for a T1000 event works for a less devastating flood as well, but their might be simpler and cheaper measures to survive these flood events. To make these plans for less extreme floods additional research is needed.

The second research question was:' **What is the course of action to ensure the safety of people on the study island during a T1,000 flood event and how should the design masterplan be adapted to make this possible?**'

Using the water depth and flow velocity obtained form the hydraulic model, it became apparent that leaving the study island is possible during any moment of a T1000 flood event. However, travel during the flood is limited to big motor propelled boats. This is especially the case when the water depths are at their highest. But when the water starts to subside travel with smaller boats will become possible. Travel with smaller vessels by residents is seen in literature at lower inundation levels. But the exact moment during a T1000 flood event this is possible is not known. Additional research can investigate this by looking into a threshold of water depth and/or flow velocity after which evacuation (in smaller boats) is justifiable.

Evacuating the island was found to be a viable option. However, this is dependent on the water depth as this determines if a certain shelter location has non-inundated surface area. Although figure 19 shows if there are potentially sufficient locations, there is currently no insight into at which water levels these locations are usable. To gain this insight the figure has to be updated based on the additional research into water depth changing overtime, during and after a flood.

The best course of action was found to be staying on the island. The hydraulic model proved it is possible. However, certain things and adjustments to the design masterplan are required to do this as mentioned in chapter 6.3. There is a possibility that key elements of the design masterplan, like the dyke and lock get damaged. The proposed crisis response plan assumes this does not happen. Some consequences of damage and resulting changes to the design masterplan are briefly mentioned in chapter 6.3. But a proper crisis response plan need a clearer course of action in case of major damages. However, the chance of major damage might be severely lower for less extreme flood events (<T1000).

Residents currently get supplies like food, water and fuel for their boats by traveling to shops with multiple floor levels, which are still operational despite inundation. Due to the higher water depths of a T1000 flood compared to more common floods there will be less locations for this. As water levels decrease after a flood getting supplies off island becomes more viable again. But the duration of the time period when it is impossible to get supplies off island (so the time for which supplies have to be available on the study island) is unclear. The current plan states a supply of at least one week, but this might not be enough if supplies from the mainland are not available for a prolonged period of time, in which case a bigger supply is needed on the island.

8 Conclusion

With rising sea levels and more extreme precipitations events caused by climate change, the chances of extreme floods keep increasing. For the study island, a location that is already subject to yearly floods, this means that it is only a matter of time before disaster strikes. The planned developments on the island therefore need thorough protection from floods, due to the hydrology of the Chao Phraya river.

When a T1000 flood hits the area there are multiple response possible for residents of the island. The main strategies are to stay on the island and live out the flood or to evacuate and weather the flood off island. A decision between these option can and should not be made lightly, so to support either choice insight is needed into the impact of a T1000 flood. To achieve this a hydraulic model was made, which helps answer the first research question: "*What is the impact of a T1,000 flood on the hydrological conditions around the study island?*"

From the model results and literature research we can conclude that the impact is severe for both the study island and its surroundings. A T1000 flood will result in inundation of at least several meters, rising to a maximum of 5.23m +MSL. This means that the entire current island will flood, but with the implementation of the design masterplan all homes and buildings are safe during extreme floods. The inundation will spread across the entire central delta plain of Thailand, in which the study island is located. This inundation will last for multiple months, constraining the lives of residents and damaging the environment. Despite this, the river and surroundings are still navigable by large boats. Therefore, residents can get supplies and aid to survive the flood.

With a clearer image of a T1000 flood the proper crisis response can be chosen, which answers the second research question: "*What is the course of action to ensure the safety of people on The study island during a T1,000 flood event and how should the design masterplan be adapted to make this possible?*"

Based on the preformed research, staying on the island is the best course of action to take in response to a extreme flood event. The hydraulic model results prove that this is viable, since part of the island remains non-inundated. The design masterplan can be adjusted to included all necessities needed to stay safely on the island during a flood. Residents are also more likely to adhere to this course of action, compared to evacuation, since they fear for thieves taking their belongings. On top of that, this course of action is also in line with the ambitions of the client, making the study island a resilient city that can independently keep function during a flood.

With both research questions answered the objective of this research has been achieved. The objective was: *'To investigate the hydrological characteristics during extreme floods up to T1000 in and around the study area. Furthermore, recommend a course of action to the client in case of extreme flooding of the study island.'* With the help of a hydraulic model a T1000 flood event was simulated and the impact on the hydrological conditions of the study area were determined. Supported with further literature research, staying on the study island during a T1000 flood event is the recommended course of action for the client.

