Potential Measures to reduce Fluvial and Tidal Floods in the Pampanga Delta

MSc Thesis

by

A.C. (Arnold) van 't Veld

January, 2015

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This research is performed in partial fulfilment of the requirements for the degree of Master of Science in Hydraulic Engineering and Water Resources Management at Delft University of Technology and National University of Singapore.

Delft, 14 January 2015

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Preface

This graduation thesis concludes the double degree programme “Hydraulic Engineering and Water Resources Management” started in August 2012 at the National University of Singapore and Delft University of Technology. The curriculum includes courses about the physical behaviour and modelling of water and sediments in sea’s, coastal waters, rivers and small channels. The research is proposed by the Filipijnengroep Netherlands and later on supported by Nelen & Schuurmans and Nationwide Operational Assessment of Hazards Project.

I am greatly indebted to a lot of people, too many to mention all of them, for their help during this research. In this way, I want to thank the persons that are not mentioned below. In special I thank

- Sir Hernando (Pampanga River Flood Forecasting Warning Center) and Sir Rigor (Angat Dam Operator) for their insides and detailed data about their River Basins;
- NOAH with Sir Lagmay, Sir Tanjuakio, Sir Reyes and others for the support towards other agencies, providing laptop and accommodation and sharing all the knowledge and data in the project;
- Sir Cruz and Madam Villanueva for using their network, arranging appointments, meetings and accommodation, and being a discussion partner for organizing thoughts;
- Evert and Dick (Filipijnengroep Netherlands) for providing the subject; familiarizing me with the subject; introducing me to important contacts in the Philippines and reviewing the reports;
- Colleagues at Nelen & Schuurmans for answering technical questions, providing a fruitful working environment and allowing me to use all the facilities;
- Fons, Guus and Nick (Graduation Committee) for joining me to the Philippines (Fons and Guus) and for their feedback and encouragements;
- Olivier (daily supervisor) for creating an obligation free relation with the company, a relax and fruitful supervision, giving insights in writing reports and improving presentations;
- My friends in Rijnsburg and Delft for their support and encouragements during tough times during the research period;
- My parents and brother for their support and encouragements and the reviews of the report, especially the in-depth reviews of my brother;
- My fiancée for her love, being a discussion partner for organizing thoughts, reviewing and more;
- and above all, God for guiding, protecting and blessing me during the whole research.

Arnold van ’t Veld
Delft, January 2015

Abstract

The Pampanga and Angat River Delta, located on the northern side of the Manila Bay in a large alluvial plain, are regularly confronted with worsening fluvial and tidal floods. The fluvial floods are caused by typhoon and southwest monsoons and damages houses, roads and harvest of many rice paddies and fishponds. The tidal floods are caused by storm surges and high tides and are merely unpleasant because roads are not accessible and some houses are flooded. The large flood events, normally a combination of a fluvial and tidal flood, are causing an economic setback pertaining a vicious circle.

Eight municipalities formed an alliance of coastal communities to tackle these flood related problems. The following research question is determined based on their problems:
"What are the effects of potential measures to reduce the fluvial and tidal floods in the Pampanga and Angat River Delta, Philippines?"

To assess the performance of potential measures, a 3Di model is used to estimate the current and future scenario with Pedring 2011 as representative storm event. A digital terrain model including sea and river bathymetry with a resolution of 1 x 1 m covering an area of 900 km^2 is used as input for the model. The main inflows during Pedring 2011 are the Pampanga River at Mount Arayat with a peak discharge of 2800 m^3/s and Manila Bay with a storm surge enhanced tide of 1.8 m above MSL.

Subsidence rates up to 4.5 cm/year due to groundwater extraction are the main cause of the worsening floods. With subsidence, the flood extent in the populated areas increases from 80% to 87% in 50 years. The flood damage in the Pampanga and Angat River Delta increases from 1.5 to 2.1 billion pesos mainly due to the increase in damage in the populated area.

Three measures have a positive impact on fluvial and tidal floods, have minor side effects, and are applicable in combination with all other measures. With *precipitation predictions*, the dam operation of Angat and Bustos dam could be improved by maximising the use of their flood storage capacities. This measure has the highest benefit-cost ratio of 21. The current levees protecting the city centres of Masantol and Macabebe are very lucrative to be monitored and *maintained* at the current elevation. The yearly costs are estimated at 11 million pesos/year. Groundwater extraction regulation and new potable water sources is an expensive measure with a maximum of 145 million pesos/year, but could stop the current subsidence.

Two measures with large effects remain: *fishpond dike height regulation* and *flood prevention with levees and tidal gates*, like the Pampanga Delta Development Project. The former measure reduces the fishpond dike height just above spring tide, opens the gates during a fluvial flood and compensates the owners. This reduces the flood through the additional flow capacity towards Manila Bay making this measure beneficial. A *fishpond flood channel* consisting of around four neighbouring fishponds is advised to start with as first phase, because of its efficiency and feasibility. *Flood prevention* is possible by creating an expensive closed systems of levees, road elevations, tidal gates and fishpond dikes. This measure protects the area in the closed system, but enhances the flood outside the area.

List of abbreviations

ABB-BP	Alliance of Coastal Communities in Bulacan and Pampanga
BODC	British Oceanographic Data Centre
CBDRR	Community-Based Disaster Risk Reduction
DEM	Digital Elevation Model
DTM	Digital Terrain Model
DREAM	Disaster Risk Exposure and Assessment for Mitigation
GEBCO	General Bathymetric Chart of the Oceans
JICA	Japan International Cooperation Agency
LiDAR	Light Detection And Ranging
MSL	Mean Sea Level
NIA	National Irrigation Administration
NOAH	Nationwide Operational Assessment of Hazards Project
PDDP	Pampanga Delta Development Project
PAGASA	Philippine Atmospheric, Geophysical & Astronomical Services Administration
PRFFWC	Pampanga River Basin Flood Forecasting & Warning Centre
SLR	Sea Level Rise

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1 | Introduction

On the northern side of Manila Bay, see Figure 1.1, multiple coastal municipalities are regularly confronted with fluvial and tidal floods. The main approach of the government regarding floods is reactive; consequences of the flood are solved after the event. With the help of the Japan International Cooperation Agency (JICA), the national and regional government initiated a couple of flood mitigation projects. Multiple levees were constructed in the Pampanga River Basin and a Flood Forecasting Warning System has been set up for both the Angat and Pampanga River. However, the flood forecasting warning system is merely meant for evacuation, the levees are only partly working and the tide can still freely enter the area through Manila Bay. (Hydroterre Consultants, 2008; Gaillard, 2008)

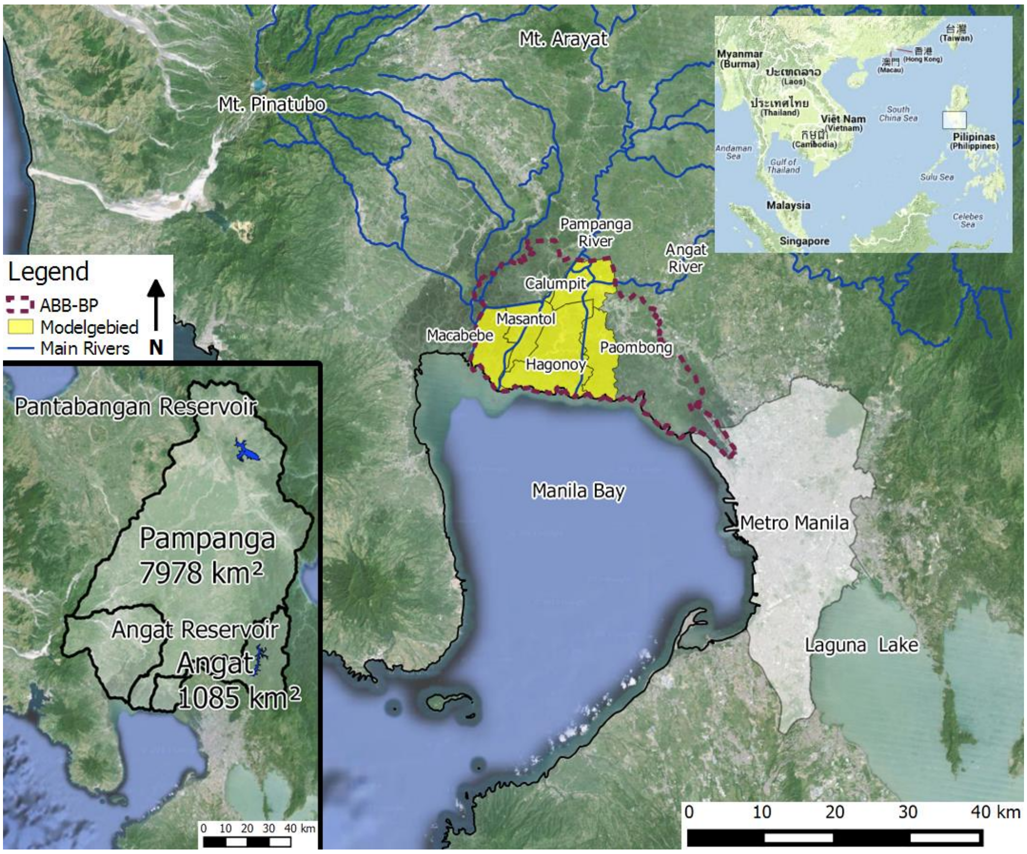

Figure 1.1 – Left: main catchments draining through ABB-BP with main reservoirs; Right: Locations of the ABB-BP, main rivers, study area, Mt. Pinatubo and Metro Manila on a Satellite Map (PRFFWC, 2014a; Google Maps, 2014)

In 2010, eight municipalities decided to form an alliance, Alliance of Coastal Communities in Bulacan and Pampanga (ABB-BP), to tackle flood related problems in this area, see the black dashed line in Figure 1.1 for the location. The goal of this alliance is to strengthen the coastal zone, deal with high river flows and adapt to relative sea level rise. Furthermore, the ABB-BP hopes to attract the attention of the national government, World Bank, Philippine or Asian Development Bank to find investment partners. The alliance cooperates with Dutch partners:

the Filipijnengroep Netherlands, Nelen & Schuurmans and Delft University of Technology; and with local partners: National Institute for Geological Services of the University of the Philippines, the Nationwide Operational Assessment of Hazards Project (NOAH) of the Philippine Department of Science and Technology and the Bulacan State University.

The ABB-BP is divided in three regions based on hydrology of which the second region is studied in this report, see Figure 1.1. Starting from left to right, the first region consists of a part of Macabebe and Masantol. This region is in the Porac River Basin and is separated by a high levee from the Pampanga River Basin. The second region consists of Calumpit, Hagonoy, Paombong and the remaining part of Macabebe, Masantol and is located in the Pampanga and Angat River Basins. This region is called the Pampanga and Angat River Delta in this report. The third region consists of Bulacan, Malolos and Obando and has no rivers flowing into the area making the tide and rainfall – run-off the most important mechanisms.

1.1 Problem formulation

According to JICA et al. (2011), 757,000 is the highest number of people affected during a typhoon between 2003 and 2006 in the Pampanga, Angat and Porac River basin. Still, “only” a maximum of 16 people were killed during one typhoon in this period. Good evacuation plans on municipal level are one of the main reasons for this relatively low number of deaths. However, the damage is large, especially on the aquaculture and infrastructure and in the long run on the whole economy. (Hagonoy, 2012; PDRMMO Bulacan, 2014) The poor are the most affected by the floods because they lack resources. The rich have enough money to raise their fishpond dikes to protect their harvest. The consequence is that they have to choose between harvesting early or facing the risk of losing their harvest. Both options result in a food shortage. Most poor do not have the money to raise their houses. The way the poorest survive is due to the strength of the social networks in those villages. (Gaillard, 2008)

The infrastructure is impassable and even damaged during large floods. Since the sinking of the floods is slow and roads cannot be repaired instantaneously, the evacuation of the area becomes difficult and the economy of the region is severely damaged. Remote areas are hardly accessible for external aid and rarely receive money from government aid funds to restore their infrastructure or other belongings. In the urban areas, the external aid is available. Other consequences of the floods on infrastructure are for example:

- children who cannot go to school;
- a public transport disruption;
- a stop in the sale and distribution of goods by retailing businesses.

In many municipalities and provinces, important roads are elevated to counteract the infrastructure disruption. (Gaillard, 2008)

In contrast to the fluvial floods, the frequent tidal floods are regarded unpleasant, since these last for a couple of hours and only have minor consequences. The fluvial flood with a frequency of one in every one or two years is making the aqua- and agriculture unstable. Together with the disruption on the infrastructure, these large flood events cause an economic setback resulting in a vicious circle of staying in the same economic situation especially for the poor people.

Although there are currently many causes of increasing floods in the Pampanga River Delta, land subsidence seems to be the most important effect for the future flood scenario. Every centimetre of subsidence worsens floods, since the ABB-BP is in open connection with the sea and a large area is already below average spring tide. (Rodolfo, 2006)

To gain insight into the effect on the floods in the future, the flood characteristics (flow velocity, flood extent and depth) are estimated for the current situation and the future situation twenty to fifty years ahead without government intervention. Together with information and opinions gathered in the Philippines, potential measures are designed. To assess these measures, the cost and benefit are estimated. For this study, the following research question is used:

"What are the effects of potential measures to reduce fluvial and tidal floods in the Pampanga and Angat River Delta, Philippines?"

The research question is divided into four sub-questions:

1. What is a representative storm event and what are the flood characteristics for this event?
2. What are the expected changes for the future scenario without government intervention over twenty to fifty years?
3. What are potential measures to reduce the floods, taking into account the former initiatives, ideas of the government and wishes of the people living in the flood-prone areas?
4. What are the effects of the potential measures on the future scenario?

1.2 Relevance of the research

Around the world, there are many populated or cultivated deltas that are subsiding fast, mostly due to excessive groundwater withdrawals, see Figure 1.2. (Rodolfo, 2006) In these deltas, people have to prevent or adapt to worsening floods due to relative sea level rise. The results of this study on flood prevention in the Pampanga and Angat River Delta are highly scalable for areas with lowland converted into aquaculture along the coastline, which happens in Thailand, Vietnam, Bangladesh, China, India, Ecuador, Honduras and Mexico. (Chua, 1992) The scalability is especially high for the western coast of Taiwan, because of the similarity in geology, climatology, and land-use. (Rodolfo, 2006) Part of the research is also scalable for the many subsiding cities along the coast without space to implement measures, like Manila or Jakarta.

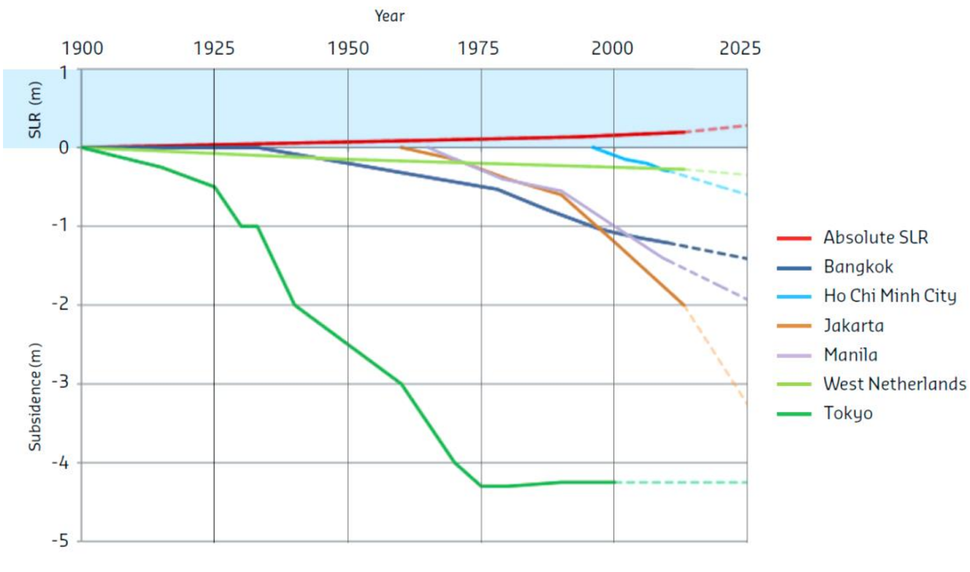

Figure 1.2 – Comparison of the land subsidence of five Asian coastal cities, and global sea level rise (SLR) (Deltares, 2014)

Several analyses have been performed on the problems in the ABB-BP area, but these reports focus on a large region and do not include all inundation causes. The report of JICA et al.

(2011) completely focuses on the fluvial floods in the Porac, Pampanga and Angat River Delta without including the tide during those events. The analysis of Rodolfo (2006) focuses on tidal floods and their main reason: the excessive groundwater use resulting in a relatively fast land subsidence; an overview of the problems due to tidal and fluvial floods is missing. Furthermore, the reports that assess measures (JICA et al, 2011; Hydroterre Consultants, 2008) are using the current situation as baseline and thereby neglect the fast land subsidence.

1.3 Outline

Chapter 2 presents the general information of the river basins draining through the study area. This includes data that is needed for the model about the river discharges and surge and tides. The chapter concludes with the selection of a representative storm event with the necessary data for modelling. The data gathered in Chapter 2 is combined with a digital terrain model and converted to a 3Di model in Chapter 3. In this chapter, the background of the 3Di model is explained in more detail by focusing on the techniques that are different than other models. Before the model is used, the model is first checked on its performance and sensitivity in this chapter as well. With the model as base, the current and future scenario for the representative storm event are estimated in Chapter 4. This chapter includes research about the expected future hydraulic changes. Chapter 5 starts with an identification of potential measures to answer the research question. The measures are selected, conceptualized and implemented with the future scenario as baseline scenario for measure comparison. The calculated effects of the measures by the 3Di model are used to estimate the benefit of the selected measures. Together with the cost of the measures, the cost-benefit analysis is completed. Combining all the chapters, the research question is answered in Chapter 6 with the conclusion and recommendations. The appendices, provides more information about calculations, creation of the elevation layer, the first selection and the details of the cost-benefit analysis.

2 | Pampanga River Basin

The goal of this chapter is giving a general overview of the river basins draining through the study area to gain insight into the background of occurring floods and to select the representative storm event. In section 2.1, the geography of the Pampanga and Angat River Basins is described. Section 2.2 provides information about the precipitation, dam management, and the discharges and bank full capacities of the rivers. In section 2.3, high water levels in Manila Bay due to tide and storm surges are described. In section 2.4, the impact of the floods is stressed by describing flood characteristics in various situations. In the last section 2.5, information is given about Typhoon Pedring, including the results of the calculations for the estimation of the tide and discharge on specific places. This section also offers insight into the severity of typhoon Pedring. Section 2.6 provides a chapter summary.

2.1 Geography

The three river basins, draining into the Manila Bay through the *Alliance of Coastal Communities in Bulacan and Pampanga* (ABB-BP) area, are bordered by several mountains with a maximum height of 1,885 m above mean sea level (MSL). Between the mountains there is a large alluvial plain with slopes of less than 3% that covers around 70% of the three river basins, see Figure 1.1. The ABB-BP is tide dominated with some river dominated features at the Pampanga River Mouth. (Bosboom and Stive, 2013) The tide dominance can be substantiated by the far tidal influence and the large alluvial plain. (Rodolfo, 2006)

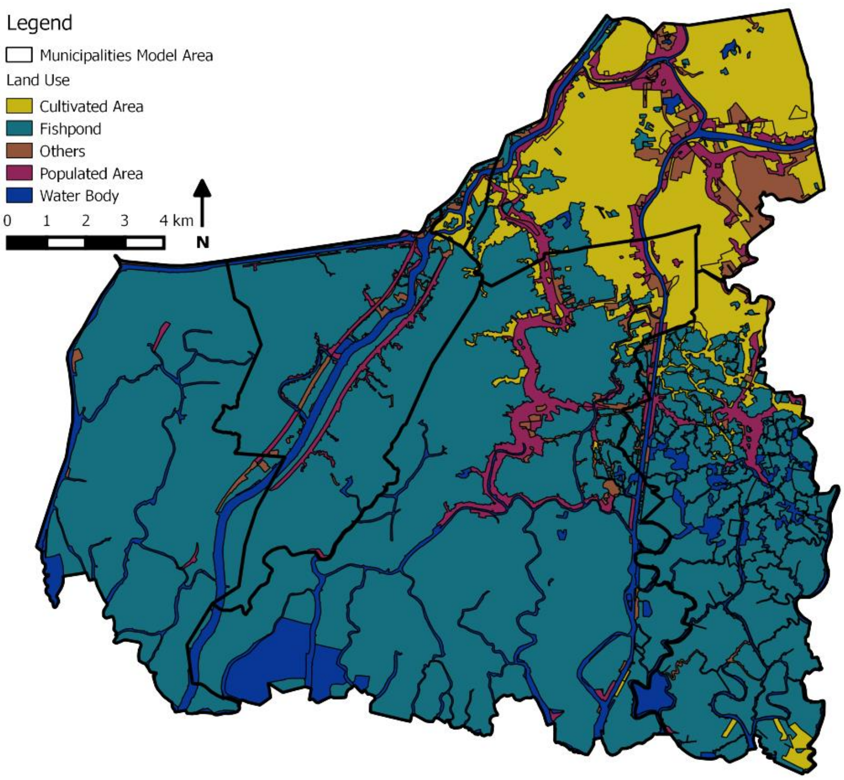

Figure 2.1 – Land use specified in five reclassified classes in the study area (PRFFWC, 2014a)

The land use (PRFFWC, 2014a) is presented in five classes, which are used in the next chapters to present the model results. The five land use classes are cultivated area, fishponds, populated area, water body and others. The cultivated area is mainly rice paddies and some orchard or nurseries and others is open and natural area, like cemeteries and brushwood. The land uses are presented in Figure 2.1.

Rice paddies and fishponds are the main land use types of the five municipalities. (PRFFWC, 2014a) Around the 70's the main land use was the cultivation of rice only. However, a lot of rice paddies are converted into fishponds due to extending saltwater intrusion. Due to this change fishponds are currently the main land use type, see Figure 2.2. (De Vos et al., 2014; Rodolfo, 2006) The "old" fishponds are in general from richer owners, which have had the money and time to create and maintain strong dikes. The "new" fishponds are former rice paddies and these owners did not have the money and time to build strong levees. Along the coast there are multiple fishponds that are converted into fishpens, fishing areas enclosed by nets, or fishponds that are left behind because they are poisoned. An example of these fishpens can be seen directly right of the Pampanga River mouth.

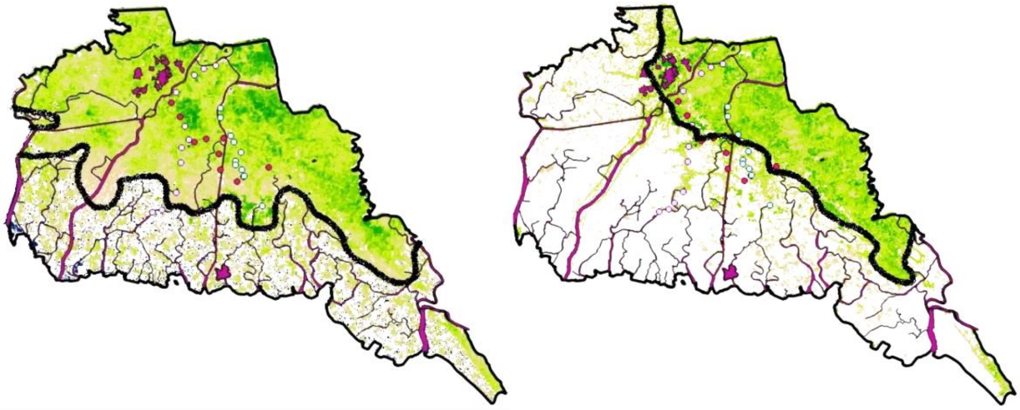

Figure 2.2 – Transition between fishponds and rice paddies between February 1976 and May 2013 based on NDVI for the ABB-BP marked by the black line (De Vos et al., 2014)

Although the land is mostly cultivated, around 400,000 people are living in these five municipalities. With a total surface area of 335 km^2, this makes a population density of 1200 pop./km^2. That is three times the average population density of the Netherlands. The populated areas can be found along the rivers starting five kilometres out of the coastline. The largest municipality is Hagonoy with 125,000 inhabitants and the smallest municipality is Paombong with 51,000 inhabitants. (Philippine Statistics Authority, 2010) According to the Japan International Cooperation Agency (JICA et al., 2011), respectively 10.8% and 13.4% of the people in Bulacan and Pampanga has an income lower than the Poverty Threshold.

2.2 Precipitation, rivers and dams

The monthly variation in precipitation can be divided in a dry and a wet season for the complete area except for a large part of the eastern mountains. The dry season runs from November to April and has average monthly precipitation depths from 30 to 160 mm. The wet season has average monthly precipitation depths from 180 to 410 mm. The total annual precipitation in the region is around 2200 mm. (JICA et al., 2011) Typhoons occur on average twice a year in this region. (Hydroterre consultants, 2008)

The largest rivers draining into the bay through the ABB-BP are the Pampanga, Angat and Pasac River, see Figure 1.1. The Pampanga River has the largest catchment of 8,000 km^2 and the longest channel length of around 270 km. The catchment includes one large reservoir, called the Pantabangan Reservoir. The Angat River is around 150 km long and has a catchment of 1,100 km^2. This catchment includes the Angat Reservoir. Finally, the Pasac River has a catchment of 1,400 km^2 and starts at Mount Pinatubo. This section focusses on the Pampanga and Angat river, since these are in the study area. (JICA et al., 2011)

The closest reliable water level or discharge measurement stations are used to estimate the flood in the study area, see Figure B.8 for the location of the measuring stations. The Pampanga and Angat River Delta have two large river inflows, the Pampanga and Angat River, and one large inflow through the Candaba Swamp:

- For the Pampanga River, the closest measurement station is measuring the water levels at Sulipan, located just above Calumpit. However, this station is tide dominated, also during peak discharges. Therefore, the station near Mount Arayat is used to predict the inflow for the Pampanga River, because there is not enough data available for the analytical approach for predicting fresh water discharge in an estuary. (Cai et al., 2014a)
- The Candaba swamp, located next to Pampanga River at Mount Arayat until Calumpit, has an average size during the dry season of 5.8 km^2 and during the wet season of 160 km^2 with monthly average water depths up to 4.5 m. The Candaba Swamp receives water by small rivers from the east side and from the Pampanga River via the Candaba Floodway. (JICA et al., 2011)
- For the Angat River the closest measurement station is Bustos Dam. At this dam the discharges were measured for Pedring 2011 and Habagat 2012.

In short, there are three main upstream inflows to the Pampanga and Angat River Delta; Pampanga River Discharge at Mount Arayat, Candaba Swamp at Mount Arayat and Angat River at Bustos Dam.

2.2.1 Pampanga River

The flow capacities of the Pampanga River and other neighbouring rivers were estimated by JICA et al. (1982), see Table 2.1 and Figure 2.3, and have not changed since then according to JICA et al. (2011) except for the Pampanga River stretch from Masantol to the river mouth. The reason for this bank full capacity increase is the construction of two levees along the river by JICA. To compare the river flow capacities, the peak discharges with a return period of 5 and 10 years of some of the rivers are given in Table 2.1. (JICA et al., 1982)

Table 2.1 – River Flow Capacities of the Rivers in the Pampanga River Delta (JICA et al., 1982); see Figure 2.3 for the locations of the rivers and the Candaba Floodway

River	Stretch	Bank Full Capacity (m^3/s)	5-yr Discharge (m^3/s)	10-yr Discharge (m^3/s)
Pampanga River	River mouth – Masantol	500 (4,300)	2,700	3,500
	Masantol – Sulipan	2,200	2,700	3,500
	Sulipan – Candaba	1,800	2,300	2,700
	Candaba – Arayat	2,500	2,300	2,700
	Arayat – Candaba Floodway	2,000	2,400	3,100
	Candaba Floodway – San Isidro	2,500	2,400	3,100
San Esteban Diversion Channel	River mouth – Masantol	1,700	-	-
Hagonoy River	Hagonoy – Diversion Point	70	-	-
Candaba Floodway	Candaba Swamp – Diversion Point	4,000	-	-

The water level measurement station of the Mount Arayat has a catchment of 6,134 km^2 which is 77% of the Pampanga River Basin. During high discharges, a part of the river flows into the Candaba swamp via the Candaba Floodway, see purple line in Figure 2.3. The Candaba Floodway starts working, if the water level at the Pampanga River exceeds the threshold of 9 m above MSL. The Candaba Swamp has multiple connections with the Pampanga River and ends in the Old Pampanga River and the Bagbag River. The Bagbag River connects the Pampanga River with the Angat River. A channel, called Labangan Floodway, was created that connects the intersection point with Manila Bay.

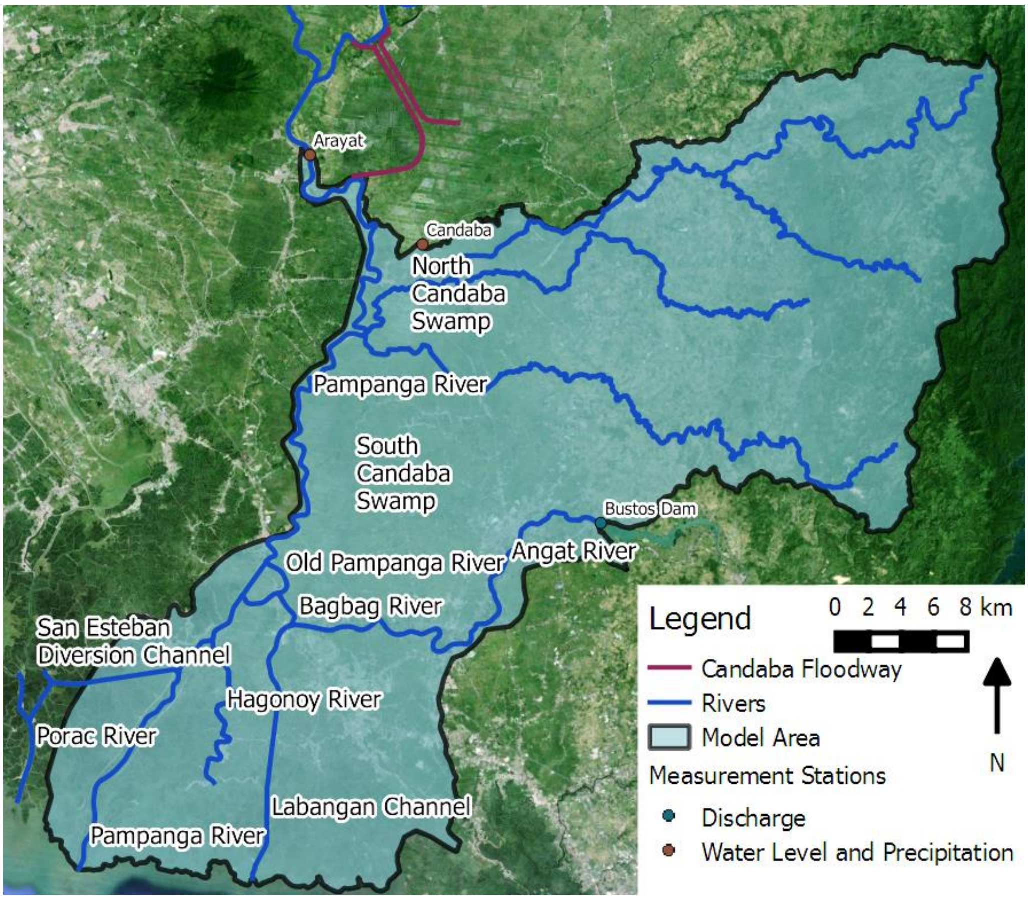

Figure 2.3 – Locations and names of the rivers in the model area below the used measurement stations and the location of the Candaba Swamp and Candaba Floodway (PRFFWC, 2014a; Google Maps, 2014)

2.2.2 Candaba Swamp

The Candaba Swamp is a retention basin with a surface area of around 250 km^2 and a retention volume of 1.4 billion m^3. Currently, the Candaba Swamp is a huge flood plain, next to the Pampanga River. The Candaba Swamp could be separated in two parts, North and South Candaba. The two swamps are separated by a levee with an average elevation of 5.5 m above MSL. The purpose of this levee is to extend the period that agricultural activities are possible for the south swamp in the wet season. Normally both swamps are flooded during high rainfall events. The catchment of 560 km^2 upstream of the measurement station in the North Candaba Swamp is around 11 times smaller than the catchment of the Pampanga River until Arayat. Next to this catchment, the Candaba Swamp exchanges water between the swamp and the Pampanga River via the Candaba Floodway. Currently, there is little to no regulation of water in and out of the swamp.

2.2.3 Angat River

There are three dams in the Angat River catchment; Angat, Ipo and Bustos Dam. The main purposes of these dams are in order

1) drinking water for Manila;
2) irrigation;
3) hydropower;
4) and flood prevention.

Ipo and Bustos Dam are diversion dams and do not have a hydropower facility. 61%, equal to 546 km^2, of the catchment is flowing into Bustos Reservoir via Angat Dam. (adapted from PRFFWC, 2014a) This is also the part of the catchment where the rain is falling. (JICA et al., 2011) Bustos Dam has six rubber gates and three washout gates and has rules for the operation of these gates, see Table 2.2. The sixth rubber gate is not used according to the operation rules and might be used as back-up. The reservoir volume between the lowest level of around 12 to 13 m and the level of the first gate operation rule is around 12 million m^3. One extra metre stores an additional volume of 3 million m^3. The flood propagation time from Bustos Dam to the boundary of the Municipality of Calumpit is between 3 and 3.5 hours. (Nippon Koei, 2011, 2012)

Table 2.2 – Gate Operation Rules of Bustos Dam (Nippon Koei, 2011)

Reservoir Level [m]	Discharge [m^3/s]	Gate Operation Rule
16.8	-	No operation of washout/rubber gates
17.0	200	3 Washout gates
17.2	700	3 Washout gates and 1 rubber gate
17.4	1,200	3 Washout gates and 2 rubber gates
17.6	1,900	3 Washout gates and 3 rubber gates
17.8	2,800	3 Washout gates and 4 rubber gates
18.0	3,700	3 Washout gates and 5 rubber gates

The Angat River flow capacity from Calumpit to the Manila Bay is around 1,200 m^3/s without informal settlers and around 500 m^3/s with informal settlers at this location. The informal settlers or squatters are an important cause of the reduction in the bank full capacity of the river, see Section 4.1. (Nippon Koei, 2011, 2012)

2.3 Tide and surge

The Pampanga River Delta is located at the Manila Bay that has an entrance width of 18 km and an entrance depth up to 60 m. (GEBCO-BODC, 2008) The tidal wave enters through the South China Sea. The bay has a prevailing diurnal tide with diurnal, K1 and O1, and semi-diurnal, M2 and S2, tidal constituents in Manila Harbour of respectively 29, 28, 19 and 7 cm. The largest astrological tide at Manila South Harbour is 1.09 m above MSL. (United Kingdom Hydrographic Office, 2004) According to Fuji et al. (2002) travels the tidal wave counter clockwise through the bay and the amplitude of the tidal constituents are the same for the mouth of the Pampanga River Delta and Manila South Harbour. This is substantiated by a two-week measurement of De Vos et al. (2014) and Hopper (2007), see Appendix A.1 for the explanation of the calculation. During these measurements a minimum peak difference is measured of -5 cm on average, while there is on average no maximum peak difference. A phase difference is measured of 55 min and 49 min for respectively high water and low water.

On top of the tide, wind and waves can raise the water level in the bay even more. The tidal amplitude can be raised by 80% at the north side of the bay during the southwest monsoon. On top of that wind waves can be generated of more than 3 m even with a limited fetch of 30 to 50 km. (Rodolfo & Siringan, 2006) The southwest monsoon enhanced tide and other seasonal variations can also be seen in the maximum monthly water level in Manila South Harbour. (NAMRIA, 2013, 2014a) In the dry season, the maximum water levels vary between 0.8 and 1.1 m and in the wet season the maximum water levels vary between 1.1 and 1.3 m.

The strength of the storms are quantified by using 6 years of water level data from Manila South Harbour (NAMRIA, 2013, 2014a) for an extreme value analysis of Gumbel type I, with monthly extreme values as input, see Table 2.3 and for the calculation Appendix A.3. These six years are used for the analysis since these years are near complete and the yearly average of the water levels is stationary. The difference between a return period of one and ten years is 31 cm meaning that the water levels with a return period of 100 and 1000 years are 1.97 and 2.28 m for Manila South Harbour.

Table 2.3 - Return periods and maximum monthly water level in m based on 6 years of measurement from 2008 till 2013 at Manila South Harbour (NAMRIA, 2013, 2014a)

Return Period (yr)	Maximum Monthly Water Level (m)
1	1.35
2	1.44
5*	1.56
10*	1.66

*5 and 10 year return period are extrapolated

2.4 Flood impact description

The problem formulation in Section 1.1 already gives an indication of the impact of the regular floods in this region for both local people and government. This subsection gives a more detailed elaboration on this topic.

The annual flood depths have increased from 0.2 to 1.0 m between 1991 and 2002 for the Pampanga River basin according to respondents in the region. Parts of Macabebe, a member municipality of the ABB-BP, are inundated three to four weeks a year. Other cities next to ABB-BP are even flooded up to nine months a year including cities that are 20 km away from the shoreline. In Bulacan, the situation changed from floods with durations of about two hours, which were caused by high tides and typhoons or southwest monsoons, to floods with durations of half a day to a day only caused by spring tide. (Rodolfo & Siringan, 2006)

Hagonoy is probably the most affected city by both fluvial as tidal floods in the ABB-BP area. Hagonoy is flooded five to seven days every month due to the high tide cycle, since the average elevation height of the downstream part of the city is around 0.5 to 1.0 m above MSL. The tide can freely enter the city of Hagonoy and surroundings since it has a direct connection to the sea through the Pampanga, Hagonoy River and Labangan Floodway. If there are tidal gates to side channels, they are mostly poorly maintained. The tidal floods have a flood depth up to 0.5 m near Hagonoy. The fluvial floods have a larger impact on the city. The recent highest water level in Hagonoy before Pedring 2011 occurred in 2004 with a water level of 2.5 m above MSL. (Hydroterre consultants, 2008) The water levels during Pedring 2011 reached even higher. (Hagonoy, 2012) For a more detailed impact description, Section 4.1 presents the results of the 3Di model are used.

Closer the coastline, the people prefer to reduce the tidal floods first. Though, the majority of the people live more upstream and prefer to reduce the fluvial floods. Therefore, the main focus is on reducing the fluvial floods.

2.5 Typhoon Pedring

For the Pampanga River Delta, the typhoon Pedring from 26 September till 30 September in 2011 was definitely the most severe storm since 1972 according to the local people. The typhoon was directly followed by another typhoon Quiel from 1 October till 4 October 2011. The high impact of typhoon Pedring drew more attention to this storm and storm events in common. Therefore, more data was gathered after this storm. Both the argument of the memory of the local people and the data availability are used to substantiate the relevance of focussing particularly on the typhoon Pedring. Most of the gathered data was recorded between 2010 and 2013.

Three types of forcings can be distinguished for the Pampanga River Delta during Typhoon Pedring. First, on the south side, the tide is dominant. Second, the rainfall falling on the upstream area of the Pampanga and Angat River basins causes multiple river inflows with three main inflows at the north side near Mount Arayat via the Pampanga River and the Candaba Swamp and at the east side via the Bustos Dam. Last, the rainfall falling directly onto the area itself.

2.5.1 Precipitation, rivers and dams

For Pedring 2011, all the precipitation volumes have been calculated including an estimation of the runoff volume from the rain on the area downstream of the measurement stations and the outflow in the Porac River and Candaba Swamp is estimated. All results are summarised in Table 2.4. For the Porac River and the Candaba Swamp, the same relation between discharge and precipitation is assumed as for the Pampanga River, since no reliable outflow could be estimated. Based on this assumption, the proportions between those outflows and the Pampanga River are respectively 0.16 and 0.17. The outflow of the Porac River is later on split into two components; 0.12 for the upstream outflow and 0.04 for the downstream outflow. The runoff for the precipitation on the area downstream of the measurement stations is calculated using of a ratio between discharge and precipitation of 0.5 until the ground is saturated by a precipitation depth of 200 mm. For precipitation depths higher than 200 mm, the ratio between discharge and precipitation becomes 1. (Nippon Koei, 2011) Given a precipitation for Pedring 2011 of 404 mm, this ratio between 0.75.

Table 2.4 – Precipitation on the upstream area and outflow of the upstream area into the downstream; the underlined values are estimated; the numbers correspond to the numbers in Figure B.8 at page 79; this figure presents the catchment areas above the outflow points and their location.

No.	Location	Precipitation [mil m^3]	Precipitation [%]	Outflow [mil m^3]	Outflow [%]
1	Bustos	455	9%	228	7%
2	Candaba	560	11%	396	12%
3	Arayat	3,269	65%	2,310	70%
4&5	Porac	507	10%	358	11%
6	Precipitation	263	5%	198	6%
	Total	**5,054**	**100%**	**3,293**	**100%**

The discharges through the Pampanga River and Candaba Swamp are estimated based on water level measurements by PRFFWC (2014c) and rating curves. For the Angat River, the discharges are available at Bustos Dam. (NIA,2011) The three discharges for typhoon Pedring 2011 are summarised in Figure 2.4. The complete calculation and verification is presented in Appendix B.

It is remarkable that the gate operation of Bustos Dam during typhoon Pedring did not correspond to the gate operation rules as presented in Table 2.2. Before the typhoon hit the Philippines, the reservoir level was 17.48 m with only one washout gate in use. This should be around 17.0 according to the operation rules. During the event the maximum reservoir level hit 17.7 m and the maximum discharge with three washout gates and two rubber gates in use was 1.370 m^3/s at 27 September at 16 o'clock.

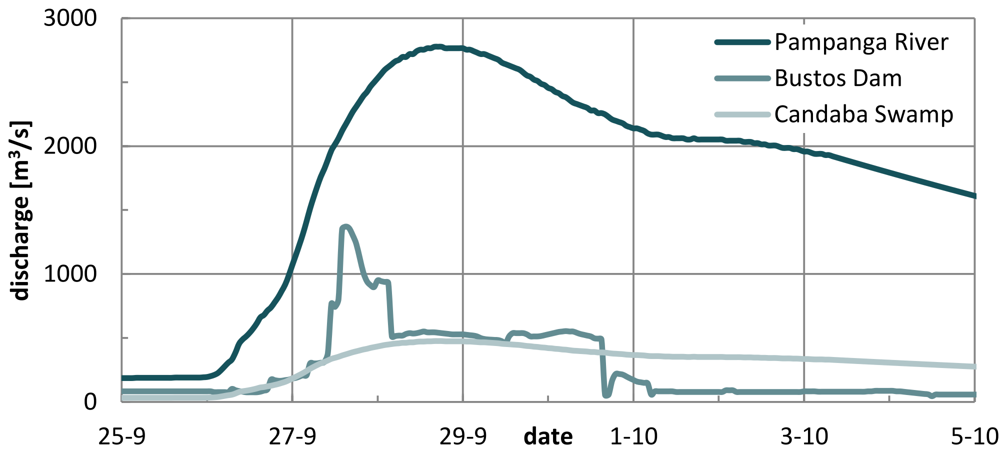

Figure 2.4 – Discharges of the Candaba Swamp, Pampanga and Angat River during Pedring 2011 (PRFFWC, 2014b, 2014c; NIA, 2011)

2.5.2 Tide and surge

The maximum water level height due to tide and storm surge also shows that typhoon Pedring is one of the severest storms of the recent years. For the typhoons Pedring and Quiel, the maximum water level of respectively 1.47 and 1.03 m in Manila Bay South Harbour was only once and 39 times exceeded in the six years of representative measured water level data. (NAMRIA, 2014)

The water levels near the Hagonoy coastline are estimated, since no tide gauge is available in the near area. For this estimation hourly tide gauge measurements at Manila South Harbour by NAMRIA (2014a) are used. The tidal component of these water levels is converted by adding the phase lag of about one hour. Since an average peak difference is small and only occurs during low water, the tidal component of the water level is assumed to be the same for Manila South Harbour and the Hagonoy Coastline.

The storm surge component is probably larger at the Hagonoy coast, since the fetch is longer. The results of a storm surge model are used to estimate the surge level near the Hagonoy coastline during typhoon Pedring 2011, see Appendix A.4 for more model information. (NOAH, 2013) The maximum water level according to the storm surge model in Manila South Harbour and Hagonoy Coastline is respectively 0.99 m and 1.48 m around 5 and 6 o'clock at 27 September. Therefore, the ratio between both locations is 1.49. This ratio is used for both typhoon Pedring and Quiel. The maximum water levels are below the maximum surge water level of respectively 1.25 and 1.5 m for 40 typhoon simulations between 1977 and 2013 by another numerical model. (De Hamer, unpublished)

Finally, the tide including storm surge for the Hagonoy coastline is computed, see Figure 2.5 for the result and Appendix A.4 for the calculation. The maximum water level during typhoon Pedring was 1.88 m above MSL at 11 o'clock on 27 September.