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10 Appendices

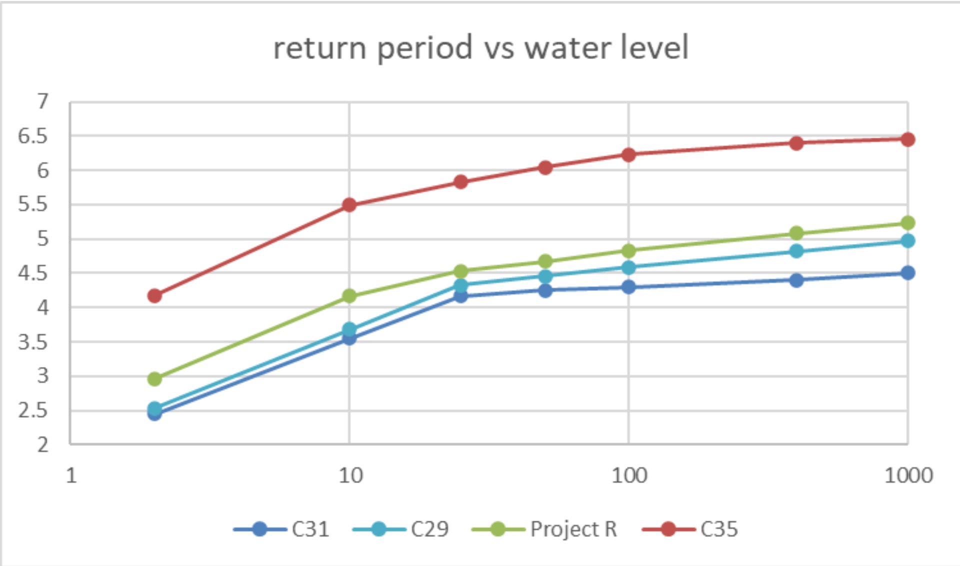
10.1 Appendix A- Expert Information

Questions		Answers
1	Is there currently a functioning flood early warning system (FEWS) for the Chao Phraya River?	The FEWs in the Chao Phraya river are still not functioning (see also answer no 3))
2	How does the government currently communicate about expected floods?	The flood dissemination is almost done by sending a fax to the governor.
3	How long in advance does the government give flood warnings? A week, a few days or only hours before the flood?	The flood warning is disseminated normally (on the main channel) about 3-5 days in advance (only for the fluvial flood). However, there are no warnings for the pluvial flood (Only the regional information of rainfall are given by TMD, Thai Meteorological Department)
4	Is the evacuation advice mandatory or can locals choose to stay behind in their homes during the flood?	The flood evacuation is not mandatory. Most people want to stay in their homes because they are worried about assets being stolen.
5	Is there an evacuation plan made by the local Ayutthaya government?	The local government has a flood evacuation plan but does not often do evacuation drills.
6	Is there a lot of debris and waste in the water during extreme floods that makes navigating the river difficult/impossible? Or do people still navigate during the extreme floods (e.g. 2011)?	The river can still be navigated during the extreme flood (Only for big boats) but accidents normally happen. There is no problem of debris for navigation.
7	Where do the local people usually get clean drinking water and food during extreme floods?	The people buy the drinking water and food from the shops (7-11) but they use river water for their daily lives (not for drinking). In all cases family boats are necessary
8	Is there a list or map of existing shelter locations in the area of Project R? Perhaps a map of the evacuation shelters during the 2011 floods?	There are not any shelters in Proj. R area. But they have shelters on mainland (normally use a temple or school with higher ground or 2 storage buildings). However, they often use tents set beside the non-flood road as shelter due to its proximity to their homes. They also leave a man to stay in their own houses (see 4)).
9	What was the flood duration of extreme floods (2011) in the past in the study area?	The flood duration of the 2011 (T25) flood was about 2.5 months and not more then 1.5 months for T10.

10.2 Appendix B- Hydraulic model results

Return period and water level data and graph

T	C31	C29	Project R	C35
2	2.45	2.53	2.96	4.18
10	3.55	3.68	4.17	5.49
25	4.17	4.33	4.53	5.83
50	4.25	4.46	4.67	6.04
100	4.3	4.59	4.83	6.23
400	4.4	4.82	5.08	6.4
1000	4.5	4.97	5.23	6.46



10.2.1 Water depth results

The figures below show the water depths for T1000 in both the reference- and design masterplan iteration 3 (MP3) scenario.