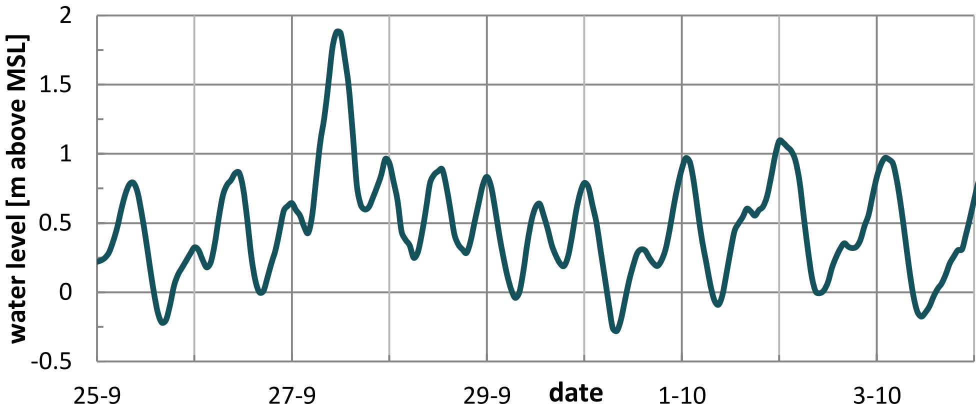

Figure 2.5 – Estimated water levels at the Hagonoy coastline during the typhoon Pedring 2011

2.5.3 Flood impact description

The Provincial Disaster Risk Reduction Management Office (PDRRMO) of Bulacan (2014) estimated that during Typhoon Pedring in total 766,000 people were affected and 36 people were killed in the province of Bulacan. The calamity damages were estimated at 2.8 billion pesos excluding the 5800 damaged houses. The municipality of Hagonoy (2012) did also estimate the calamity damage during Pedring 2011, see Table 2.5. The estimated damages are clearly not the same for both institutions and the PDRRMO of Bulacan seems to make an underestimation, e.g. because damaged housing is not included.

Table 2.5 – Calamity damages in pesos of the Municipality of Hagonoy (2012) for the typhoon Pedring 2011 converted with the exchange rate during Pedring 2011 to Euros (European Central Bank, 2014)

Category		Pedring 2011	Pedring 2011
Aquaculture		₱ 238,100,000	€ 4,044,000
Agriculture		₱ 15,700,000	€ 267,000
Social Infrastructure		₱ 25,600,000	€ 435,000
Damaged Houses	Partly	₱ 3,100,000	€ 52,000
	Severely	₱ 1,600,000	€ 28,000
Damaged Roads		₱ 369,000,000	€ 6,267,000
Damaged Bridges		₱ 55,000,000	€ 934,000
Total		**₱ 708,200,000**	**€ 12,027,000**

2.6 Area description summary

The tide-dominated Pampanga and Angat River Delta is located at the low end of a 7100 km^2 large alluvial plain and stands in open connection with the Manila Bay. Fishponds are the main land use type for respectively 14% and 67% due to the conversion of many rice paddies forced by saltwater intrusion.

The Pampanga River is the largest river in the delta with a bank full capacity of 2,200 m^3/s in the study area and a peak discharges at Mount Arayat of 2,700 m^3/s with a return period of 10 years. The other river is controlled by three dams of which Angat Dam has the largest reservoir. Next to the rivers, the storm surge enhance tides can cause large floods with storm surges up to 1.7 m with a return period of 10 years at Manila South Harbour the delta via Manila Bay. Typhoon Pedring is used as representative severe storm event with main inflows at the Pampanga River near Mount Arayat with a peak discharge of 2,800 m^3/s and Manila Bay with a storm surge enhanced tide of 1.8 m above MSL.

3 | 3Di

A 3Di model is used to estimate the flood characteristics in the study area. 3Di is used since this model can handle more data than other modelling software. The results are used to answer multiple sub-questions. In Section 3.1, the background of the model is explained in detail. In Section 3.2, the model set-up is explained. In Section 3.3, the model performance is checked by comparing the model results with flood information during typhoon Pedring. In Section 3.4, the model sensitivity is presented, since these are used as reference scenario to estimate the sensitivity. Section 3.5 gives a short model summary.

3.1 Explanation

The world is making a rapid improvement in technology. For example, more detailed geographic data is obtained with Light Detection and Ranging (LiDAR) technology. In the Pampanga River Basin, digital elevation data is available with a resolution of 1 x 1 m. (NOAH, 2014) To use this data and the increasing computer capacity for water management purposes, like flood modelling, detailed hydraulic model software is developed by the 3Di Consortium of Delft University of Technology, Nelen & Schuurmans and Deltares. Existing flood simulation software, such as SOBEK, cannot handle this resolution over a large area, because they crash when they exceed 1 million cells. Therefore, a 3Di model is created that is able to use a digital elevation model of around 900 million cells. That is equivalent to 900 km^2 on a resolution of 1 x 1 m. To handle this information, the 3Di model uses several techniques described in the next sections.

The model is based on the 2D shallow water equations consisting of the continuity equation, based on conservation of mass, and the momentum equations in two directions, based on conservation of momentum. The formulas of the continuity and momentum equations are respectively:

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0 \qquad \text{continuity equation}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + \frac{c_f}{h}u\|u\| = 0 \qquad \text{momentum equation in x-direction}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} + \frac{c_f}{h}v\|u\| = 0 \qquad \text{momentum equation in y-direction}$$

with h the water depth determined by $h = \zeta - e$, ζ the water level above plane of reference, e bottom elevation above plane of reference, u and v the depth averaged velocities, $\|u\|$the velocity magnitude, and c_f the dimensionless friction function. (Stelling, 2012)

3.1.1 Subgrid

The 3Di model consists of different 1D and/or 2D information layers, like a Digital Elevation Model (DEM) layer, which are detached from the Cartesian calculation grid, see Figure 3.1. This is the subgrid method. For 2D models, this technique is uncommon, since most models use the resolution size of the information layer for the computations, e.g. SOBEK, Delft3D and HEC-RAS. In 3Di, at least four DEM cells are linked to one calculation grid cell. This is valid under the assumption that the water level could be averaged over one calculation cell. For example in Figure 3.1, there are four or sixteen DEM cells linked to one calculation grid cell. For this example, this reduces the number of calculation cells from 32 to 5 compared to other models. (Stelling, 2012)

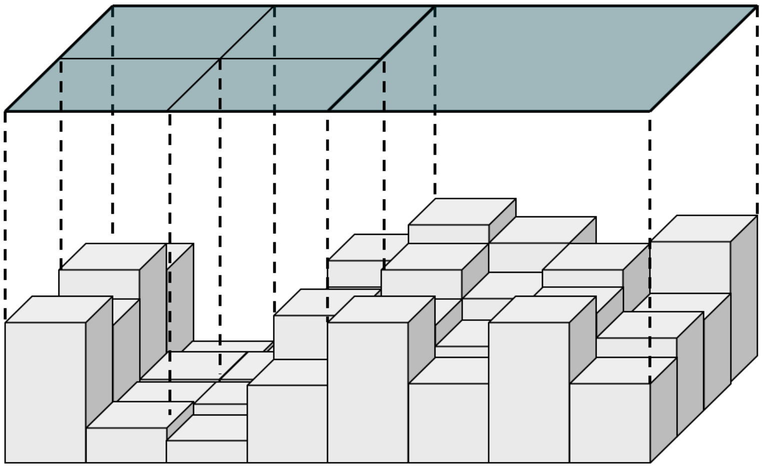

Figure 3.1 – Example of a small model with a decoupled DEM layer and quadtrees calculation grid; the low part illustrates the bathymetry of a channel and the upper part the calculation grid (adapted from Stelling, 2012)

Before the first model run, the water volumes in the calculation grid cells are calculated for every water level and stored in tables, which are easily accessible during the model run. The tables and grid need to be calculated once per DEM layer and can be reused for multiple models. This significantly reduces the runtime of models. Next to the 2D DEM layer, the model also offers the possibility to include a 1D open water network layer, 1D sewerage system layer and 2D subsoil layer, see Figure 3.2. In this report only the 2D DEM layer is used.

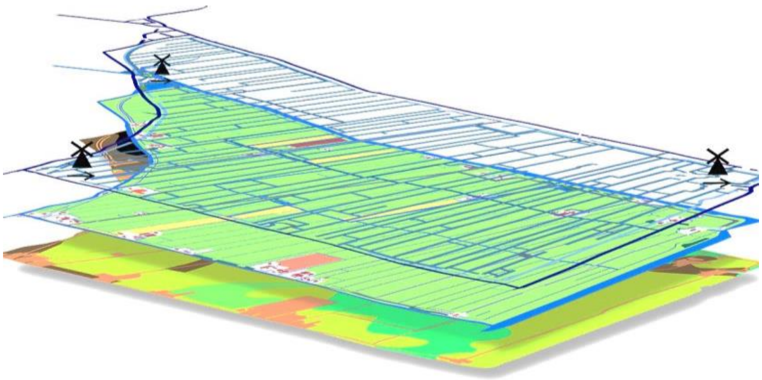

Figure 3.2 – Stacked grid of 1D open water network layer, 2D DEM layer and 2D subsoil layer. (3Di, 2014)

The structure of the calculation grid is based on quadtrees. A quadtree is a data structure based on a tree that divides a 2D region into squares with groups of four. Each of these squares could individually be divided again in groups of four, creating a hierarchical system with different resolutions, see the dark blue layer in Figure 3.1 for a quadtree with two different resolutions. Per quadtree calculation cell only one water level value is calculated. This means that DEM cells within one quadtree cell have the same calculated water level even when it is physically impossible, see Figure 3.3b. The DEM cells along the border of the quadtree cell determine if flow is possible between two calculation cells. Figure 3.3a and b illustrate that as soon as two neighbouring DEM cells are below the current water level, the two calculation cells start interacting.

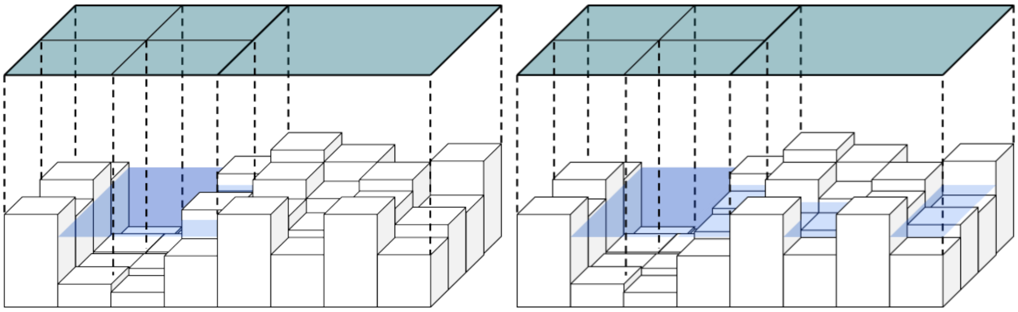

Figure 3.3 – Example of a water level on a DEM layer without (a) and with (b) interaction with the large calculation cell; figure b shows an example of a constant water level over a calculation cell even if this is physically impossible; assumed is that the water is coming from the channel

The velocity between two cells is determined based on the structure as described by the shaded cells in Figure 3.4a. A quarter of the larger neighbouring calculation cell and halve of the smaller neighbouring calculation cell are used for this calculation. To calculate the water level, a pressure gradient stencil is used as drawn in the quadtrees of Figure 3.4b.

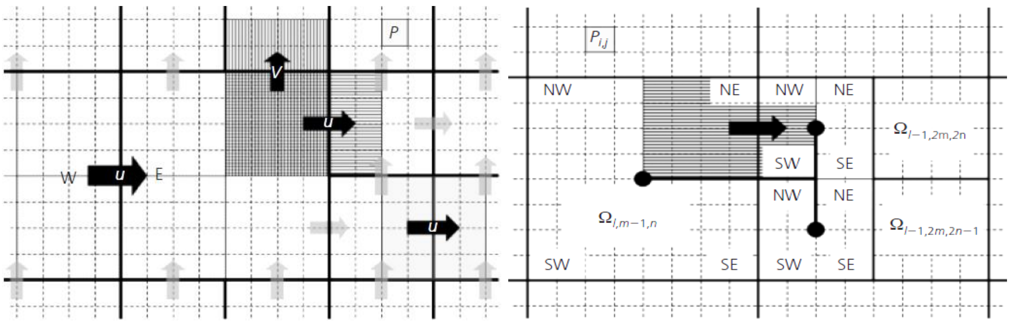

Figure 3.4 – (a) The domains used for calculating the velocity between two calculation cells with different resolution; (b) the pressure gradient stencil drawn in the quadtree structure for different resolution calculation cells. (Stelling, 2014)

3.1.2 Quadtree grid refinement

The quadtree structure makes it possible to increase the resolution at the places of interest and reduce the accuracy at less relevant places that need to be included in the model. The two variables minimum grid size and the maximum refinement level are set to specify the minimum and maximum resolution. For every refinement step, the resolution of the calculation cell becomes twice as high along the cell border; see the dark blue layer in Figure 3.3.

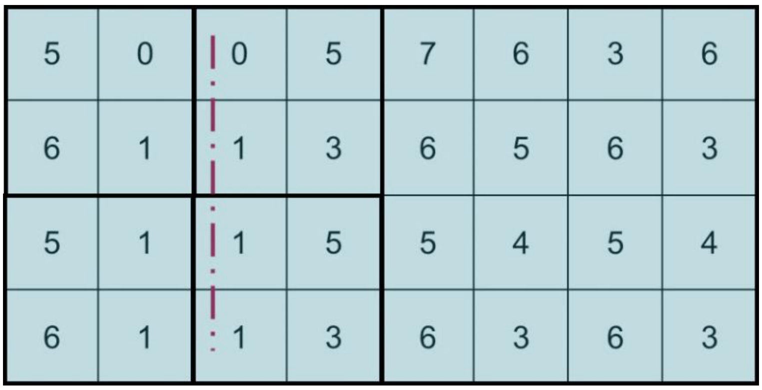

Figure 3.5 – Top view of the DEM layer with a grid refinement based on DEM or based on a line (purple – dashed line) and the DEM quantified in metres.

The 3Di model offers two methods for grid refinement: based on DEM and/or based on a grid refinement file. The first method uses two parameters: the refinement threshold (in m) and the maximum sensible elevation (in m above reference level). First a grid is generated with the largest allowed calculation cells. If the difference in the DEM in a calculation cell is higher than the refinement threshold and the DEM is lower than the maximum sensible elevation, the grid is one step further refined. This process is iterated until the grid fulfils the refinement requirements or the minimum grid size is reached. For the small example model, the grid is generated for a refinement threshold between 4.1 and 6.0 m and a minimum calculation cell of 2 DEM cells, see Figure 3.5.

The second method uses polygons and/or lines in a so-called grid refinement file to specify the refinement. Every polygon or line has a value to specify the refinement level for the DEM cells covering it. For the small example model, the grid is generated in case of a minimum grid size of two DEM cells and the purple dashed line with refinement level one, see Figure 3.5. In this report, the grid refinement file is used for specifying the quadtree calculation grid.

3.1.3 Levees

Figure 3.3 shows that the DEM cells on the border of the cell determine if flow is possible between two calculation cells. The calculation cells could become larger than important features in the model, e.g. in this report fishpond dikes with a width of around 5 m and calculation cells with a grid size of 40 m. Important features, which are not perfectly located on the border of the cells become invisible to the model, since only one water level is applied per grid cell. For example, the DEM layer shown in Figure 3.6 becomes completely inundated for a water level higher than 3 m.

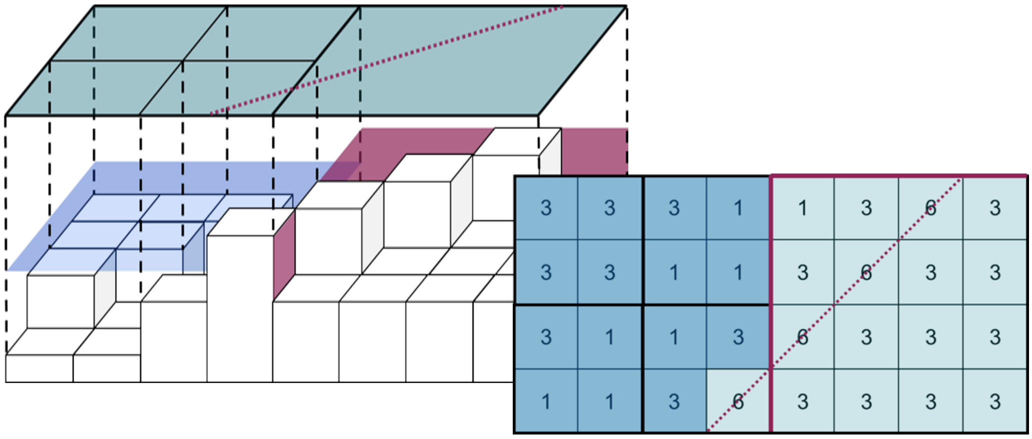

Figure 3.6 – 3D and top view of the DEM layer with a channel of 1 m above MSL deep, a levee of 6 m above MSL and a levee line (dotted purple line) and the real levee in the model (purple line and plane); assumed is that water is coming from the channel

The problem can be solved by further refining the calculation grid, but this is not always possible. The other option offered in 3Di is to create a levee file. This levee file, with lines to describe the flow determining features, prevents that water can flow over the border of the cell below a certain levee height. For the example model in Figure 3.6, a levee file is determined by the dotted line with a value of 6 m above mean sea level (MSL). Based on the levee file, the left and top border of the large grid cell are the closest options to prevent water from flowing over the dike. In this case, a small error is made for three cells, but the hinterland is protected as in reality. The former is considered as model artefact.

3.1.4 Boundary and initial conditions

In the model set-up the boundaries of a model have to be chosen. In most cases, the boundaries are not closed in reality, as the outside world interacts with the modelled area. The 2D model offers five options to simulate this interaction. The first option is to apply a spatially uniform rainfall time series over the model, but if required different over time, to simulate a precipitation event. The other four options use a boundary condition. In the model, ghost cells are created along the boundaries of the model for the application of the boundary condition. In 3Di, there are four 2D boundary types available: discharge, water level, velocity and water level-discharge relation. The first two are used in this research. The discharge boundary forces a discharge into (or if negative, out of) the ghost cell and the water level boundary forces a specific water level on the ghost cell. In the latter case, an unspecified volume of water can leave or enter the model.

In Figure 3.7, the example model shows the two boundary conditions used. The dotted and dashed lines show the drawn boundary lines that are applied by the model on the closest calculation grid borders (the solid lines). The boundary in the sea is of the *water level* type to describe the tide on the sea. In Figure 3.7, the water level in the ghost cell applied by the boundary condition is higher than the water level in the model, meaning that water flows into the model. The boundary at the river side is of the discharge type.

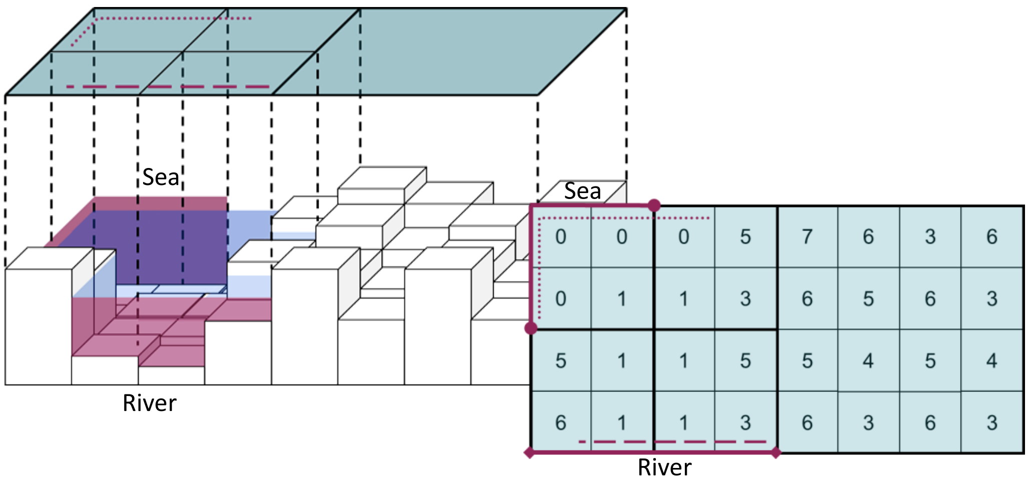

Figure 3.7 – Example model with two boundary conditions and initial water level condition; the dashed purple line simulates the discharge boundary at the channel; the dotted purple line simulates the water level boundary at the sea; blue plane simulates an initial condition of around 4 m above MSL.

However, by only applying boundary conditions, the model starts empty, which requires a long initialisation period before the model starts to represent a realistic situation. To reduce the initialisation period, an initial condition can be applied to the model. For an initial condition, two options are available in 3Di: a constant water level or a water level file. In the example model shown in Figure 3.7, the constant water level is described by a uniform water level of around 4 m. The water level file specifies a water level for every calculation cell. An often used option is that the model is initially run with constant boundary conditions for a certain period until the start date of the model period. This model run is used to create the initial water level file. This approach is used in this research.

3.1.5 Other parameters

After creating the grid, the time step and the number of 'predictor-corrector'-steps in single time steps (npc) can be selected. For every time step, the water levels and velocities are calculated. The time step is chosen between 5 and 30 seconds to avoid instability. The final time step also depends on the npc-value. The npc-value determines the amount of calculation cells taken into account ahead of the current calculation cell in the flow direction. For example, with a flow velocity of 4 m/s, a wave could travel 40 m in a time step of 10 s. For calculation grid cells smaller than 40 m, this means that the flow enters more than one cell ahead in reality. With an npc-value of 1, the flow is bounded by the calculation grid. Therefore, the npc-value should be larger than the maximum expected velocity multiplied with the time step divided by the minimum grid size.

The friction can be calculated with Chézy or Manning. In contrast with the Chézy roughness coefficient, the Manning roughness coefficient depends on the wetted perimeter of the cross-section and thereby the depth. This dependency leads to a lower roughness for deeper channels, which is more accurate. Therefore, Manning is used to specify the roughness.

The flooding threshold determines when a cell is flooded. This value is set to 0.1 m for stability purposes. When the value is set too low or to zero, the model cannot handle this kind of information accurately enough and the model tends to become unstable.

3.1.6 Limitations of the model

Density differences cannot be included in the model, meaning that a distinction between salt and fresh water cannot be made. The maximum resulting error in the water level for a sea water density of 1.022 kg/m^3 (Fuji et al., 2002) and a bay depth at the river mouth of 4 m is around 4 cm. Since the modelled flood is mainly fluvial, this effect is negligible. However, the salinity intrusion of the storm surge could not be investigated.

Short waves are not included in the model. Short waves are an important process for the fishponds along the coastline. First, they can overtop the fishpond dikes resulting in higher water levels in the fishponds. Second, they can demolish the fishpond dikes, which cause flooding in the fishpond.

Floods have a large influence on the morphodynamics of a river. (van Denderen, 2014) The 3Di model does not include the morphodynamics in the model, assuming that these are constant during the model run. The changing morphodynamics could have either negative or positive effects on the flood, but not more than a couple of centimetres in flood depth.

The model presents depth results on a resolution of the DEM layer. However, for important features, like fishpond dikes, which determine the flow in the model, the resolution in the model is similar to the resolution of the calculation grid. The important features that are too small to see by the calculation grid and are not specified in the levee file are not included. Therefore, small differences in results could occur when modelling on a coarser grid.

3.2 Set-up

A model is set up to get a picture of the flood characteristics of the current situation. This model is used as baseline scenario. This section describes the model set-up in the same order as the model is explained in Section 3.1. The most important input parameters are the boundary conditions and the Digital Elevation Model (DEM), which is treated first. Afterwards, the model parameters like time step and grid generation are described.

3.2.1 Subgrid

The subgrid used in this research is the DEM layer. The DEM layer, see Figure 3.8, consists of three main inputs, three neighbouring Digital Terrain Model (DTM) layers of NOAH (2013) with a resolution of 1 x 1 m, an ocean bathymetry map of GEBCO-BODC (2008) with a resolution of 1 x 1 km and cross-section measurements of the three large rivers for approximately every kilometre. (De Vos et al., 2014; DREAM, 2012) In Appendix C.1, the processing of the DTM is explained in more detailed. In short, the three DTM layers are mosaicked together after the height differences between the three sets were corrected. In this operation also one flight band, that is substantially higher, is corrected. Based on 58 Benchmarks (NAMRIA, 2014b; Hydroterre Consultants, 2006, n.d.; Hagonoy, 2014a) the created layer is lowered by 1.8 m to snap the layer to MSL. Furthermore, a small gap in the Candaba Swamp is filled and the expressway on piles through the Candaba Swamp is removed. The accuracy of the LiDAR measuring data itself is around 20 cm. The difference between the benchmarks and the original DTM is caused by three reasons:

1. the offset of the benchmark from original location with different height,
2. the processing error to get the DTM from the Digital Surface Model,
3. and the real error in height.

The standard deviation of this difference is 29 cm.

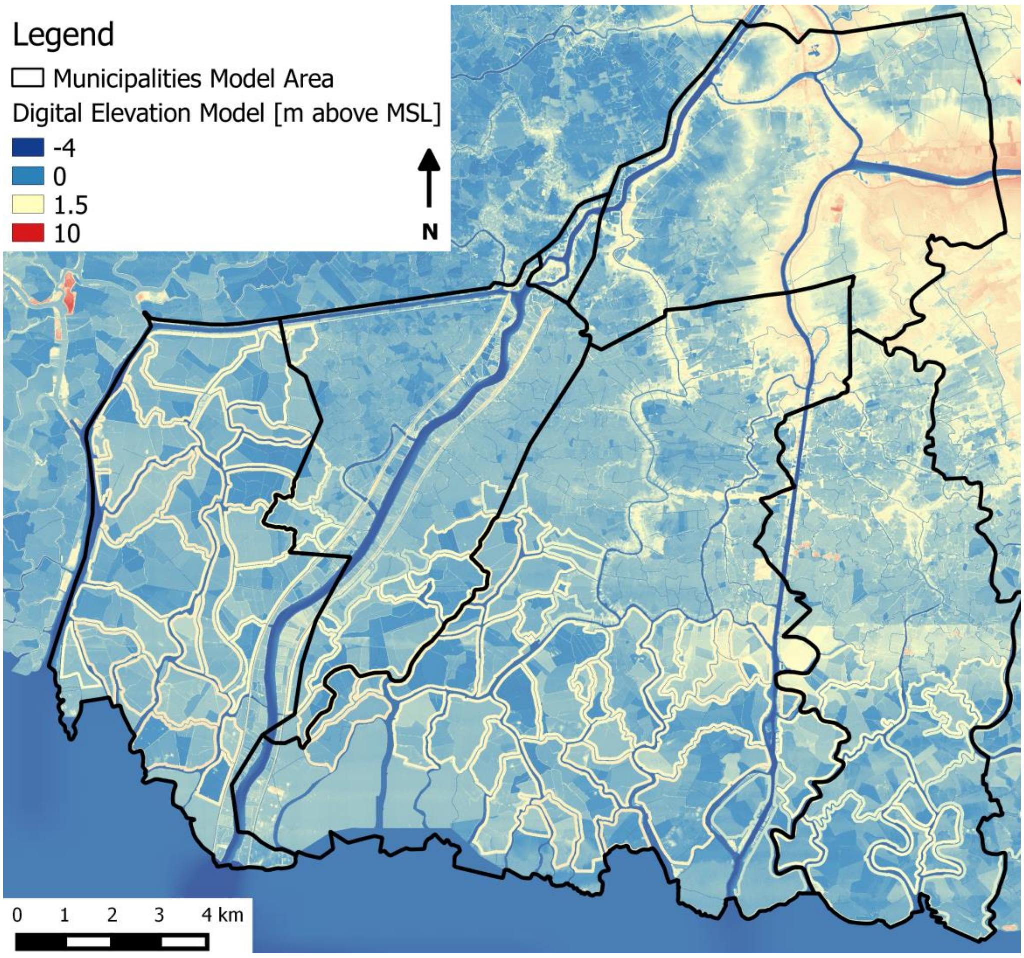

Figure 3.8 – DEM with a resolution of 1x1 m consisting of a DTM by NOAH (2013), a bay bathymetry map by GEBCO-BODC (2008) and river bathymetry layer based on cross-sections of De Vos et al. (2014) and DREAM (2012); the fishpond dikes are widened to 60 m for modelling purposes.

Additional river bathymetry needs to be added to the DTM, as LiDAR measurements reflect on water. De Vos et al. (2014) measured cross-section data in the San Esteban Diversion and Labangan Channel, Pampanga, Angat, Old Pampanga and Bagbag River. Cross-section measurements of *Disaster Risk Exposure and Assessment for Mitigation* (DREAM, 2012) are added for the upstream part of the Pampanga River, since De Vos et al. (2014) stopped measuring in the Pampanga River just above Calumpit. In Appendix C.2, the locations of the cross-section measurements are plotted. Appendix A.2 is used to correct the measurement data for the tide.

The cross-section measurements cannot easily be interpolated to get the river bathymetry, since the river is curved and the cross-sections measurements are only available once per kilometre. With the help of the method of Merwade et al. (2005), a method is created to interpolate the bathymetry over the centreline of the river by making use of a conversion from Cartesian coordinates of the Universal Transverse Mercator projection to Orthogonal Curvilinear Coordinates. This method is further described in Appendix C.2. The tidal inlets are deepened to 2.9 m and the small rivers and creeks are deepened to 1.7 m. These values are estimated based on measurements by De Vos et al. (2014).

The LiDAR data also reflects on the water of the fishponds making the elevation of the conventional fishponds around 0.5-1.0 m higher. (Ledesma, 2014) The elevation of the fishponds could be lowered, but the fishponds also have water inside during the storm events. It is assumed that the fishponds in the system have the same water level as during the LiDAR measurements and that this water volume is a dead volume during the storm events. This assumption is realistic, since the fishpond owners do not open their ponds during the storm events.

For the part of the bay that is included in the model, the bathymetry maps of GEBCO-BODC (2008) are used with a resolution of 1 x 1 km. Due to the low resolution, the map does not fit tight to the coastline according to the LiDAR measurements. Therefore, this map is slightly adjusted to make it fit to the coastline and the river mouths.

Finally, the model boundary is determined. On the north side, the model inflow at the upper side is at Arayat and Candaba station, on the west side at Bustos Dam and on the south side at the bay. The border is determined by the hydrologic basins, see Figure 1.1, however some exceptions are made. First, the left side of the Candaba Swamp is bounded by an elevation of 8 m, since the water levels in the swamp do not exceed 7.62 m. Furthermore, the Porac River is included in the model, while it is not in the catchment, because this river forms a connection with the Pampanga River by the San Esteban Diversion Channel. On the right side, a cut-off is made, to reduce model size with a buffer around the Municipality of Paombong. The remainder is outside the study area and therefore not relevant.

For model stability, it is advisable to create a sponge layer, an artificial reservoir, in front of the model with approximately the same size as the grid for every boundary condition. This sponge layer absorbs the unwanted high frequency waves that could not be absorbed by the "closed" water level or discharge boundary. In the transition from shallow to deep water, the waves become short and short waves are damped more easily than long waves. The reservoirs are added to create one single DEM file as input for the model, see Figure 3.9. For modelling purposes, the resolution is changed from 1x1 m to 2x2 m, since normal computers run out of memory by handling almost 2 billion DEM cells.

3.2.2 Quadtree grid refinement

The calculation grid has a different grid size than the resolution of the DEM file, as explained in Section 3.1. The minimum advised calculation grid size is based on the total number of grid cells, which is advised to be below 100.000 calculation cells. Using this number of calculation cells as guideline, it is unfortunately not possible to create a grid that is smaller than the fishpond dikes of 5 m wide. Since the fishponds are an important aspect for the tidal intrusion and the sinking of the floods, these need to be included. To overcome this problem, all the important fishpond dikes are extracted and widened based on the average height of that fishpond by a width larger than the diagonal of the smallest calculation cell, see Figure 3.8. The averaging also solves the many processing errors that make non-real holes in the fishpond dikes. Only the fishpond dikes are selected that have clear closed dikes which happen to be the traditional fishpond area, see Figure 2.2. The grid generation is shown in Figure 3.8 with a minimum grid size of 40 m.

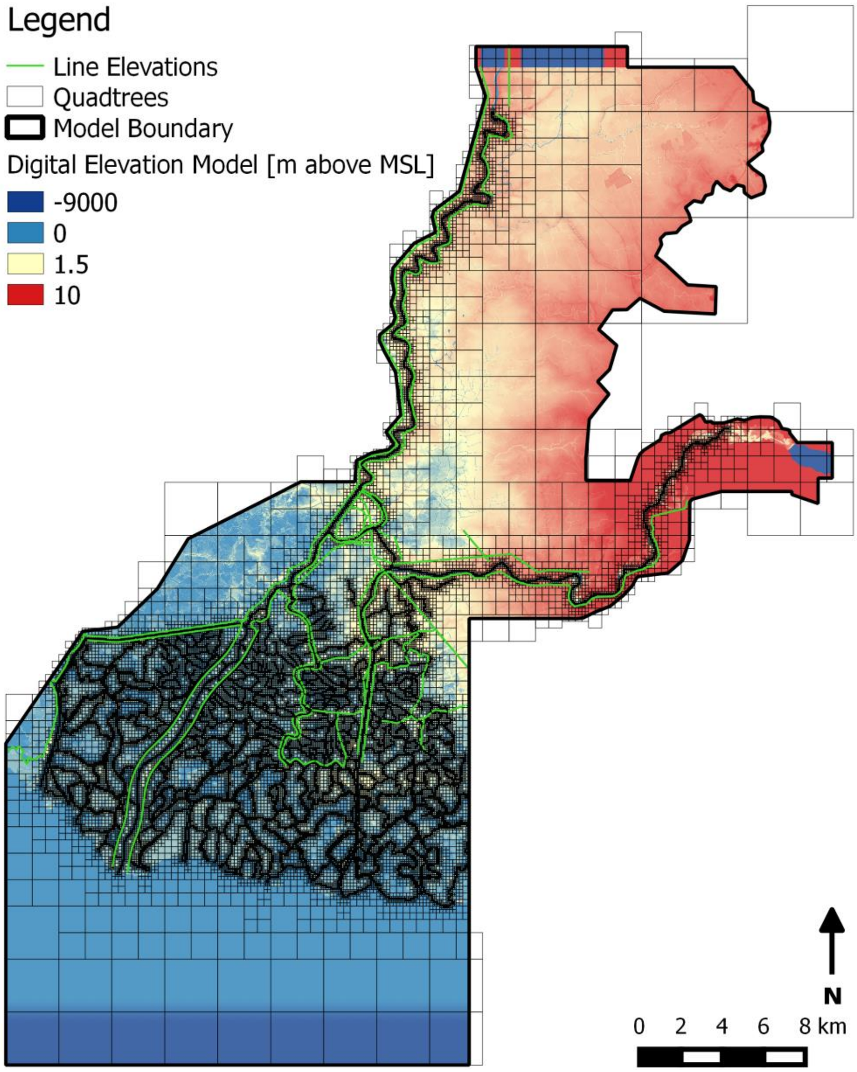

Figure 3.9 – Grid generation and adapted DEM including deep reservoirs at the boundaries for modelling purposes and levees (NOAH, 2014)

3.2.3 Levees

Since the minimum grid size is larger than many elevated roads and levees, an additional levee-file is added to the model. This file includes line elements with elevation data that block one or more of the grid cell borders up to the inserted height. The elevation of the line elements are based on the average elevation in the DEM layer under the line elevations. If the elevation level is exceeded by the water level, the water could flow into the neighbouring cell. The included levees or elevated roads are presented in Figure 3.9. Unfortunately, the fishpond dikes could not be implemented in the levee-file, since the levee-file would block the flow in the channels between the fishponds. This is caused by multiple levees in one calculation cell.

3.2.4 Boundary and initial conditions

The boundary conditions are based on the data adapted and presented in Section 2.5. Discharge boundaries are used for the Pampanga River, Candaba Swamp and Bustos Dam. Water level boundaries are used for the tide. The model runs from 25 September 2011 0:00 up to 5 October 2011 0:00. The first day is used for initialisation. To create an initial water level file, seven days are run from 18 September 2011 0:00 to 25 September 2011 0:00 with constant boundary conditions based on 25 September 2011 0:00.

3.2.5 Other model parameters

The timestep and number of 'predictor-corrector'-steps in single time step (npc) need to be selected together. If the npc-value is too low and the time step is too high, the wave speed is faster than the model could handle and the flow velocity is bounded by the distance of the minimal grid size multiplied with the npc-value and divided by the timestep, for example a time step of 60 sec with a npc-value of 1 and a grid size of 60 m means a maximum flow velocity of 1 m/s. For this model the optimal setting is a timestep of 10 seconds with an npc value of 1, providing a maximum wave speed of 4 m/s.

The roughness is set to 0.03 $s/m^{1/3}$ which is comparable to natural channels with some weeds or short grass. (Ankum, 2002) The sensitivity of this assumption is tested in Section 3.4.

Both rain and the inflow to the Porac River are neglected. The precipitation is only a small percentage of the inflow of the model, see Table 2.4, and the uncertainty of the precipitation is high since it is based on point measurements only. Furthermore, excluding the rain gives a clear vision if the fishponds are flooded or not. The Porac River is excluded since no reliable inflow is available for this river and it probably has a minor influence on the floods in the area. Both assumptions are checked in the sensitivity analysis, see Section 3.4.

3.2.6 Limitations of the model set-up

Outside of the study area the resolution is lower and thereby the results in this area are less reliable. The area just left of the Pampanga River Dike and San Esteban Diversion Channel Levee is only modelled to see if these levees overflow during the storm event.

The model does assume saturated soil during the event, meaning no infiltration. Interception, precipitation and evaporation is not included in the model. Furthermore, there are many fishpond dikes, levees and elevated roads added to the system that in reality have tidal gates or pumps, for example the Pampanga River Dike in Masantol has large tidal gates. These are assumed to be closed during the whole event. Combining this, one can conclude that the subsidence of the water level after the storm takes more time than in reality, while the storm event itself is modelled properly.

Because a DTM is used, the houses are not included in the DEM layer. Also the houses from illegal settlers in the river banks are removed, making the capacity of the river larger than in reality. This could result in an underestimation of the flood. In urban areas, the houses could prevent or slow down the flood from flowing further into the area. This could result in a different spread of the flood. The advantage of using the DTM is that bridges, trees and other objects that do not block the flow, but are included in the Digital Surface Model, are removed. Furthermore, one can estimate the water depth in the houses more easily.

The fishponds are currently modelled with the assumption that the water level at the start of the storm is dead storage and not contributing to the flood. The fishponds are therefore not deepened to its estimated real value. Due to this assumption, the water surface of the fishponds is now seen as land surface. Floods over land travel much slower than floods over water. The effect of these limitations is only visible in the fishpond and does not affect the volume of the flood, because the levees around the fishpond are much higher which is creating free flow over the levee.

Lastly, the DEM is measured during the dry season in January. The bathymetry of rivers could change rapidly due to the difference in discharges, resulting in a deeper river for the wet season. The effects of such changes are estimated to be small for the maximum water depth and flood extent.

3.3 Performance

On 3 October 2011 between 0 and 1 AM (NOAH, 2011), a satellite made an almost cloud free picture of the flood during Pedring 2011, see Figure 3.10. This picture is compared with the flood map from the model at 3 October 2011 at 1 AM. The flood extent for the satellite map is roughly estimated by the white line.

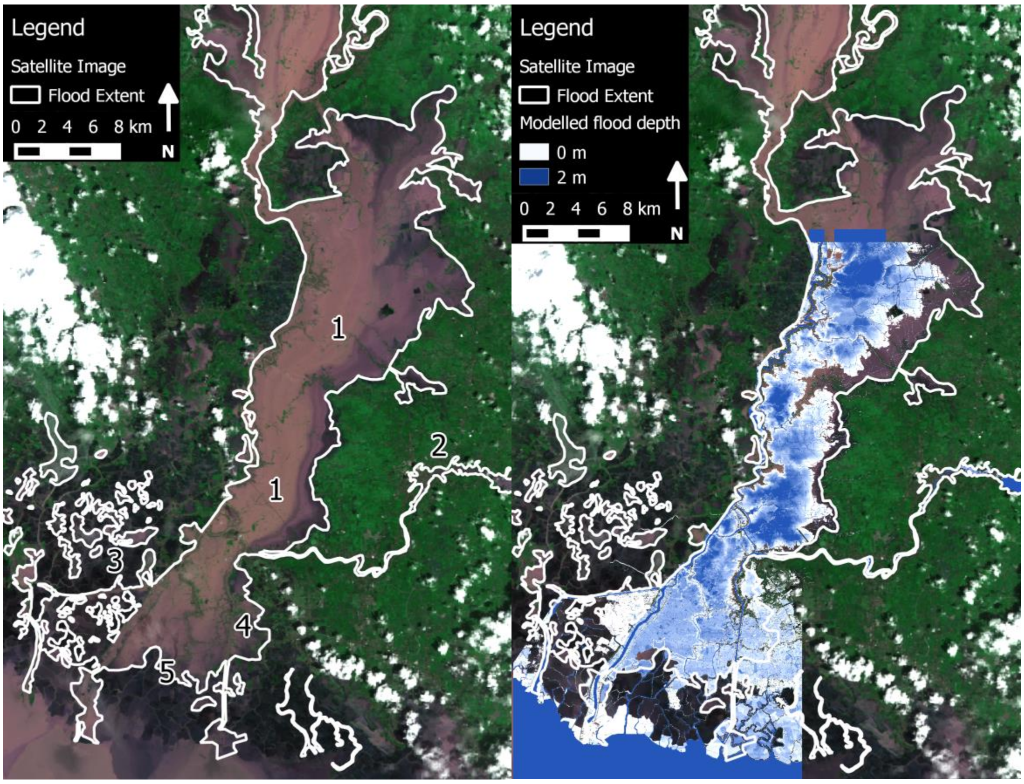

Figure 3.10 – Model results of 3 October 2011 at 1 AM compared with a satellite image of 3 October 2011 taken between 0 and 1 AM (NOAH, 2011)

A performance analysis based on Figure 3.10 is preformed and presented based on the numbers in Figure 3.10a:

1. The Candaba swamp upstream gives an underestimation of the flood extent and this underestimation diminishes by going downstream. This can be explained by the usage of

the discharge boundary instead of a water level boundary and by combining the inflow from the west side with the inflow from the north side. This reduces the water level, but gives the same discharge as reality and results in a more or less correct flood extent downstream in Candaba.

2. For Bustos Dam the flood extent is smaller since the water does enter the flood plains. This could be caused by the extrapolation of the bathymetry from half way the Angat River till the start of Angat River after Bustos Dam.
3. The Pampanga River Dikes do not overflow upstream of the Municipalities of Masantol and Macabebe for both maps. The flood in the other three municipalities is comparable.
4. On the west side of Paombong, the flood extent is larger than on the satellite image. The flood extent for the urban area of Paombong looks similar.
5. For the fishpond dikes, the situation is not completely correct, especially on the west side of the Pampanga River and in the Municipality of Paombong. This area is very sensitive for the inclusion of fishpond dikes and for small changes in fishpond dike height, so in detail the results are not comparable. However, in general, the results are comparable, since the flood wave is hindered by the fishpond area and some of the fishponds are flooded. The differences between the traditional fishpond area, close to the coastline, and the extended fishpond area are clearly visible.

The maximum water levels were also checked by a former mayor of Hagonoy (personal communication, 24 September, 2014) on four specific locations in the centre of Hagonoy and in San Juan, Hagonoy. Three of the four locations where approximately right and one of the four locations has an error of about 30 cm (1 feet).

The shape of the flood wave is not comparable with the measurements of Candaba and Sulipan. (PRFFWC, 2014c) For example, the flood wave reached the Sulipan water measurement station at 30 September around 14 o'clock, while the model shows the peak at 29 September around 17:30. Moreover, the flood wave in the model has a higher speed than in reality, from Candaba to Sulipan the flood propagation time is for the model and in reality respectively 9.5 and 18 hours. The phase lag is not only caused by the model itself, since the water level measurement station in Sulipan has an unrealistic delay up to four hours for the tide. (PRFFWC, 2014c; De Vos et al, 2014) Two model causes of this difference in propagation time could be the difference in roughness or the lack of the inclusion of the levee separating the north from the south swamp of 5.5 m high. The propagation time of the tidal wave of around 1.5 hour is correct for the wave travel from the Pampanga River mouth to Sulipan.

The maximum wave speed of 4 m/s is exceed in only a couple of cells in the study area, proving that the assumptions of the npc-value of 1, a timestep of 10 seconds and a minimum grid size of 40 m are suitable for the model.

3.4 Sensitivity

For presenting the results of the model runs, the 5 land use classes described in Section 2.1 are split per municipality in the study area resulting in 25 categories for which the flood characteristics could be calculated. In this report, the categories with an area smaller than 5 km, except for the populated area, and the *water body* and *others* categories are excluded from the presented results. For the flood depth, the average is used as characteristic value. For the flow velocity, the average flow velocity plus the standard deviation is used as characteristic value. The addition of the standard deviation is based on the argument that during evacuation along the travelled road there is always a part where the water is flowing faster.