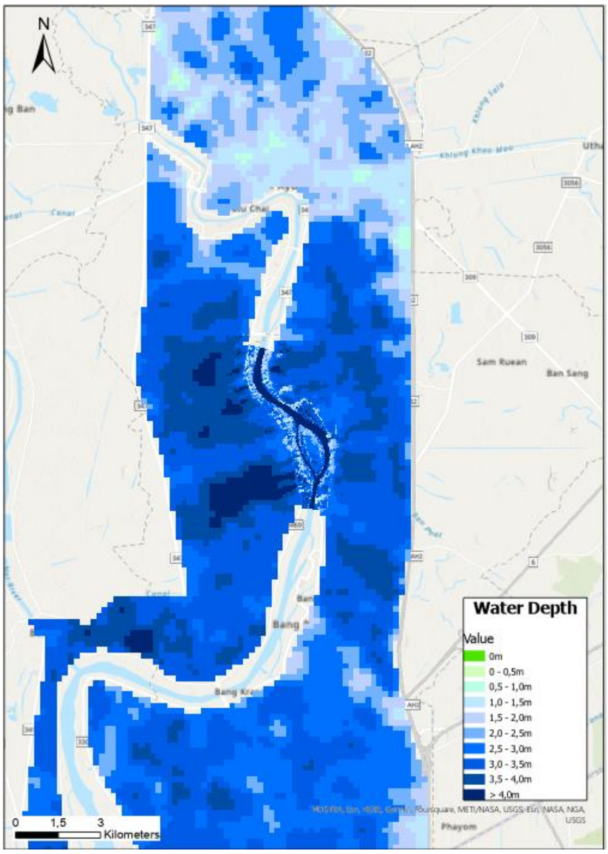


Figure 20, water depths T1000 reference scenario scale 1:100.000

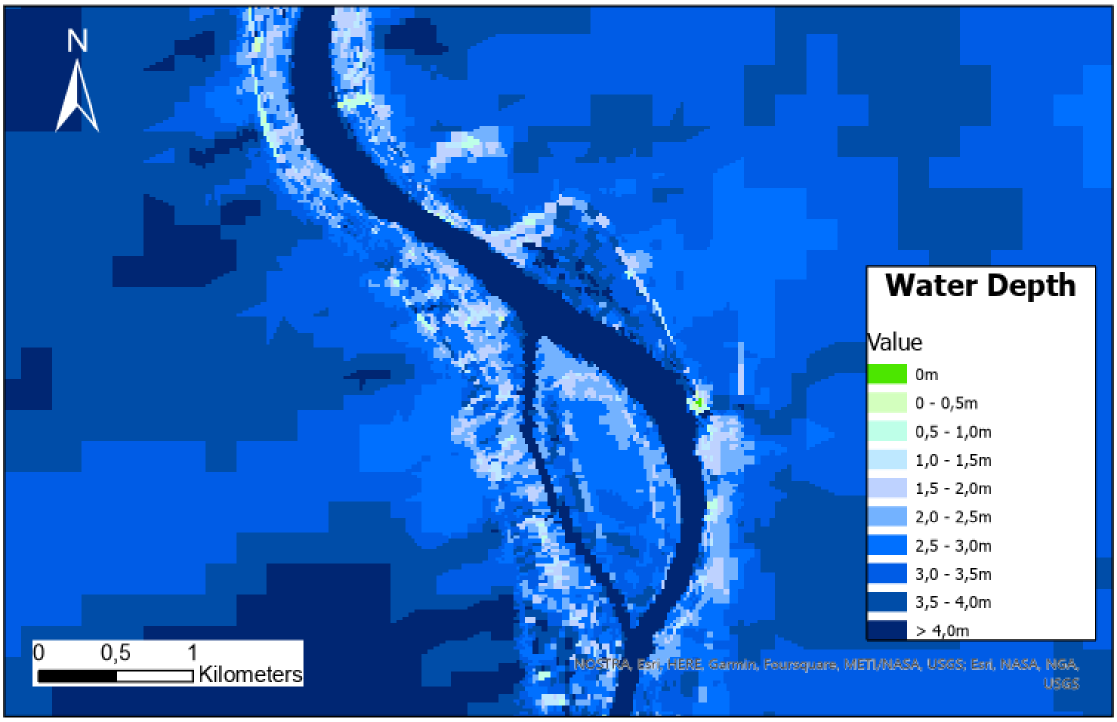


Figure 21, water depths T1000 reference scenario scale 1:34.000

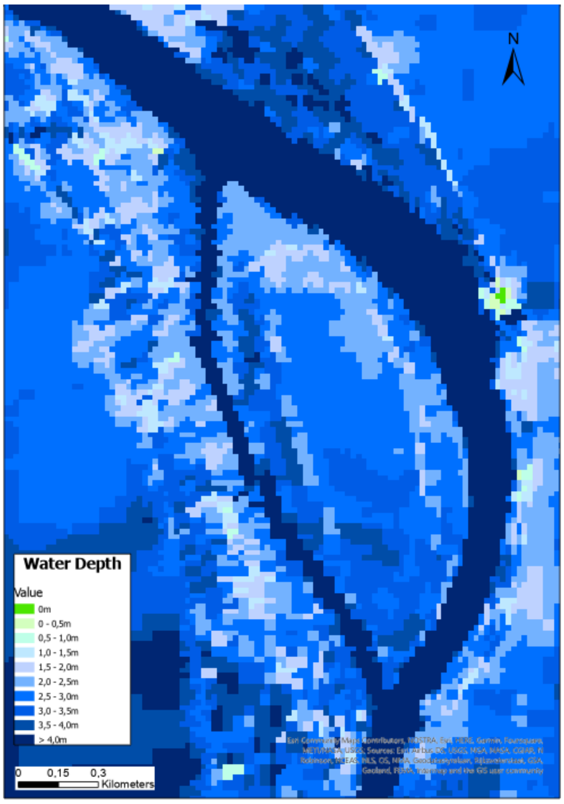


Figure 22, water depths T1000 reference scenario scale 1:10.000

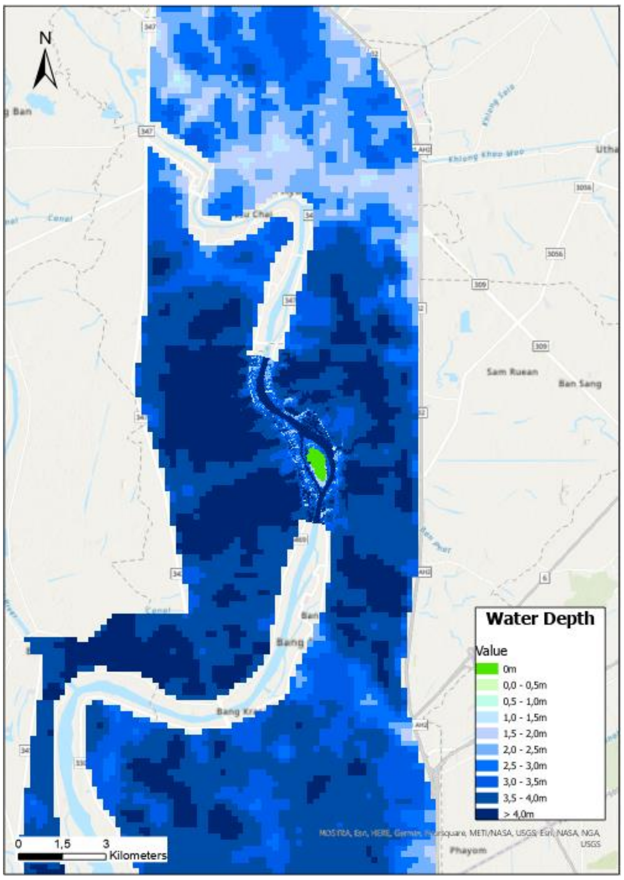


Figure 23, water depths T1000 MP3 scenario scale 1:100.000

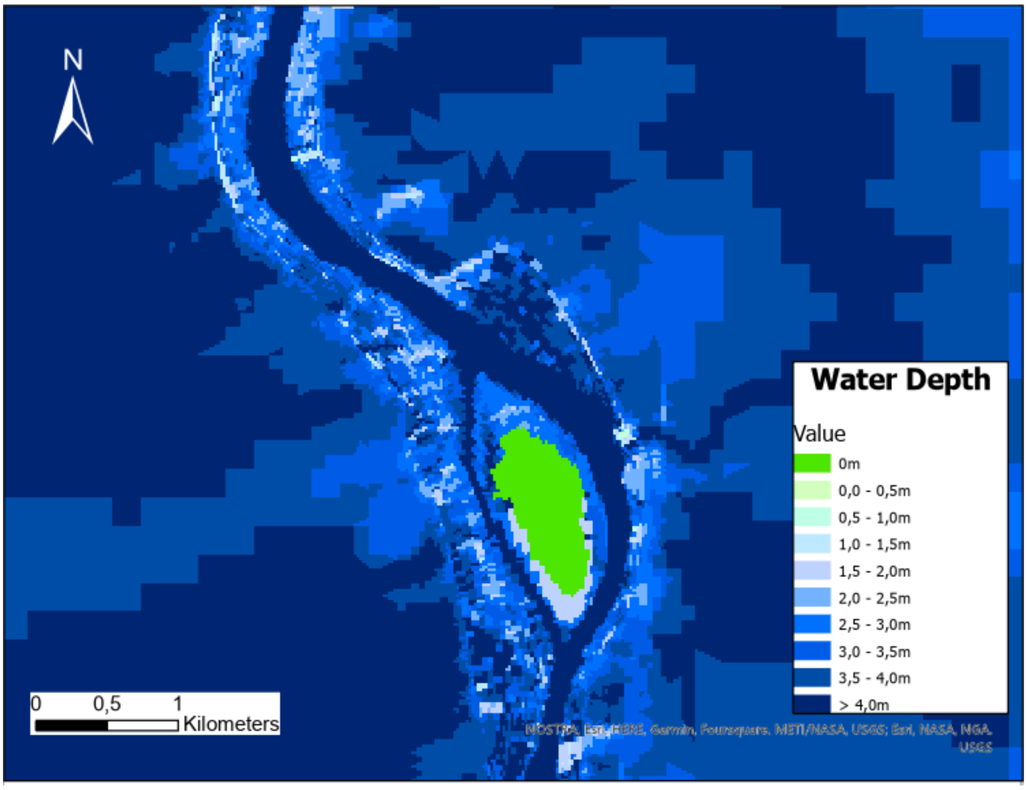


Figure 24, water depths T1000 MP3 scenario scale 1:34.000