Five parameters are checked on sensitivity; DEM resolution, roughness, timestep, precipitation and the Porac river inflow. Since the original DEM was on 1x1 m, a super computer is used to check the sensitivity of the assumption to model on 2x2 m. The assumed roughness is based on channels; however the other areas do not have such a low roughness. The roughness is doubled to a value of 0.06, comparable to brushwood according to Ankum (2002). The timestep is reduced to one second to check the relevance of the ten second timestep assumed combined with the npc-value of one. Lastly, the neglect of the Porac river inflow and the rainfall on the study are checked on sensitivity. The sensitivity analysis is done on the percentage flooded area, the mean water depth and the 84% maximum water depth based on the land use classes per municipality and is summarised in Table 3.1. The remarkable changes in this table are treated more thoroughly.

Table 3.1 – Percentage flooded area for three land use types per municipality for the baseline model compared with the difference for five sensitivity model runs

Town	Land Use	Base	1x1m	Porac	t = 1s	Roughness	Rainfall
Calumpit	Cultivated Area	92%	0.1%	0.1%	0.0%	0.0%	1.4%
Hagonoy	Fishpond	55%	-1.1%	0.1%	-0.1%	0.0%	33.1%
Macabebe	Fishpond	21%	1.6%	2.9%	0.0%	0.0%	60.9%
Masantol	Fishpond	78%	0.5%	0.2%	0.0%	0.0%	14.1%
Paombong	Fishpond	90%	0.1%	0.0%	0.0%	0.0%	7.0%
Calumpit	Populated Area	66%	0.1%	0.2%	0.0%	0.0%	2.4%
Hagonoy	Populated Area	93%	-0.1%	0.1%	0.0%	0.0%	0.7%
Masantol	Populated Area	74%	0.2%	0.8%	0.0%	0.0%	2.6%
Paombong	Populated Area	92%	-0.1%	0.2%	0.0%	0.0%	0.8%

The model is not sensitive for the timestep and the roughness coefficient. For the sensitivity of the resolution and the Porac River, the flooded area show small difference up to 0.6%, except for the fishpond area up to 2.9%. The latter is due to the additional or lacking flood of one or more fishponds, for example at the inflow of the Porac River. The difference in water depth is smaller than 1 cm. The sensitivity model run for the model including rainfall shows a larger difference, because the rain is falling on every calculation grid cell. This means that at least the lowest part of every calculation grid cell is flooded for one time step. Therefore, the average water depth is used to check the sensitivity of the rainfall. The average water depth increases with only 1-3 cm, proving that the sensitivity for rainfall is low.

3.5 Model Summary

To assess the performance of potential measures, a 3Di model is used to estimate the current and future scenario with Pedring 2011 as representative storm event. A digital terrain model including sea and river bathymetry with a resolution of 1 x 1 m covering an area of 900 km^2 is used as input for the model.

About the model performance, the timing of the flood shows difference by comparing the measurements of PRFFWC (2014c) with the model. The difference is found in an unrealistic phase lag in the measurement station and a faster propagation time. The maximum water level looks correct based on the experience of the mayor of Hagonoy and the satellite image of 3 October 2011. (NOAH, 2011) The total inflow volume of the storm, see Subsection 2.5.1, and the modelling of the fishpond dikes that obstruct the flood wave is correct, which results in an in the order or magnitude correct maximum water level in the study area. The model is most sensitivity for the neglected rainfall, which causes an error of 1-3 cm.

4 | Current and Future Scenario

The representative storm event, Pedring 2011, is used to determine the current flood characteristics to answer the first sub-question. Furthermore, the expected hydraulic changes are identified and the hydraulic effects are estimated by the model for the future scenario without government intervention over twenty to fifty year. This answers the second sub-question.

In Section 4.1, the flood characteristics for typhoon Pedring 2011 are estimated. One should understand the historical context of the area to be able to predict the future. Therefore, in Section 4.2, all the causes of floods according to literature and local opinions are elaborated. In Section 4.3, the predicted hydraulic changes of these causes in the future scenario are estimated. In Section 4.4, the future flood characteristics are presented. Section 4.5 presents a short conclusion about the scenarios.

4.1 Current situation

The flood characteristics, flood extent, flood depth and flow velocity, are used to describe the impact of the floods in the study area. The results from the model are summarised in Figure 4.1 and Table 4.1. The flood depth and velocity ranges up to respectively 2.2 m and 0.82 m/s. In the current situation, the city centres of Macabebe and Masantol are not struck by the tidal or fluvial flood from the Pampanga River. However, these municipalities could still be flooded by a flood wave coming from the Porac River Basin or by the storm surge enhanced tide via channels outside of the model domain.

Table 4.1 – Peak model results for the baseline scenario for three land use types per municipality

Municipality	Land use	Area (km^2)	Flooded area (%)	Average flood depth (m)	Velocity (m/s)
Calumpit	Cultivated Area	27	92%	1.47	0.52
Hagonoy	Fishpond	72	55%	0.74	0.51
Macabebe	Fishpond	39	21%	0.25	0.57
Masantol	Fishpond	30	78%	0.85	0.49
Paombong	Fishpond	32	90%	1.03	0.60
Calumpit	Populated Area	5	65%	0.63	0.82
Hagonoy	Populated Area	5	93%	0.90	0.61
Masantol	Populated Area	2	74%	0.76	0.39
Paombong	Populated Area	2	92%	0.65	0.54
Study area	No water body	265	66%	0.81	0.54

The total damage for the study area is estimated at 1.5 billion pesos, see Appendix E for the calculation method. The largest effect municipality is Hagonoy with 513 million pesos directly followed by the municipality of Calumpit with 509 million pesos damage. The damages of the city centres of Masantol and Macabebe are not included in the damage estimation, because they are outside the study area.

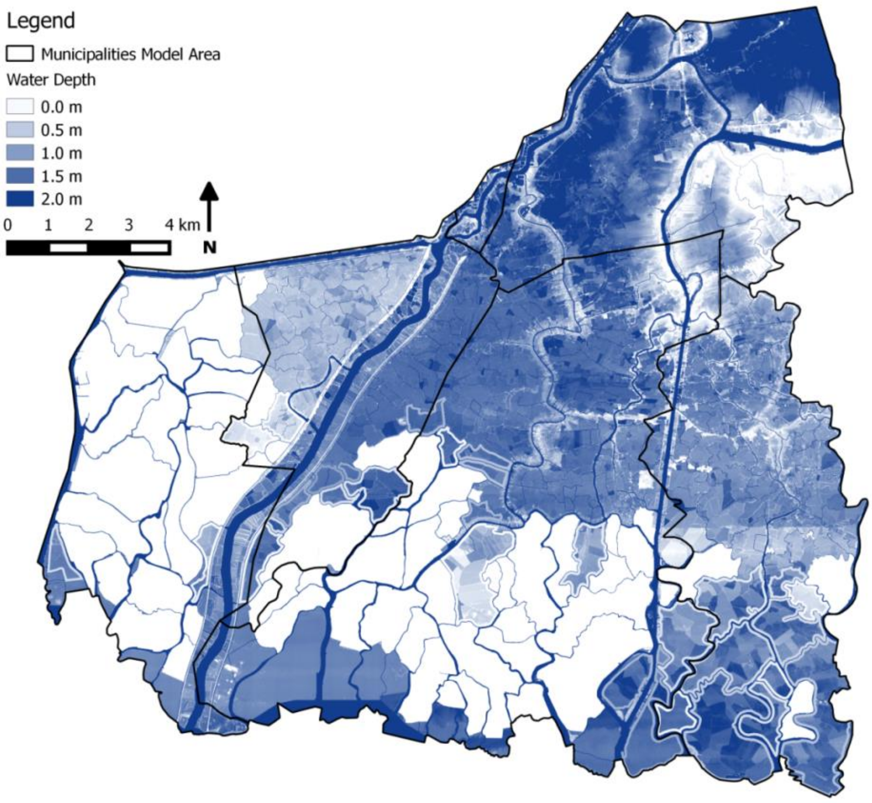

Figure 4.1 – Maximum water depth in the study area for the baseline scenario during Pedring 2011

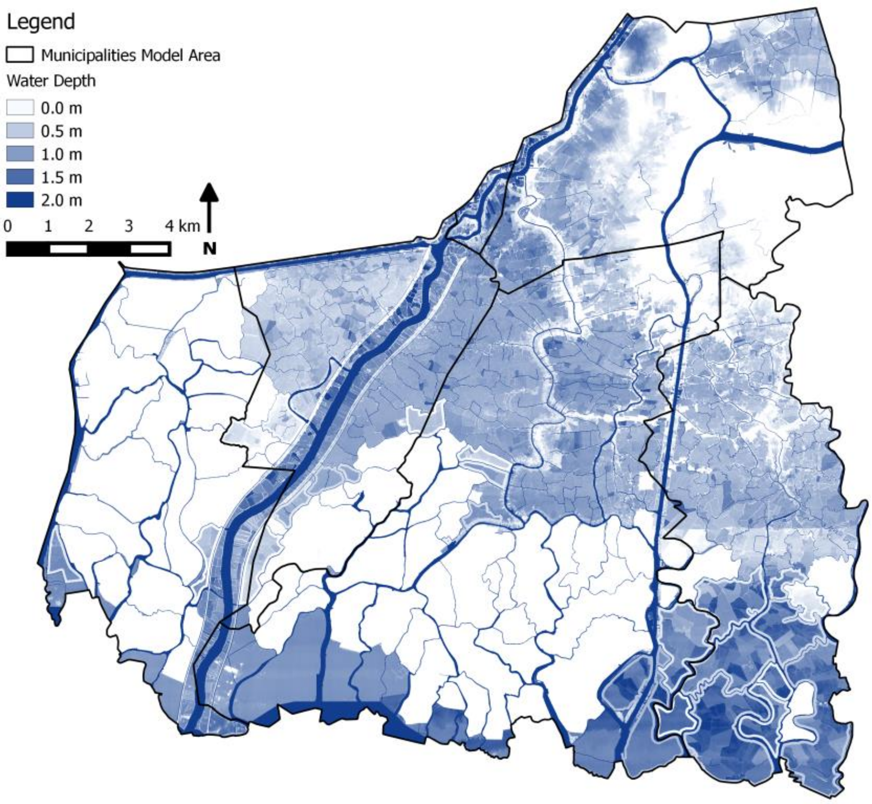

Figure 4.2 – Water depth in the study area for the baseline scenario during the storm surge enhance tide on 27 September 2011 at 1 PM

The focus of this report is on fluvial floods. However, Pedring 2011 also offers the possibility to look closer into the tidal issues, since a storm surge hit the coast before the fluvial flood peak flows into the study area. The tidal flood peaks at Sulipan around 13 o'clock on 27 September and flooded 58% of the study area with an average flood depth of 0.47 m. The results from the model for this point in time are summarised in Figure 4.2. Flood depth and velocity ranges up to respectively 1.3 m and 0.42 m/s. The effect of the tidal peak is still severe, but much less than the fluvial flood peak on top of the tidal flood.

4.2 Causes of floods

The causes of floods are summarised in the next list:

a) Sediment increase due to eruption of the Pinatubo volcano;
b) Deforestation upstream in the catchment and along the bay;
c) Control restrictions of the upstream dams;
d) Subsidence mainly due to ground water extraction;
e) Channel encroachment by occupants, squatters and fishponds;
f) Incomplete flood control systems.

All these causes are further explained in the next paragraphs.

ad a) Sediment increase due to eruption of the Pinatubo volcano

In the year 1991 one of the worlds' largest volcano eruptions occurred at Mount Pinatubo, see Figure 1.1 for the location. This eruption spread a large volume of lahar over the complete area up to Metro Manila. The lahar that fell on the upstream part of the catchment has slowly distributed into the river by rainfall run-off. Nowadays, the sediment volume in the rivers is more than before the eruption, since a large volume of lahar is still accumulating in the upstream part of the catchment. The total sediment volume in the Pasig-Potrero and Porac-Gumain river basin, two small rivers in the Porac river basin, increased from 17 to 62 m^3/ha/year and 14 to 56 m^3/ha/year respectively. Moreover, these sediment volumes are expected to remain the same for the upcoming 100 year. (JICA et al., 2011)

A large portion of the increased sediment volume is accumulating in the downstream part of the catchment. This sediment decreases the depth of the channels, that decreases the river flow capacity for fluvial floods and reduces the tidal intrusion due to an increase in roughness.

ad b) Deforestation upstream in the catchment and along the bay

A lot of land is deforested, especially in the upper part of the Pampanga River Delta. This deforestation is caused by agricultural use and human settlements. The deforestation is mostly done by heavy machines that are compacting the top soil layer causing a drastic reduce in the soil infiltration capacities. (Ziegler et al., 2006) The effect on the hydrology is:

1) An increase in the peak discharge causing floods in the downstream areas;
2) A decrease of the discharges during dry periods;
3) An increase of the sediment volume in the river.

However, the forest is not only decreasing in the upstream area, also along the coast. There the area with mangrove forest decreases significantly, since a lot of mangrove forests are converted into fishponds. The mangrove deforestation decreases the roughness along the shoreline which reduces damping of the tidal wave into the study area. Furthermore, the waves break at the fishpond dikes instead of in the mangrove forests. (JICA et al., 2011)

ad c) Control restrictions of the upstream dams

The operation rules divided the storage of the Angat Dam in three zones: Flood Control Zone, Operating Zone and Drought Zone. The Operating Zone is up to 210 m in the wet season and up to 212 m in the dry season. The remaining volume up to the designed flood water level of

219 m is respectively 176 and 142 million m^3. Below 212 m, the usable storage is 660 million m^3. During floods, the dam operator is bounded by the following rule from National Water Resources Board (2009):

> "When the water level is within the operating zone and there is incoming weather disturbance, pre-release shall be allowed provided that the flood operation shall not adversely affect the requirements of the water supply and its recovery to its full capacity. The Operator/FFSWDO shall submit to National Water Resources Board for approval the flood operation plan indicating the volume of water to be released and its release time." (pp. 3)

To fulfil this rule, the dam operator starts pre-releasing based on the four rain gauges with a response time of one hour to Angat Reservoir. In the downstream area, the local and provincial government blame the dam management of Angat Dam for the occurring floods in the region. The governor even interfered with the Angat Dam Operator during Pedring 2011 causing a forced higher peak discharge two days later at Angat Dam during the peak discharge from Pampanga River. The Angat Dam operator listens strictly to the operation rules.

There is almost no attention for Bustos Dam regarding flood control, because the maximum capacity of 15 million m^3 is much smaller than Angat Dam. The catchment upstream of Bustos Dam is 1.64 times larger than for Angat Dam.

ad d) Subsidence mainly due to ground water extraction

The subsidence due to ground water extraction is often not linked with the worsening floods. Floods are explained away by the government and local people under the guise of climate change. (Rodolfo & Siringan, 2006) In the Pampanga River Delta, the subsidence continues with up to 4.5 cm/year, see Figure 4.3. (Eco, 2011; Soria, 2009) Subsidence rates up to 0.38 cm/year due to tectonics and natural compaction is an order lower which means that the current subsidence rates are related to human activity. The largest corollary effect is the saltwater intrusion. Nowadays, the tide can enter up to 20 km inland and small changes in relative sea level rise extends this area rather quickly. (Rodolfo & Siringan ;2006)

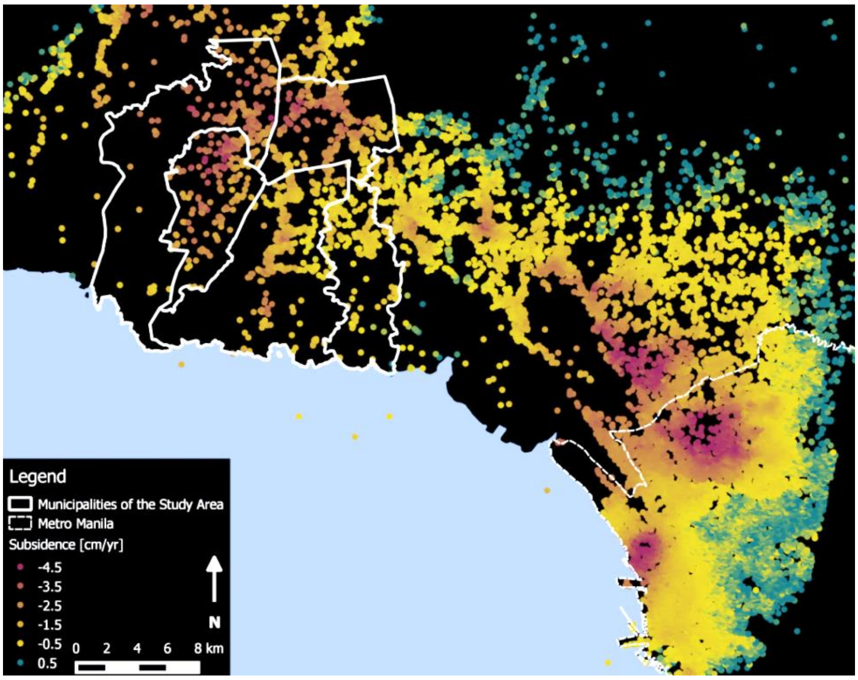

Figure 4.3 – Subsidence in centimetres in the study area (Eco, 2011)

The water district of Hagonoy states that the groundwater extraction is regulated for the pumping stations, larger than 5 horsepower. They try to reduce the number of large pumps. The fishponds and resorts are not using pumps at all according to the water district in contrary of Rodolfo & Siringan (2006). The water district does not switch to the Bulacan Bulk Water Supply Project, that supplies water from other sources than groundwater extraction, since the cost after treatment doubles per cubic metre of potable water from 12.15 pesos to 25 pesos. Water treatment of the Pampanga River cost around 10 times more to make it potable than the currently extracted groundwater.

In contrary to Hagonoy, the municipality of Macabebe deals with illegal groundwater extraction with large pumps. The effect of the difference regulation is shown by the subsidence data between 2003 and 2006. (Eco, 2011) The municipality of Hagonoy has a maximum subsidence of 3.3 cm/year and the municipality of Macabebe has a maximum subsidence of 4.5 cm/year, see Figure 4.3.

ad e) Channel encroachment by illegal settlers and incomplete flood control systems

Illegal structures are built on the river banks, varying from fishponds to houses. These obstructions limit the flow capacity of the rivers and magnify the fluvial flood problems. Several mechanisms make the people built along the rivers. First, fishponds are often illegally built close to or even in the river. (Rodolfo & Siringan, 2006) Second, a lot of economic activity, especially in Hagonoy is situated along the rivers. Building a house in those regions increases the chance of having a job. Especially in the Labangan Channel & Angat River, the encroachment of the channel by housing happened due to the construction of the Angat storage dam. As it seems like the river requires less capacity, because the discharge during heavy rainfall events is topped off. The people built their house on the river bank, because they do not realise that the bank still needs full capacity when large volumes are released from the Angat storage dam. (Hydroterre consultants, 2008) This result in a reduction of river flow capacity up to 1200 m^3/s. (Nippon Koei, 2011)

The flood control system proposed by JICA is incomplete according to Hydroterre Consultants (2008), since only one phase is complete. This results in, for example, missing flood control gate structures at the entrance point of the Hagonoy River. Due to this incompleteness, the Pampanga River still overflows during high precipitation events, flooding the city of Hagonoy.

4.3 Future hydraulic changes

The subsidence is the most relevant cause for floods in the study area of all above described causes, especially for future flood predictions. Over 20 to 50 years, subsidence up to 4.5 cm/year could cause up to 2.2 m subsidence resulting in a huge flood increase in the area if no measures are taken. The future scenarios assume no government intervention. Furthermore the “incomplete flood control systems” and “control restrictions of the dams” are taken into account. Sediment increase and deforestation are hard to predict and for these causes the current situation is assumed for the future.

Eco (2011) estimated crustal deformation in the area around Manila Bay, including the study area, based on a method described by Hopper et al. (2007). The satellite images from Envisat’s ASAR sensor between 2003 and 2006 are used as input and the software MAINSAR is used for processing. The measured crustal deformation includes both horizontal and vertical displacement. Soria (2009) shows that no lineaments are present in the study area, which points at horizontal displacement. Furthermore, the displacements are round circles pointing at horizontal displacement through ground water extraction. The subsidence rates are presented in Figure 4.3.

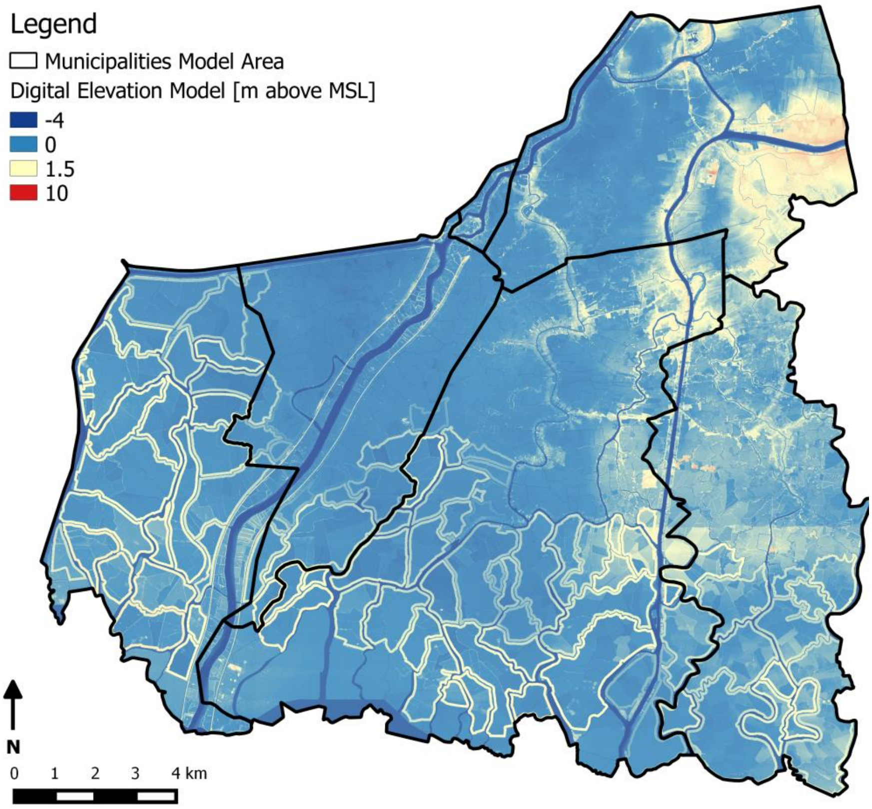

Figure 4.4 – DEM layer for the future scenario with 50 years of subsidence (NOAH, 2014; Eco, 2011)

The Digital Terrain Model (NOAH, 2014) was measured recently and is representative for the current situation. The subsidence data is linearly extrapolated to estimate the future scenario without government intervention over 20 to 50 years, see Figure 4.4. This could be an underestimation if the groundwater extraction is enhanced during these years. However, it could be an overestimation if the withdrawal of groundwater is stopped due to the saltwater intrusion or the compaction limit is reached. Up to now, typical values for the undergone compaction are 30 to 40 percent for the first 10 m soil below ground level. (Soria, 2009) The lower ground layers are sensitive to compaction as well, since swallow and deep wells are used up to 200 m. (Hagonoy Water District, 2014)

For the future scenario without government intervention initially two models are set-up. These models are created by using the Digital Elevation Model (DEM) layer generated for the current situation and subtracting the 20 and 50 year of subsidence from this layer. To make this possible, the natural neighbour method is used to interpolate the point subsidence data of Eco (2011). The elevations in the levee-file are also adjusted.