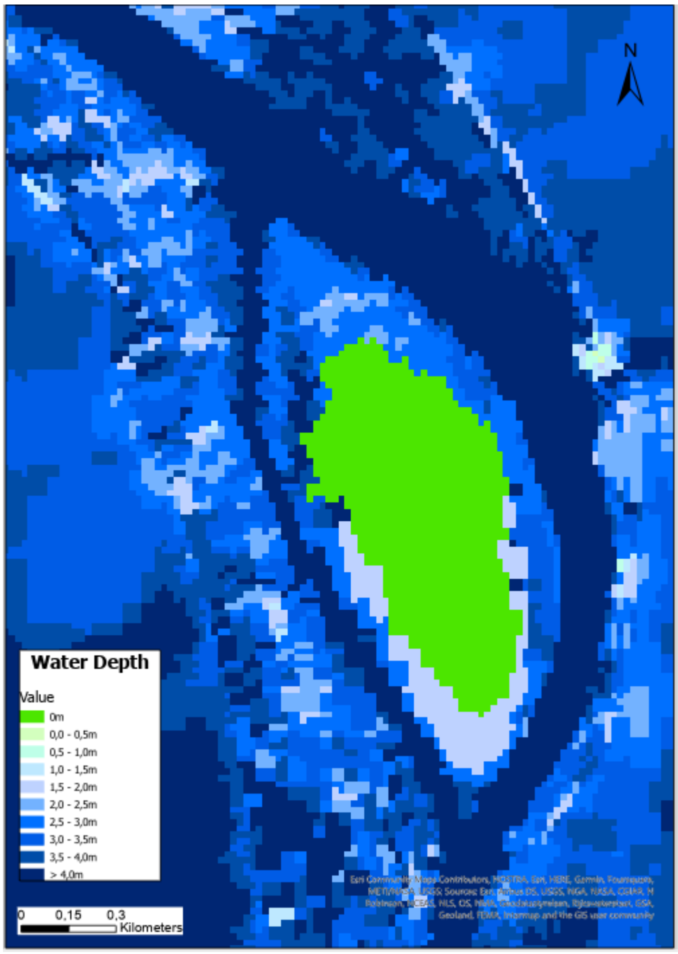


Figure 25, , water depths T1000 MP3 scenario scale 1:10.000

10.2.2 Flow velocity results

The figure below show the flow velocities for a T1000 flood event in both the reference- and MP3 scenario.