After the first model runs, the model for 50 year subsidence shows that most of the fishponds are submerged. This has a large positive effect on the flood depth upstream. However, expected is that the rich fishpond owners will raise their dikes to protect their harvest. A third model is made with the assumption that the fishponds dikes remain at the same level as for the baseline scenario. In short, three models are added: a baseline with 20 year subsidence, a baseline with 50 year subsidence and a baseline with 50 year subsidence and maintained fishpond dikes.

4.4 Future flood scenario

The results from the model for the three future scenarios with subsidence are summarised in Figure 4.5 until Figure 4.7. The two figures present the water level difference compared with the baseline scenario; purple shows the water level increase and blue shows the water level decrease.

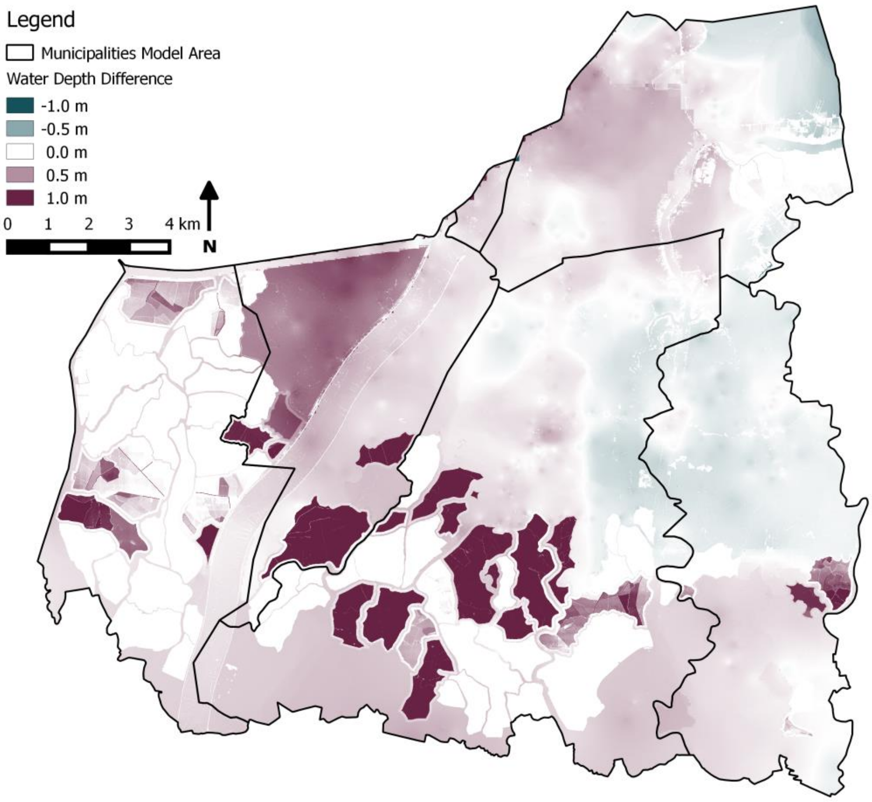

Figure 4.5 – Water depth difference in the study area for the future scenario with 20 years of subsidence without fishpond dike maintenance

For both the scenario with 20 and 50 years of subsidence, the traditional fishpond area with the strong dikes start to subside, causing a large increase in the flooded area of the fishponds. For the 20 year scenario, only a few traditional fishponds are flooded and no connection with the bay is created, meaning that the water is still stuck upstream of the fishpond area. Combined with the upstream subsidence, this is causing increasing water depths in the study area. The total damage in the study area is estimated at 1.8 billion pesos, see Appendix E for the calculation method. For the 50 year scenario, there is an open connection to the bay, since the fishpond dikes are too low to withstand the fluvial and tidal floods. This open connection makes drainage to the bay for the fluvial flood much easier and a large decrease in flooded area and water depth is measured. This reduces the total damage in the study area to 1.0 billion pesos. For both models the flow velocity does not vary much compared the baseline model with average flow velocity differences of respectively 0.04 and 0.05 m/s. The maximum difference in flow velocity is 0.17 m/s for the populated area in the municipality of Calumpit.

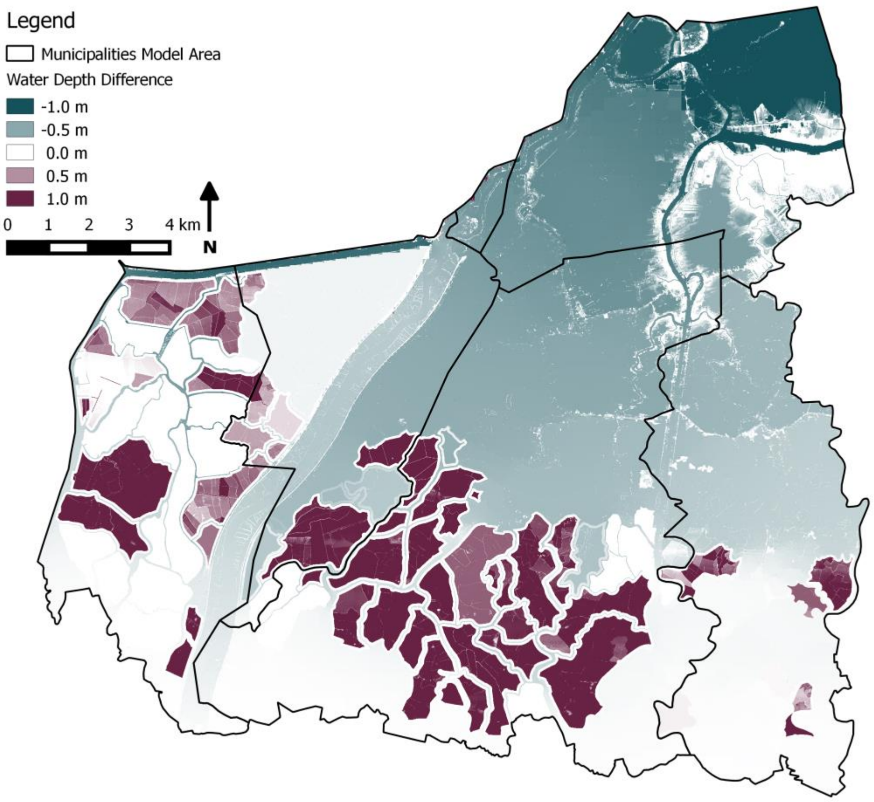

Figure 4.6 – Water depth difference in the study area for the future scenario with 50 years of subsidence without fishpond dike maintenance

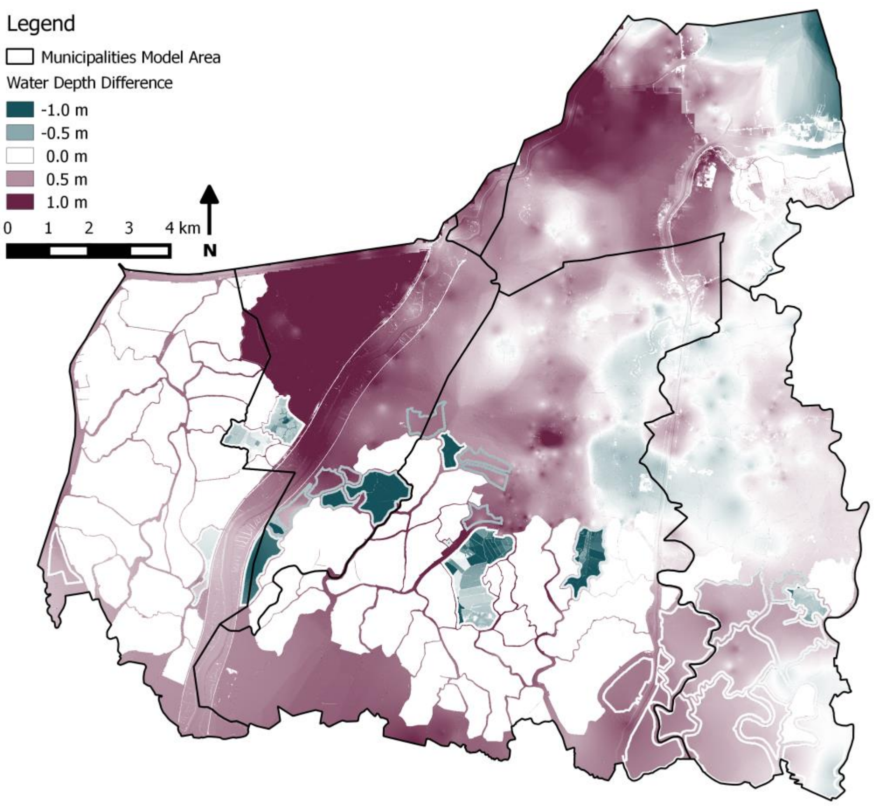

Figure 4.7 – Water depth difference in the study area for the future scenario with 50 years of subsidence with fishpond dike maintenance

For the 50 year scenario, the multiple fishponds are immediately flooded by the initial tide level of 0.26 m above mean sea level. As discussed before, this is not likely to happen if the rich fishpond owners are not leaving the area. They will probably maintain their dikes to the original level from the baseline scenario. Raising the dikes to this level leads to even less submerged fishponds, since the other part of the study area could retain more water due to the increase in capacity by subsidence, see Figure 4.7. Except for the populated area of the municipality of Paombong, the complete study area becomes submerged by an extreme hazard. The water depth and flow velocity in the study area ranges up to respectively 2.70 m and 0.72 m/s. The total damage in the study area is estimated at 2.1 billion pesos.

Since the 50 year scenario with maintenance is more likely to happen in the future, this scenario is used as baseline scenario to estimate the effect of the measures described in the next chapters.

4.5 Scenario conclusion

In the future, the tidal and fluvial floods will worsen. Subsidence is the main cause of the worsening floods. The current rates will cause up to two metres of subsidence in 50 years. Excessive (illegal) ground water extraction is the main contributor to subsidence. The downstream conventional fishponds are another important factor in the distribution of the fluvial floods. The overflowing water of the rivers is blocked by the fishpond dikes, since the channels between the fishponds cannot handle the large quantity of water fast enough. The estimate damage cost based on the 3Di model increases with 40% from 1.5 billion pesos to 2.1 billion pesos for the Pampanga and Angat River Delta in 50 years.

5 | Measure Analysis

In Section 5.1, five potential measures, that are reducing tidal and/or fluvial floods, are selected by using the knowledge of the future scenario and 3Di model. This answers the third sub-question. In Section 5.2, these five potential measures are explained in more detail. In Section 5.3, the hydraulic effects of the measures are estimated for the potential measures. In Section 5.4, the benefits are estimated based on the hydraulic effects and the costs are roughly valued. The combination of section 5.3 and 5.4 provides the answers of the last sub-question about the effects of the potential measures. Section 5.5 provides a short conclusion.

5.1 Selection of measures

This section summarizes the selection of five potential measures to reduce fluvial and/or tidal floods in the Pampanga River Delta, see Table 5.1. In total 17 measures are identified consisting of former initiatives, cause based measures and local ideas. These measures are selected on applicability (by the government), quantifiability, effect on fluvial and tidal flood reduction, and total benefits over the study area. In this section, the measures are shortly explained including a short reasoning why they are selected or not. Appendix D provides per not selected measure more information about the measure and, if applicable, model results and benefits. The other sections in this chapter provide the same information for the selected potential measures.

Table 5.1 – Summarisation of the identified measures with the implementation terms and the purpose of the measure; measures of type F are effective against fluvial floods and measures of type T are effective against tidal floods; the bold measures are selected for further investigation in this report.

Potential measures	Type	Short term (0 – 5 yr)	Mid term (5 – 20 yr)	Long term (20 – 50 yr)
Flood Forecasting & Early Warning	F	X		
Improved Dam operation	F	X		
Convert fishpens into fishponds	T	X		
Dredging	F	X	X	
Measures on small scale	F	X	X	
Fishpond dike height regulation	F	X	X	
Tidal Flood Control Hagonoy	T		X	
Hagonoy Flood Mitigation	T		X	
Community-Based Disaster Risk Reduction Program	T & F	X	X	X
Smart Road Elevations	F (& T)	X	X	X
Reforestation	F		X	X
Levee Maintenance	T & F		X	X
PDDP-II – Ring levee	F		X	X
PDDP-III – Retention basin	F			X
Building with nature	T			X
Groundwater Extraction Regulation	T & F			X
Combination of Measures	T & F			X

Flood Forecasting & Early Warning Systems uses measuring stations and trained personnel to forecast floods and provide a warning for the affected people. This measure is *not* selected since it is reactive and does not reduce the flood. (Nippon Koei, 2010)

Improved dam operation uses tide and weather prediction to optimize pre-releasing and the use of flood storage capacity, while current control restrictions remain intact. This measure is *selected* because it has a positive impact on both fluvial and tidal floods.

Convert fishpens into fishponds changes fishnets back into fishpond dikes to dampen the tidal wave amplitude. This measure is *not* selected since the effect is small and negative towards the fluvial floods.

Dredging enhances the flow capacity of the river, which normally contributes to a reduction in floods upstream of the dredging activities. This measures is *not* selected because the effect is minimal for fluvial floods in a delta area and negative for the tidal floods. (Cai, 2014b)

Measures on small scale focus on household scale by building multiple-storey houses of stone or houses on piles, educating people and dealing with garbage properly to avoid clogging of waterways. This measure is *not* selected because the flood reduction is small or negligible.

Fishpond dike height regulation improves the drainage of the fluvial flood while the tidal intrusion is still dampened. This measure is *selected* because it has a large positive impact on fluvial floods, while the tidal floods are affected meticulously.

Tidal Flood Control Hagonoy uses several tidal gates and a sheet pile wall to protect populated area of Hagonoy against the tidal floods. This measure is *not* selected since the tidal flood can still enter the town proper by multiple other routes. (Hagonoy, 2014b)

Hagonoy Flood Mitigation Project uses gates to prevent tidal and fluvial floods in the populated area of Hagonoy. This measure is *not* selected because the floods bypasses the gates over land without the construction of embankments. (Hydroterre Consultants, 2008)

Community-Based Disaster Risk Reduction Program involve the inhabitants in the identification, selection and decision process of measures. This measure is *not* selected in this study, but is advised to implement since it enhances awareness of floods, political support and acceptability of the - by the government implemented - measures. (Gaillard, 2008)

Smart road elevations uses the often applied road elevations as levee by elevating selected roads. This measure is *not* selected since solely elevating selected roads moves the flood which reduces the benefits of the measure to around 0.

Reforestation restores the infiltration capacity of the soil in the upstream area which decreases the river discharge due to the decrease in surface run-off. This measure is *not* selected because the effect is hard to estimate and more detailed studies are needed for the upstream area to quantify the gain in peak discharge reduction. (Paap, 2014)

Levee maintenance protects the city centres of Macabebe and Masantol against tidal and fluvial floods from Pampanga River. This measure is *selected* because it protects populated area with an relatively cheap and feasible project.

PDDP project phase II protects the complete delta area, except for the river beds, with levees against the fluvial flood. This measure is *not* selected since this measure does not protect the area against tidal floods which reduces the benefits of this expensive measure drastically. (JICA et al., 1982, 2011)

PDDP project phase III reduces the flood by converting the Candaba Swamp in a retention basin. This measure is *not* selected because the benefits are small compared to the cost of the project, the sensitivity of the operation and environmental impact on the Candaba Swamp. (JICA et al., 1982, 2011)

Building with nature is a concept that uses small dams made of prunings to capture sediment along the coast and provide a basis for natural mangrove reforestation. This measure is *not* selected since the main effect is on wind waves instead of reducing floods. (Didde, 2014)

Groundwater extraction regulation reduces or stops the current subsidence by using other sources for potable water. This measure is *selected* because it has a positive impact on both fluvial and tidal floods and it solves one of the causes of worsening floods.

Combination of measures combines smart road elevations, tidal flood control, improve dam operation and levee maintenance to enhance each other's benefits. This measure is *selected* since the benefits increase largely because floods are prevented behind the structures.

5.2 Potential measures

The background of the potential measures is presented in this section.

5.2.1 Improved Dam Operation

The goal of this measure is to use tide and weather predictions to optimize timing of the release, the amount of pre-releasing, and the use of the flood storage capacity of the dams in the Angat River Basin within the current regulations. Two Pilipino institutions, PAGASA and NOAH WISE, are improving their precipitation forecast up to respectively 5 and 7 days ahead and PAGASA is making typhoon track predications up to 3 days ahead. Such forecasts could be used if an accuracy of around 70% could be achieved that the reservoir level ends in the flood control zone, according to the Angat Dam Operator.

Hsiao et al. (2013) already concluded that knowledge about precipitation and runoff during typhoons could improve dam operation. An ensemble meteorological modelling system could be used to forecast the precipitation based on multiple typhoon tracks. With an ensemble model, the certainty of precipitation depths could be calculated easily by making use of the mean and standard deviation. For example for typhoon Nanmadol, the mean and standard deviation of the precipitation based on eighteen ensemble members are available for a two day prediction starting at respectively 1.5 and 0.5 days before landfall at Taiwan. For a forecast of 1.5 and 0.5 days before landfall, between respectively 28-42% and 32-67% of the observed accumulated precipitation over two days could be identified as precipitation that falls with a 68% certainty for various river basins in Taiwan.

This report presents the following formula to use the predictions from the ensemble model to estimate the pre-release spilling discharge until the next forecast update:

$$Q_{spill} = \frac{V_{res,0} + \sum_{k=0}^{n}\left(\mu_{p,k} + \sigma_{p,k}\right) \cdot A_{catchment} - V_{res,HWL}}{t}$$

with Q_{spill} the available spilling discharge (m^3/s), $V_{res,0}$ the current reservoir volume preferably including the estimated run-off volume in the catchment based on rain gauges (m^3), $\mu_{p,k}$ the estimated precipitation during timestep k (m/timestep), $\sigma_{p,k}$ the standard deviation on timestep k (m/timestep), $A_{catchment}$ the catchment area (m), $V_{res,HWL}$ the required reservoir volume after the event (m^3), t duration until the next forecast (s), k number of prediction time step and n total number of prediction time steps.

The maximum gain in flood volume for Angat and Bustos Dam could be more than 100 mil m^3 if the lowest results of Hsiao et al. (2013) are used. In the worst case with a wet season flood level of 210 m, a discharge of respectively 400 m^3/s and 700 m^3/s could have been spilled, resulting in a pre-released flood volume of 95 m^3. The first day the reservoir level started at 206.53 m above mean sea level (MSL), therefore no spilling discharge would not have been possible under the current rules. However, around 300 m^3/s could have been spilled the second day based on the formula presented above resulting in an additional spilled volume of 26.2 m^3. For Bustos Dam in both situations, the complete reservoir could be pre-released if this is safe and environmentally acceptable, resulting in an additional spilling discharge of 220 m^3/s and an increase in flood retention volume of 13.5 m^3.

The precipitation forecasts, combined with the tide prediction and the PRFFWC flood bulletins of the Pampanga River, can also be used to predict if a release is necessary during the storm event and to determine the right timing. First, the Dam Operators could estimate the upcoming amount of precipitation to estimate the expected reservoir level without releasing. For typhoon Pedring, these kind of predictions would have made an additional volume of 100 m^3 available for retention. Because, the Angat dam operator allowed the reservoir to rise up to 214 m instead of 219 m since another typhoon Quiel was coming with an unknown precipitation depth. Also Bustos dam operator could use this kind of information to carefully use the additional volume up to 13.5 m^3 to lower the peak of the flood wave. Using data from the Pampanga River Flood Forecasts and the tide prediction could help in choosing the right timing of release to avoid a superposition of peak discharges of various rivers and high tide.

To estimate the maximum effect of this measure, the dam operation is assumed to be able to retain the water during the storm surge and the peak discharge from the Angat River. In this scenario, no discharge is flowing into the study area from the Angat River.

5.2.2 Fishpond Dike Height Regulation

The goal of this measure is to improve the drainage towards Manila Bay without affecting the current dampening of the tidal amplitude by adapting the fishpond dike height. The main and small rivers between the fishponds do not provide enough flow capacity for the fluvial floods. The flood is blocked by the conventional fishpond dikes along the coast.

This report proposes to open several fishpond gates during fluvial floods and regulate the fishpond dike height of the conventional fishponds along the coast of Pampanga and Angat River Delta. The fishpond height is proposed at just above spring tide of 1.1 – 1.3 m above MSL, except for the fishpond dikes directly along the coast. With this elevation the fishponds will not overflow in the dry season and the tidal damping in normal situation is not affected. If the water level rises above the regulated level, the fishponds overflow. First, this creates additional flood storage. Second, the fishpond starts flowing and contributes to the drainage of the area. Opening the gates of the fishponds contributes even more to this drainage capacity. The fishpond dikes along the coast should at least remain at their current height to protect the hinterland against storm surges. The fishpond owners should be compensate for the losses made in the wet season.

A fishpond flood channel as first phase is proposed which affects only a couple of fishponds. A couple of neighbouring fishponds from north to south are selected to lower their fishponds at an elevation of 1.1 m above MSL and open their gates during a fluvial flood, see Figure 5.1. In the second phase, another fishpond flood channel could be added, for example in Paombong.