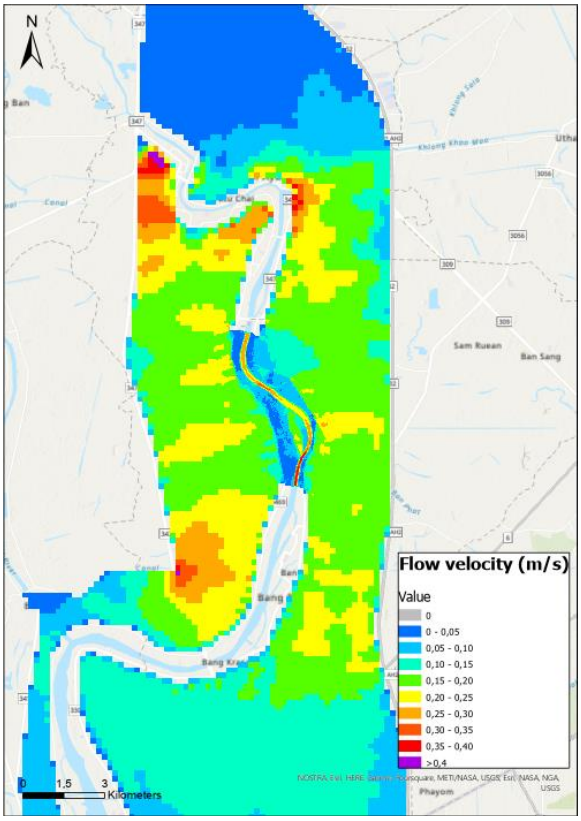


Figure 26, flow velocity T1000 reference scenario scale 1:100.000

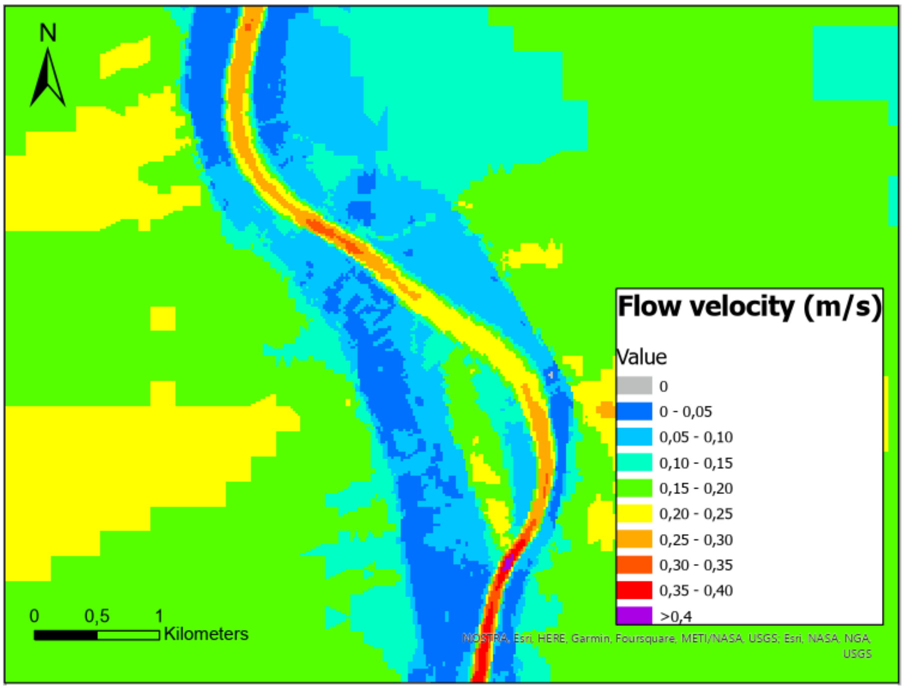


Figure 27, flow velocity T1000 reference scenario scale 1:34.000

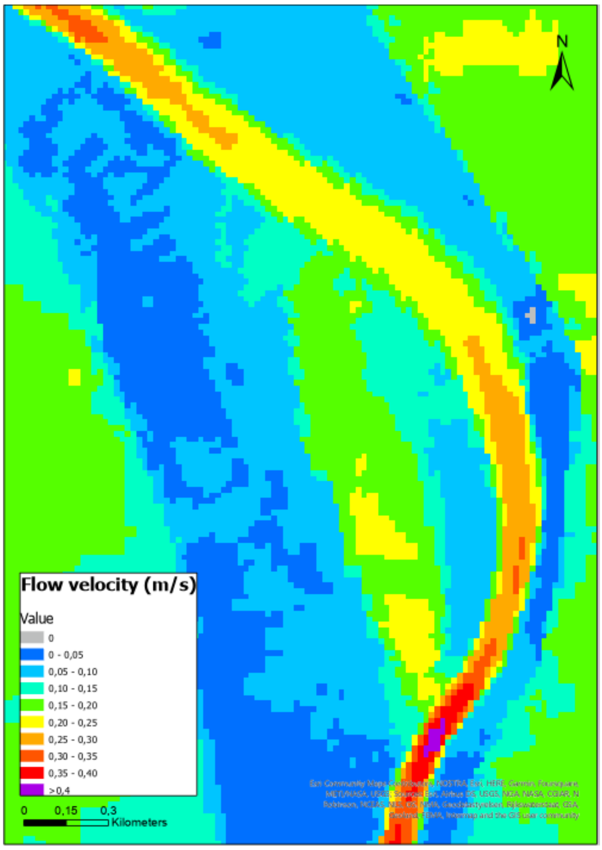


Figure 28, flow velocity T1000 reference scenario scale 1:10.000

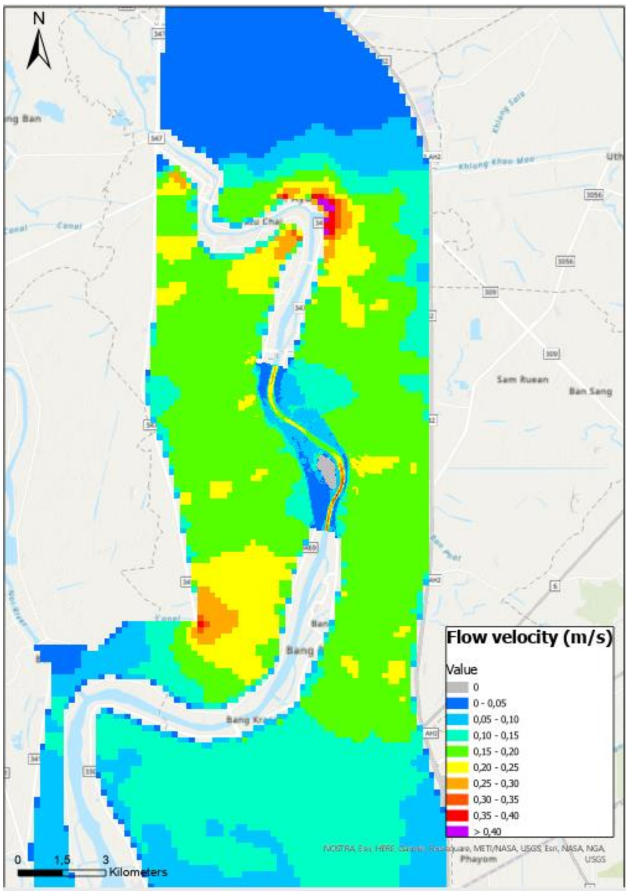


Figure 29, flow velocity T1000 MP3 scenario scale 1:100.000

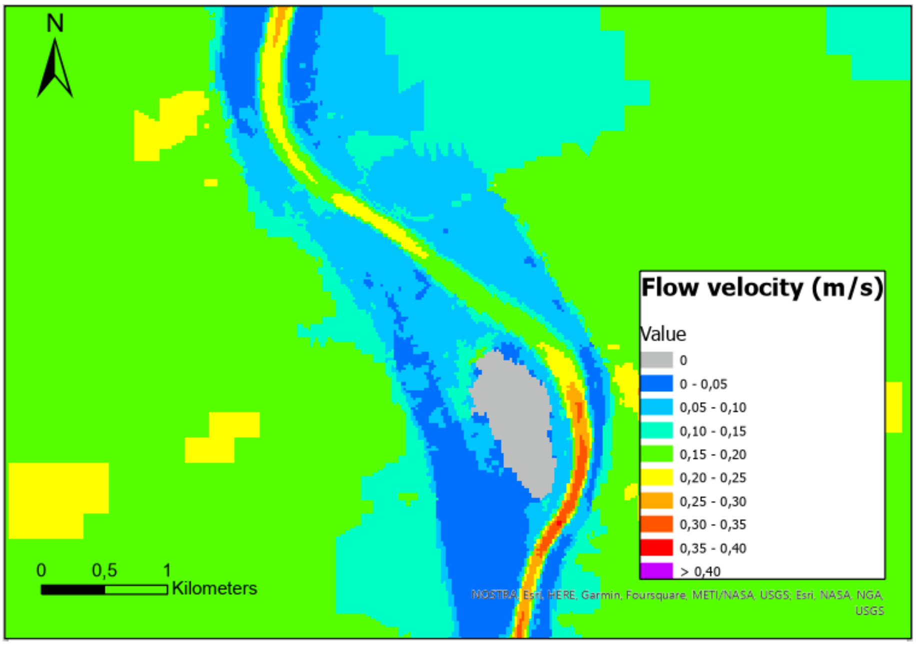


Figure 30, flow velocity T1000 MP3 scenario scale 1:34.000

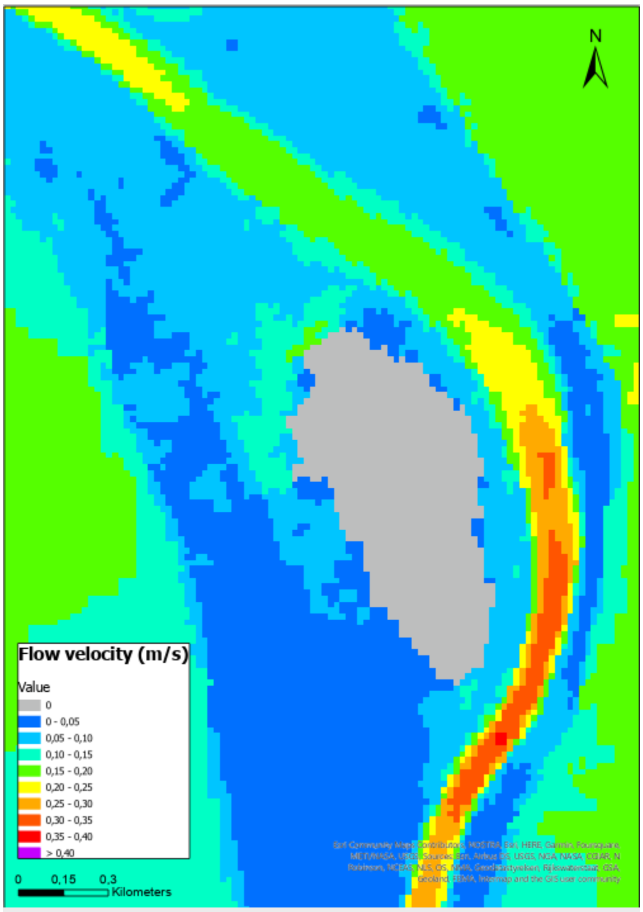


Figure 31, flow velocity T1000 MP3 scenario scale 1:10.000

10.3 Appendix C – hydraulic model calibration

The summer bed roughness (yellow) was varied until the difference in water level between the reference water level at a gauging station (green) and the simulation water level at the same gauging station (blue) were acceptable.

20230601 extended 1D2D model	**T1**	**T2**			**T10**			**T25**			**T50**		**T100**		**T400**		**T1000**