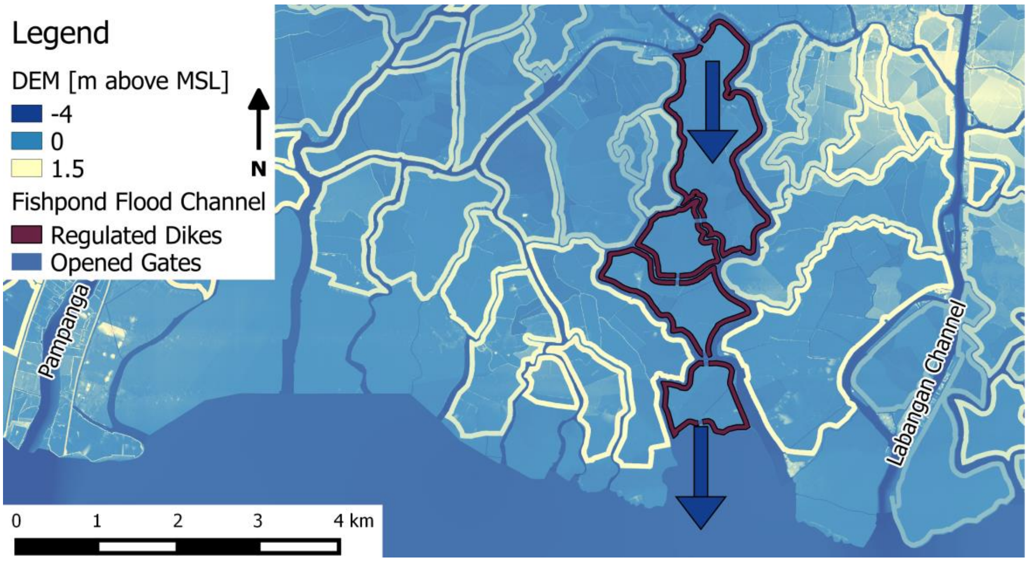

Figure 5.1 – Fishpond Flood Channel of four neighbouring fishponds in Hagonoy (NOAH, 2014)

The results of the two future scenarios with 50 year subsidence are compared to estimate the effects of changes in the heights of the fishpond dikes.

5.2.3 Levee Maintenance

The purpose of this measure is to maintain the function of the current levees by protecting them against subsidence due to ground water extraction and its own weight. Three steps are required to assess whether a levee should be monitored during the upcoming 50 years:

1. Identify the levees that lose their function in the future scenario
2. Monitor the elevation of the identified levees yearly
3. Heighten the levees based on the measured subsidence rates

The levees most important levees to be included in the analysis are:

1. The levee along the San Esteban Diversion Channel protecting the centres of Masantol and Macabebe
2. The levee along the Pampanga River protecting the centres of Masantol and Macabebe
3. The levee along the Angat River protecting the municipality of Paombong

Other levees, for example the levees constructed in PDDP phase I, are less important since they do not protect an area against floods and/or are elevated high enough to withstand the subsidence rates of the upcoming 50 years by far.

All levees above are subsiding based on the data presented by Eco (2011). Monitoring is advisable to keep the levees at the same elevation. The water levels and expected levee height in the future scenario with 50 year subsidence are compared to estimate if monitoring is required in order to prevent overflowing by a storm event like Pedring 2011.

5.2.4 Groundwater Extraction Regulation

The goal of this measure is to prevent the delta from subsiding further by regulating the groundwater extraction.

Tokyo could act as a good example to other coastal cities because in the contrary to other Asian coastal cities, Tokyo completely reduced its subsidence to zero since 1975, see Figure

5.2. In the early sixties, the city of Tokyo adapted restrictions on groundwater use and after around 10 years these restrictions worked and the subsidence completely stopped. Other mitigation options for human-induced subsidence applied in Tokyo are using lighter building materials and apply active recharge of the aquifers. The latter could also speed up the process to stop subsidence.

For the Pampanga River Delta multiple steps should be taken to complete stop or reduce the current subsidence rates:

- Research is needed to estimate the current recharge rates of the groundwater and the time required to recover the groundwater level to its original level.
- All the locations with illegal groundwater extraction should be identified and need to be regulated or completely stopped.
- Other sources of potable water need to be implemented to compensate for the reduction in groundwater extraction.

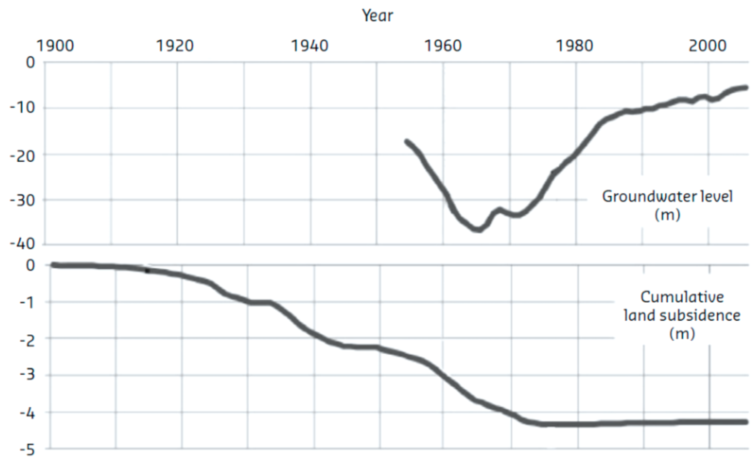

Figure 5.2 – Cumulative land subsidence and groundwater level between 1900 and 2011 in Tokyo (Deltares, 2014)

The municipalities could connect to the more expensive Bulacan Bulk Water Supply Project or should investigate if other sources of potable water are applicable. The Bulacan Bulk Water Supply Project distributes the water of Angat or Bustos Dam to the participating municipalities in the province of Bulacan. The cost of this water, including treatment and distribution, inside the municipality increase from 12.15 to 25 pesos/m^3. The treatment of open water in the study area would cost around ten (Hagonoy Water District, personal communication, May 21, 2015) Other potable measures, like rainwater harvesting systems or combining atmospheric water generators with air-conditioners, might be more lucrative.

The effects of groundwater extraction regulation for the upcoming 50 years are estimated by comparing the future scenarios with 20 and 50 years of subsidence. This assumes that 20 years are needed to completely stop the subsidence rates in the Pampanga River Delta.

5.2.5 Combination of Measures

The goal of this measure is to combine the multiple identified measures to enhance each other's benefits by creating a closed system. The overall effect of small measures is negligible since the water could easily find another route due to the flat area and the many rivers and channels in the area. By also blocking the other routes with other measures a closed system is created that prevents water from flowing into a specific area during a flood. A disadvantage is that this measure causes a decreased perception of the danger of large storm events because floods occur less.

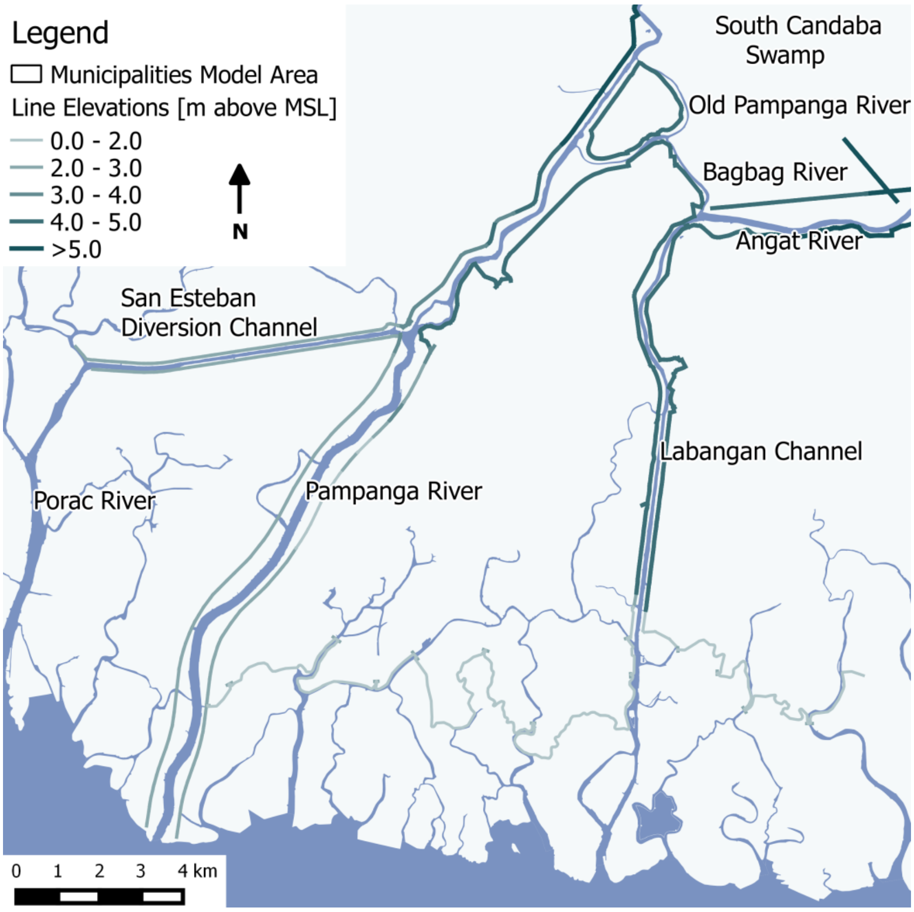

Figure 5.3 – Combination of measures including smart road elevations along Labangan Channel, Pampanga, Old Pampanga and Bagbag River, maintenance of the levees protecting the city centres of Masantol and Macabebe, and tidal gates protecting the area above the conventional fishponds

The following measures are included in this combination of measures, see Figure 5.3:

- Tidal flood control gates and structures in Hagonoy, Masantol and Paombong
- Smart road elevations based on the PDDP project
- Levee maintenance
- Additional road elevation along Candaba Swamp in Calumpit
- Improved dam operation by using precipitation forecasts

13 tidal flood control gates are placed between the fishponds in the model area to protect the hinterland against storm surge enhance tide during typhoon events. Together with the relatively high conventional fishpond dikes, the tidal flood control gates form a closed system at the south side of the populated area of Hagonoy and Paombong. The tidal flood control gates are connected to smart road elevations along Labangan Channel, Bagbag River and the Pampanga River. All the listed levees in Section 5.2.3 are maintained at the current elevation to protect against the rising water level due to the construction of the elevated roads. Furthermore, the road at the south side of the Candaba Swamp is elevated to reduce the water level in Calumpit along the Angat River. The dam operation is improved to lower the water level in the rivers and to reduce the necessary elevation of roads.

The structures are included in the levee-file with a high enough elevation to withstand the fluvial flood, see Figure 5.3. The necessary height could be determined based on the maximum water level during Typhoon Pedring 2011.

5.3 Effects of measures

This section provides an overview of the effects of potential measures. The effect of the measures are estimated by the 3Di model, except for levee maintenance because the effect is protected area is outside the model area. The results are summarised in Table 5.2. The *combination of measures* is causing the largest water depth reduction over the study area.

Table 5.2 – Percentage flooded area for three land use types per municipality for the scenarios: improved dam operation (IDO), groundwater extraction regulation (GWER), fishpond dike height regulation (FDR) and the combination of measures (CoM)

Category		Area	Flooded Area (%)				
Town	Land Use	(km2)	Main	IDO	GWER	FDR	CoM
Calumpit	Cultivated Area	27	93%	-2%	-1%	**-16%**	**-21%**
Hagonoy	Fishpond	72	50%	-0%	**+23%**	**+31%**	**-13%**
Macabebe	Fishpond	39	21%	-0%	**+18%**	**+27%**	+4%
Masantol	Fishpond	30	70%	-0%	**+23%**	**+19%**	-2%
Paombong	Fishpond	32	89%	-0%	+5%	+8%	-2%
Calumpit	Populated Area	5	74%	-3%	-7%	**-40%**	**-35%**
Hagonoy	Populated Area	5	96%	-2%	-2%	**-17%**	**-66%**
Masantol	Populated Area	2	91%	-0%	-6%	**-24%**	**-16%**
Paombong	Populated Area	2	95%	-2%	-5%	**-26%**	**-42%**
Study area	No water body	265	54%	-1%	**+13%**	**+12%**	-12%

5.3.1 Improved Dam Operation

Improved dam operation shows solely flood reduction, see Figure 5.4. Logically, the effect is the largest along the Angat River and Labangan Channel. The flood reduction is on average around 15 cm and in the Angat River up to 30 cm. The effect of changes in the Angat River is bounded by the Pampanga River Dikes.

5.3.2 Fishpond Dike Height Regulation

The fishponds dike height regulation shows the largest effect on the flood reduction, see Figure 5.5. Most of the fishponds are flooded and this forms a more open connection with the bay. The advantage is a large reduction in the average water depth over the whole study area of 30 cm and a large decrease in flooded populated area. In Calumpit, the water depth even reduces up to 1.5 m. A small disadvantage is that the urban area becomes slightly more sensitive for the tide. For example, the water level due to the storm surge enhanced tide at 27 September 2011 14:00 increases with 3 cm in the populated area of Hagonoy. A larger disadvantage is that the conventional fishpond area becomes much more sensitive to lose their harvest during a high spring tide or storm surge enhance tide. All the fishponds flooded in Figure 5.5 start already overflowing during the storm surge.

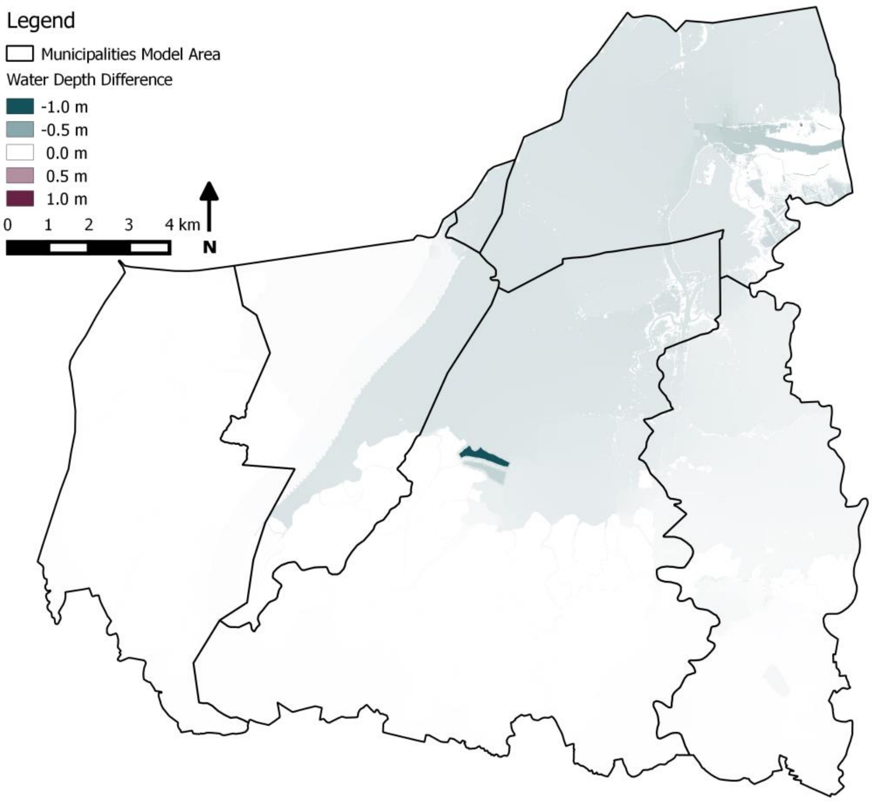

Figure 5.4 – Water depth difference for the improved dam operation scenario

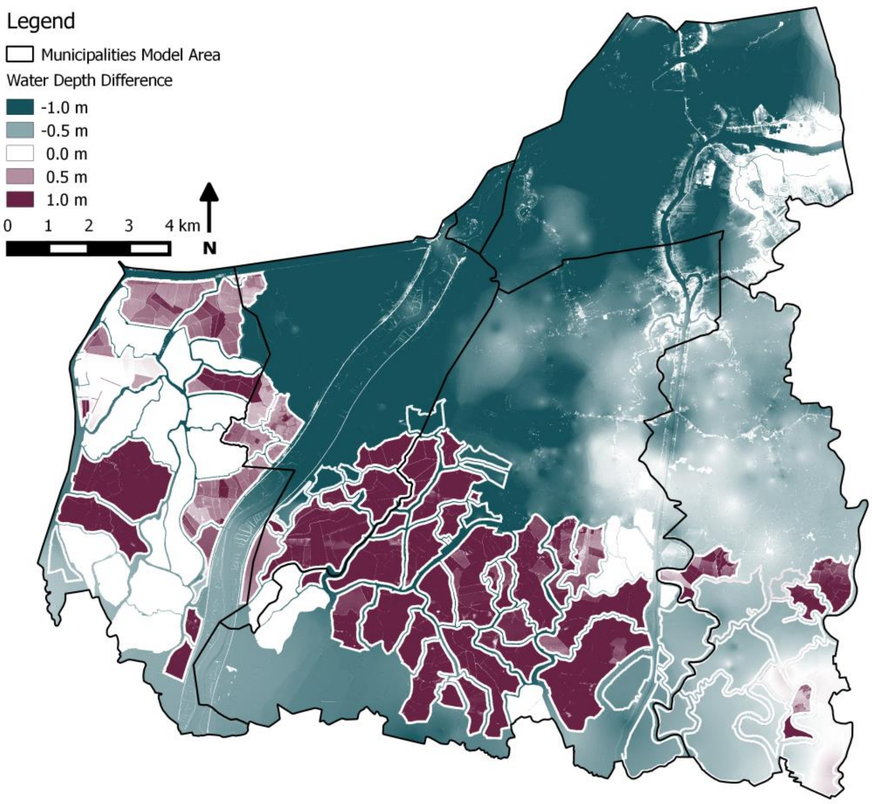

Figure 5.5 – Water depth difference for the fishpond dike height regulation

5.3.3 Levee Maintenance

The model results show that the San Esteban Diversion Channel Levees requires maintenance and that the other levees prefer maintenance unless a large structural measure is implemented in the delta. In the future scenario, the levee along the San Esteban Diversion Channel are subsiding too far to even withstand a normal tide. This causes a tidal flood via the diversion channel and fluvial flood from the Pampanga River in the city centres of Macabebe and Masantol. The current levees along the Pampanga and Angat River are only overtopped in the *combination of measures* scenario or any another scenario with large structural measures. Still, monitoring and maintaining these levees is advisable because it relatively easy protects a large area against floods larger than Pedring 2011.

5.3.4 Groundwater extraction regulation

The groundwater extraction regulation measure reduces the water level in the study area on average around 13 cm and for the populated area up to 50 cm. A couple of submerged fishponds also contribute to the water depth reduction, since the submerged area becomes 13% larger, see Figure 5.6.

Overall, the effect of the ground water extraction regulation is limited, because the capacity of the system to deal with fluvial floods does not change largely. Still, the effect on the tide is one to one for the area below MSL. This area covers more than 50% of the study area including the fishponds. For the area above MSL the tidal flood increase is equal to the tidal damping. This affects at least 75% of the Pampanga and Angat River Delta with an elevation of 0.5 m or less.

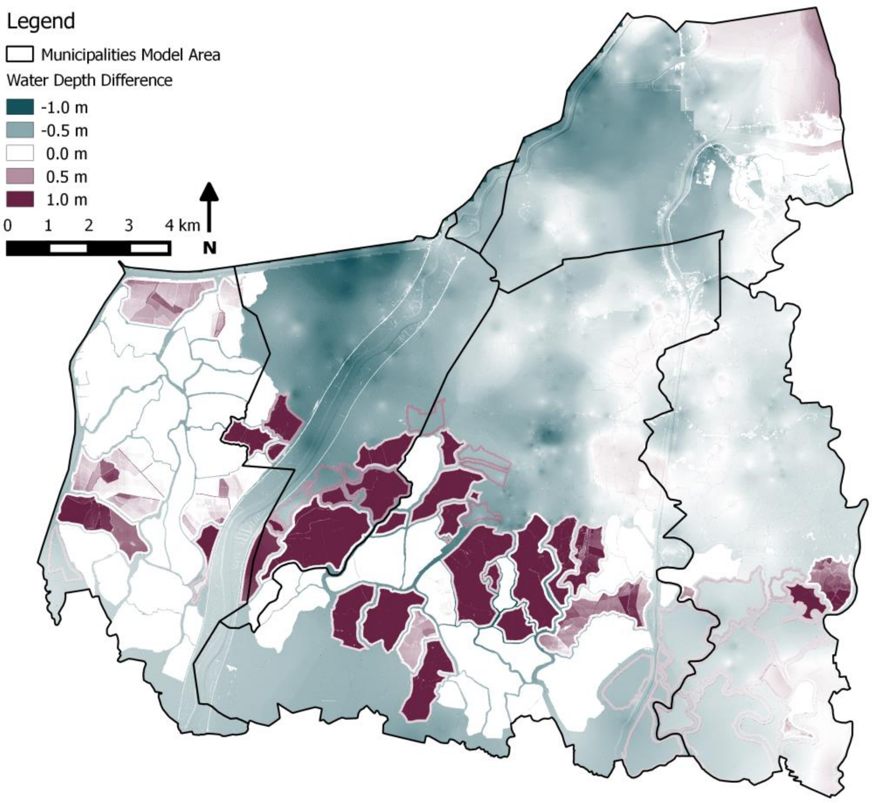

Figure 5.6 - Water depth difference for the groundwater extraction regulation scenario

5.3.5 Combination of measures

The *combination of measures* prevents selected areas from flooding, while at other places the water is piled up, see Figure 5.7:

- Hagonoy and Calumpit, between the two main rivers, are completely prevented from floods by the elevated roads, levees, tidal gates and fishpond dikes. This reduces the water depth around 2 m.
- The fishpond dikes in Paombong, east of the Labangan Channel are not high enough to prevent the storm surge from entering the "closed" area. Nevertheless, the flood is significantly reduced with water depth reductions between 0.5 and 1.0 m.
- In the floodplains of the rivers, the fishponds west of the Pampanga River, and the Candaba Swamp, the water depth increases up to 1.5 m. Still, only little additional urban area is flooded in the Candaba Swamp.
- For the municipality of Calumpit along the Angat River, the additional road elevation along the south side of the Candaba Swamp is causing a water depth reduction of around 20 cm at the south side of this road. Advised is to elevate more roads in this area to create a closed system in this part of Calumpit.