WL C31 (node 002)	1.97	2.44	2.44	2.44	3.54	3.54	3.54	4.16	4.16	4.16	4.24	4.24	4.29	4.29	4.39	4.39	4.49
Q C35	1040	1294	1294	1294	1620	1620	1620	1712	1712	1712	1756	1756	1787	1787	1823	1823	1835
Q S5	520	825	825	825	1533	1533	1533	1936	1936	1936	2241	2241	2546	2546	3156	3156	3559
roughness 1D down main	0.017	**0.017**	**0.017**	**0.017**	**0.017**	**0.03**	**0.025**	**0.025**	**0.035**	**0.04**	**0.04**	**0.05**	**0.05**	**0.06**	**0.06**	**0.07**	**0.07**
roughness 2D river friction...3.pol	0.017	**0.017**	**0.017**	**0.017**	**0.017**	**0.03**	**0.025**	**0.025**	**0.035**	**0.04**	**0.04**	**0.05**	**0.05**	**0.06**	**0.06**	**0.07**	**0.07**
roughness 1D up main	0.017	**0.018**	**0.018**	**0.017**	**0.018**	**0.03**	**0.025**	**0.025**	**0.035**	**0.04**	**0.04**	**0.05**	**0.05**	**0.06**	**0.06**	**0.07**	**0.07**
roughness winterbed 1D up		0.05	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
roughness winterbed 2D		0.05	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
roughness winterbed 1D down		0.04	0.1	0.2	0.04	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
roughnes floodplain			0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
ref C31	**1.98**	**2.45**	**2.45**	**2.45**	**3.55**	**3.55**	**3.55**	**4.17**	**4.17**	**4.17**	**4.25**	**4.25**	**4.3**	**4.3**	4.4	4.4	4.5
C31				4.5		3.56											
ref C29	**1.6**	**2.44**	**2.44**	**2.44**	**4**	**4**	**4**	**4.69**	**4.69**	**4.69**	**4.8**	**4.8**	**5**	5	5.1	5.1	5.2
C29		2.53	*2.52*	*2.53*	3.65	3.71	3.69	4.29	4.32	4.35	4.43	4.49	4.55	4.62	4.77	4.85	5
ref C35	**3.25**	**4.19**	**4.19**	**4.19**	**5.48**	**5.48**	**5.48**	**5.87**	**5.87**	**5.87**	**6.07**	**6.07**	**6.22**	**6.22**	**6.4**	**6.4**	**6.46**
C35		4.19	4.21	4.17	5.24	5.59	5.49	5.54	5.74	5.83	5.86	**6.04**	6.06	6.23	6.27	6.44	6.47
WL study island				***2.95***			***4.17***			***4.57***		***4.72***		***4.86***		***5.11***	***5.26***