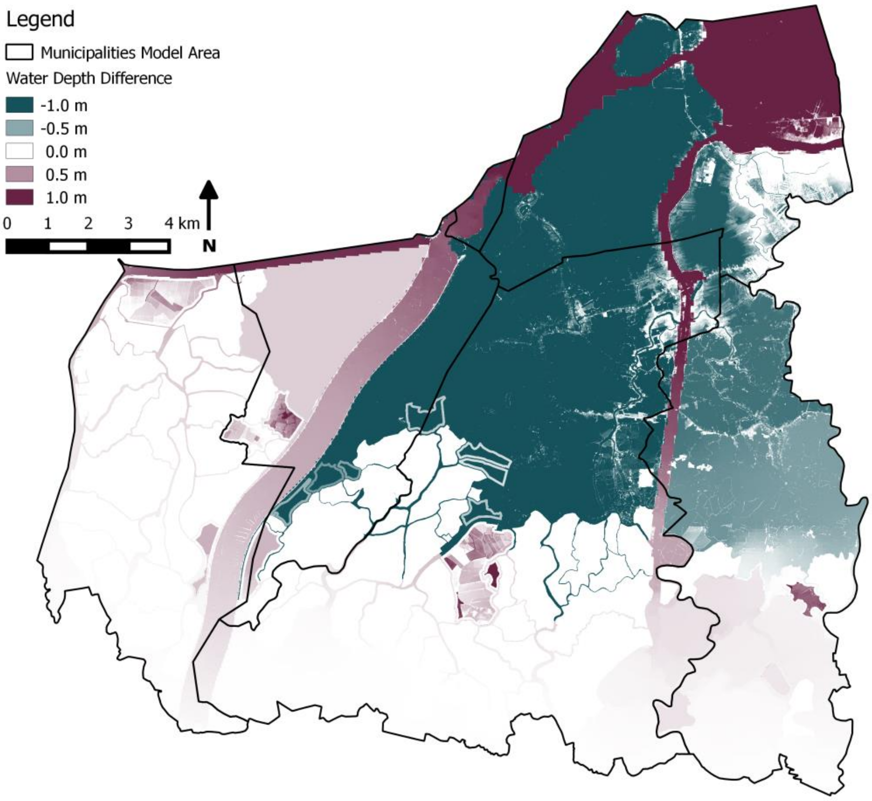

Figure 5.7 – Water depth difference for the *combination of measures* scenario

For a rough design of the height of road elevations, the following data could be used. The water level in the Pampanga River is raised at Sulipan from 2.2 up to 3.5 m above MSL and at the diversion point with the diversion channel from 1.5 up to 2.2 m above MSL. The Labangan Channel is raised at Bagbag river from 2.0 m above MSL up to respectively 3.4 m. At the end of the road elevation at Labangan Channel, near Santa Elena, the water level is around 2.0 m.

Another advantage of the *combination of measures* is that the floods due to spring tide could be prevent inside the closed area.

5.4 Cost – benefit analysis

The *fishpond dike height regulation* and *improved dam operation* measure are already lucrative for typhoons with a return period of 10 years like Pedring 2011. This is based on a calculation of the benefit-cost ratio for all the measures, see Table 5.3 and Appendix E for the calculation method. One should realise that next to the large typhoons, also damage due to small typhoons or high tide could be prevented or reduced by one of the measures.

Table 5.3 – Results of the Cost – Benefit analysis for the five modelled potential measures plus the creation of fishpond flood channel from Hagonoy towards the coastline; the benefits only represent the damage reduction of typhoons with a return period of 10 years; the benefit-cost ratio is determined over 50 year; the last column represents the flood prevention of the city centres of Macabebe and Masantol (City Centres M&M)

Measure	Initial Cost [mil ₱]	Yearly Cost [mil ₱/yr]	Benefit [mil ₱/yr]	Benefit-Cost ratio [-]	City Centres M&M
Improve Dam Operation	-	1	18	21	
Fishpond dike height regulation	707	75	113	1.1	
Fishpond Flood Channel	84	25	-	-	
Levee maintenance	-	17	-	-	Yes
Groundwater extraction regulation	-	145	35	0.2	
Combination of measures	5,411	66	95	0.3	Yes

Improved Dam Operation could be easily obtained by hiring two employees capable of using an ensemble typhoon forecasting model. Initial cost that might be applicable is a training. Since no construction costs are required, this measures has the highest benefit-cost ratio.

The *open system* measure with a *fishpond flood channel* as first phase is four times more profitable than the *combination of measures*. The cost includes the adaptation of the fishpond dikes to just above spring tide level and the salary of a dike height regulator. The damage compensation for fishpond owners is included in the estimation of the damage due to the typhoon. Advised is to compensate the fishpond owners for the damage on their harvest in the wet season.

The *levee maintenance* is a required lucrative measure for the North San Esteban Diversion Levee and a preferred measure for the West Pampanga River Levee and the East Labangan Channel Levee. For this measure, the levee height needs to be regularly monitored to estimate the subsidence of the levee, requiring one or two employees. The costs of the maintenance are based on the expected subsidence. The cost for the maintenance of the required levee only is 6 million pesos/year.

The *groundwater extraction regulation* is the most expensive project due to the increase of the cost of a cubic metre of water if the Bulacan Bulk Water Supply Project is used as source for 50% of the water demand. According to the Hagonoy Water District (personal communication, May 21, 2015), the price increases from 12.15 to 25 pesos/m^3 including treatment and distribution. In this case, still 50% of the potable water is gained by groundwater extraction and research is needed if this is sufficient to stop subsidence. Other sources of water, like rainwater harvesting system, could be more lucrative than the Bulacan Bulk Water Supply Project and are worth investigating. Other costs are the removal or regulation of the illegal pumps.

The *combination of measures* stays relatively expensive, although the reduction in cost and the increase in benefits compared to the PDDP project phase II. The reduction in costs for compensation, resettlement and livelihood issues is around 2 billion pesos, due to the use of road elevations instead of the construction of levees. For this project, 61 km of elevated roads and levees with 37 small and large tidal gates need to be maintained or built to create a closed system. The *combination of measures* shows less benefit than the *fishpond dike height regulation* because the latter reduces the average water depth in urban areas more than the former due to the set-up of water in Calumpit.

5.5 Measure analysis conclusion

The social and financial impact of *fishpond dike height regulation with gate opening during fluvial floods* is much less than the *preventive measure with structures*. The former has a negative effect solely on fishpond owners, starting from four owners. The latter has a negative effect for all people living along the elevated roads and people living outside the protected area. Furthermore, the latter causes a decreased perception of the danger of the large storm events. Financially, the *fishpond* measure is around four times cheaper and has a positive benefit-cost ratio.

To make one of the potential measures feasible, the municipalities need to cooperate for three main reasons:

1. Most measures need to exceed the municipal borders to be effective;
2. A positive influencing measure for solely one municipality often negatively influences the neighbouring municipality;
3. The projects become more feasible if all the positively influenced municipalities are financially supporting the executive municipality.

6 | Conclusion and recommendations

6.1 Conclusion

The research question of this report is to identify and estimate the performance of potential measures to reduce the fluvial and tidal floods in the Pampanga and Angat River Delta, Philippines. The research question is answered by taking into account the current delta and the expected changes, e.g. subsidence, for a future scenario without government intervention over 20 to 50 years.

The Pampanga and Angat River Delta is located at the low end of a 7100 km^2 large alluvial plain and stands in open connection with the Manila Bay. The tide enters the area, including the urban part, easily by the many channels or the large rivers: Labangan Channel and Pampanga River. During spring tide, part of the area is currently flooded resulting in an inundation period of weeks to even months a year. Furthermore, typhoon events or the southwest monsoon are causing precipitation events with a high intensity, causing a large flood wave into the delta. These fluvial floods can destroy houses, roads and the harvest of the rice fields and fishponds.

In the future, the tidal and fluvial floods will worsen. Subsidence is the main cause of the worsening floods. The current rates will cause up to two metres of subsidence in 50 years. Excessive (illegal) ground water extraction is the main contributor to subsidence. The downstream conventional fishponds are another important factor in the distribution of the fluvial floods. The overflowing water of the rivers is blocked by the fishpond dikes, since the channels between the fishponds cannot handle the large quantity of water fast enough. The estimate damage cost based on the 3Di model increases with 40% from 1.5 billion pesos to 2.1 billion pesos for the Pampanga and Angat River Delta in 50 years.

Only a few measures have a positive impact on fluvial and tidal floods, and are applicable in combination with all other measures. With precipitation predictions, the dam operation of Angat and Bustos dam can be improved by maximising the use of their flood storage capacities. This measure needs to be implemented by the dam operators and accepted by the boards of the dams and has by far the highest benefit-cost ratio. The current levees along the Pampanga River and San Esteban Diversion Channel protecting the city centres of Masantol and Macabebe are very lucrative to be maintained at the current elevation to compensate for the subsidence, since these could protect the area against tide and river discharges. Ground water extraction regulation can stop the current subsidence, which becomes lucrative in the long run or if low-cost potable water sources are found. Other measures with minor side effects are improved evacuation and early warning systems, and small scale measures, like building houses on piles. However, these measures do not reduce the floods.

For flood prevention, a combination of large infrastructural changes to prevent both fluvial and tidal floods is required, like in the Pampanga Delta Development Project that protects against fluvial floods. Structures to protect against fluvial floods that might fit in the local context are levees, smart road elevations or retaining walls. These structures are most beneficial if constructed in the neighbourhood of the rivers because then the river capacity is not limited and the largest area is protected. The structures to protect against the tidal floods are a combination of tidal gates and relatively high conventional fishpond dikes. This measure becomes effective only in combination with protection against fluvial floods and vice versa due to far extend of low elevated areas and the many channels. These measures require much cooperation of the local, regional and even national government. The impact on society is probably large, but if working, the damage, e.g. on harvests and houses, is prevented in the protected area. The urban area upstream of the study area is hardly affected, since most water is retained in the Candaba Swamp. The enhanced flood effects on the environment of the Candaba Swamp need to be further investigated.

For flood reduction, other options are worth investigating. *Regulating the fishpond dike heights* just above spring tide and *opening the fishpond gates* create a more open connection to the bay to improve drainage of the fluvial floods. The limited counter effect is that the storm surge enhance tide enters the system slightly more easily. A first phase of this measure could be a fishpond flood channel. Such a channel restricts the dike heights and opens the gates of a couple of neighbouring fishponds, while the other fishponds are still free to determine their dike height.

The social and financial impact of *fishpond dike height regulation with gate opening during fluvial floods* is much less than the *preventive measure with structures*. The former has a negative effect solely on fishpond owners, starting from four owners. The latter has a negative effect for all people living along the elevated roads and people living outside the protected area. Furthermore, the latter causes a decreased perception of the danger of the large storm events. Financially, the *fishpond* measure is around four times cheaper and has a positive benefit-cost ratio.

To make the above described potential measures feasible, the municipalities need to coope-rate for three main reasons:

1. Most measures need to exceed the municipal borders to be effective;
2. A positive influencing measure for solely one municipality often negatively influences the neighbouring municipality;
3. The projects become more feasible if all the positively influenced municipalities are financially supporting the executive municipality.

6.2 Recommendations

For the municipalities in the *Alliance of Coastal Communities in Bulacan and Pampanga* (ABB-BP), I would like to provide the following recommendations:

- The ABB-BP is advise to implement the fishpond dike height regulation and gate opening. A fishpond flood channel is a feasible first phase of this project and is implementable by the local government itself;
- The municipality of Macabebe and Masantol are advised to monitor their levee elevation and maintain them if subsiding;
- For all the municipalities in the ABB-BP it is advised to start with using other sources of groundwater extraction like the Bulacan Bulk Water Supply Project and rainwater harvesting systems to prevent potential problems for the next generation. Simultaneously, another research could help to find various sources of potable water and determine the acceptable rate of groundwater extraction in the study area.

The topics for further research could be:

- Investigating the two not-included parts of the ABB-BP on floods. The first area is consists of the municipalities of Macabebe and Masantol in the Porac River Basin. These municipalities are confronted by both fluvial and tidal floods. The second area consists of the municipalities of Malolos, Bulacan and Obando. This area is confronted by tidal floods and floods due to rainfall-run-off;
- Investigating various sources of potable water to decrease the groundwater extraction, the recharge, maximum allowable groundwater extraction and the impact of the progressive saltwater intrusion on the groundwater.
- Investigating the optimum elevation level for fishpond dike regulation or the optimal design for a fishpond flood channel, taking into account both fluvial and tidal floods. Additionally, measures to preserve the fish in the regulated ponds during floods are worth investigating as well;
- Investigating the environmental impact of the potential measures on the study area and especially the Candaba Swamp. A water depth increase in the Candaba Swamp could have large adverse environmental effects. For example, the bird migration could be hindered when the flood does not subside fast enough. For the study area itself, creating a closed system could result in a change in environmental conditions, like the salinity;
- Investigating the strength of the road constructions to withstand the water pressure of the flood wave need to be assessed if the smart road elevation measure is implemented. Furthermore, the effects and chance of a road breach are worth investigating.

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Appendices

Table of Contents

Appendix A

Tide and Storm Surge

This appendix includes all the tide and storm surge calculations that are used in chapter 2.

A.1 Tide comparison Manila with Pampanga River Mouth

Between 5 and 20 January, De Vos et al. (2014) measured the pressure head with an interval of 2 minutes near the mouth of the Pampanga River. During this period, there were no storm events, not even rainfall, in the upstream catchments: Pampanga, Angat and Porac. Therefore, the measurements of De Vos et al. are used to relate the tide at Manila South Harbour with the Pampanga River mouth. The tide in Manila South Harbour is predicted by WXTide (Hopper, 2007) on an interval of two minutes, because no water level measurements are available at Manila South Harbour for this period. The pressure head of De Vos et al. (2014) is made comparable with WXtide by:

1. using a low pass filter with phase lag correction to filter the high wave frequencies from the raw data of De Vos et al. (2014);
2. extracting the average difference between datasets from the pressure head data.

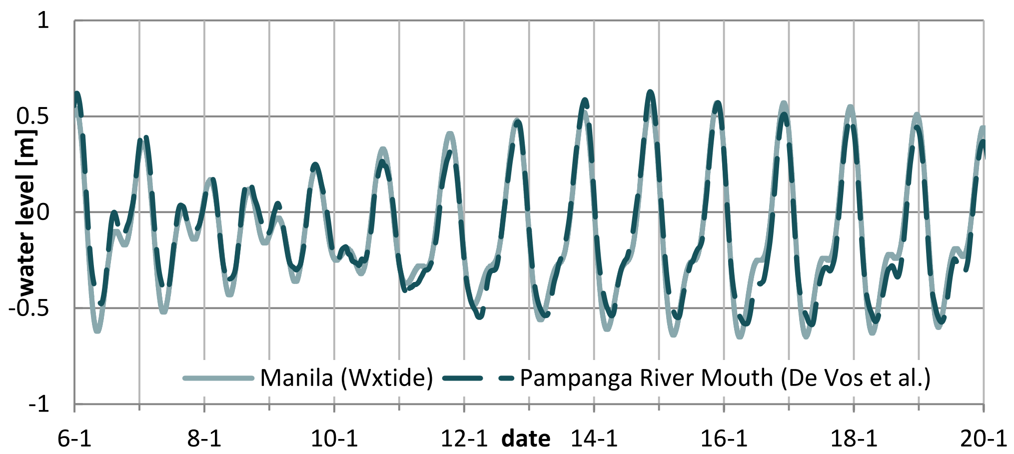

Figure A.1 – Processed Pressure Head Measurements of the Pampanga River Mouth (De Vos et al., 2014) compared with Predicted Water Level at Manila South Harbour (Hopper, 2007)

The comparison is made on phase lag and peak difference, since these are the most significant characteristics of the tide that has an influence on the flood. The phase lag determines if the peak of the tide coincides more or less with the peak discharges from the rivers during storm events. The peak difference determines the flood depth and extent, especially in the coastal areas. The daily minima and maxima, in total 30 measured points, are used for comparison. The minimum and maximum peak difference is respectively -0.05 and 0 m that means that low water is 0.05 m lower at Manila South Harbour. The phase lag for low and high water, calculated over all minima and maxima, is respectively 49 and 55 minutes.

A.2 Tide comparison Pampanga River Mouth and Sulipan

The same method, as described in section A.1, is used for the comparison of the water levels at Sulipan and Manila. The water level at Sulipan is measured by De Vos et al. (2014). Thereby, the assumption is made that the discharge of the Pampanga River is low and that there is little to no head difference. This assumption could be made because no rainfall was measured by the rainfall measurement stations in the Pampanga River Basin during the month January in 2014. The results are presented in Figure A.2.

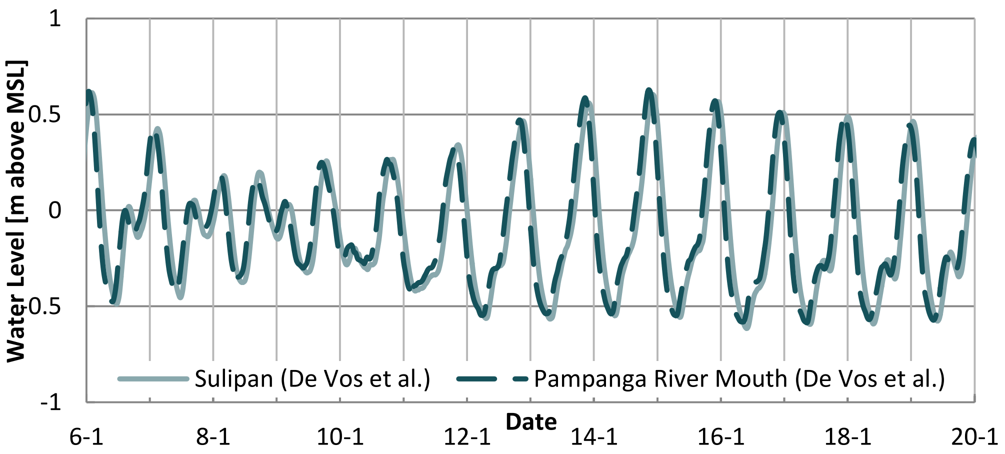

Figure A.2 – Processed Pressure Head Measurements of the Pampanga River Mouth compared with the Pampanga River at Sulipan (De Vos et al., 2014)

The minimum and maximum peak difference is respectively -0.02 and 0 m that means that low water is 0.02 cm lower at Sulipan. The phase lag, based on the smallest error, is 88 minutes.

A.3 Tide analysis Manila

Hourly water level measurements are available between 1984 and 2013 from a tide gauge at Manila South Harbour. (NAMRIA, 2013, 2014a) First, the average water levels and the completeness of the data are checked. The average water levels are checked to determine a stationary period, since the measured water levels are subjected to change like sea level rise or subsidence of the tide gauge of around 1.1 cm/year. (Raucoules et al., 2013) Between 2007 and 2013, the dataset is near complete with a minimum percentage of 94% for one year. Before 2007, a lot of data is missing and therefore not reliable for frequency analysis. Furthermore, the average water levels between 2008 and 2013 are varying between 16 cm to 26 cm above mean sea level (MSL). From 2007 onward the water levels of the near complete years are smaller than 8 cm above MSL. Based on these two arguments, the years 2008 to 2013 are used for the extreme value analysis.

The dependency of water levels on monthly basis is low, because the water levels in Manila Bay respond rapidly to changes in the system as can be seen by the movement of the tide along the bay. The main exception is a storm on the last day of the month and the first day of the next month. The monthly maximum water levels between 2008 and 2013 are used for an extreme value analysis of Gumbel. The method itself is assumed to be a common theory and therefore not further explained. Figure A.3 shows that Gumbel is an adequate method to interpolate and extrapolate the expected water levels for certain return periods. The results are summarised in Table 2.3.

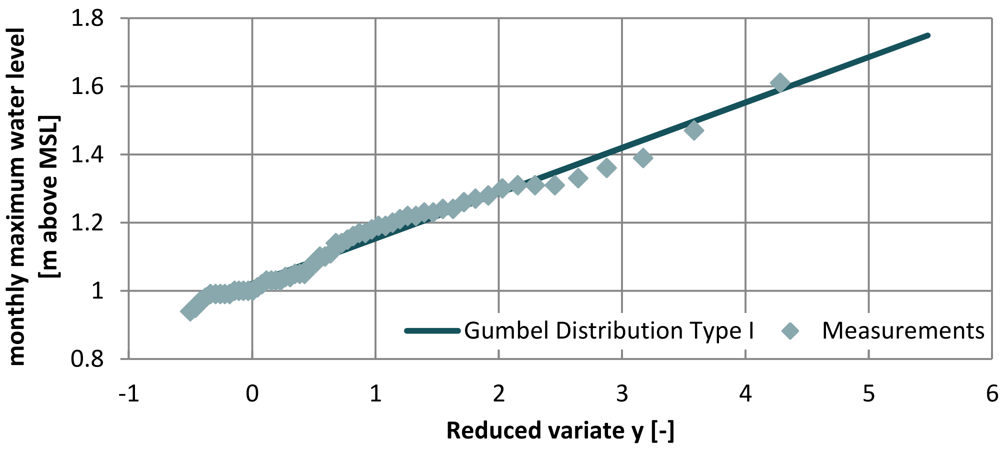

Figure A.3 – Type I Gumbel distribution of monthly maximum water levels at Manila South Harbour (NAMRIA, 2013, 2014a)

Next to the extreme value analysis, the average monthly maximum water levels are calculated and summarised in Figure A.4. This calculation is used to support the occurrence of the effects of the southwest monsoon enhanced tide and other seasonal variations. One important component that contributes to the monthly maximum water level is the prevailing winds. Fuji et al. (2002) summarised these different wind directions in Figure A.5 and this shows that the prevailing southwest wind is causing higher water levels in Manila Bay.

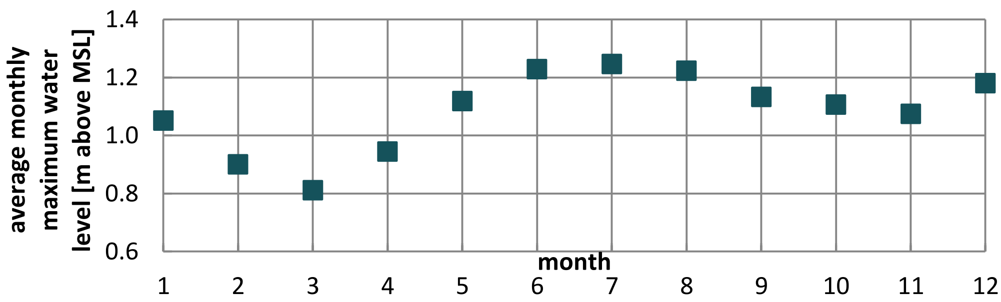

Figure A.4 – Average Monthly Maximum Water Levels at Manila South Harbour between 2008 and 2013 (NAMRIA, 2013, 2014a)

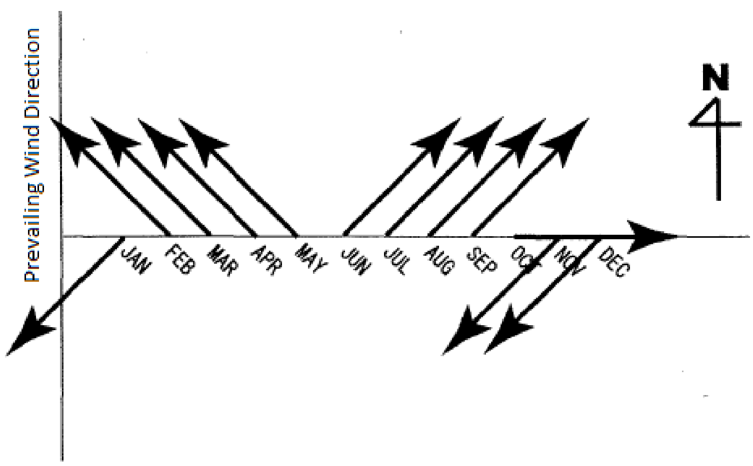

Figure A.5 – Prevailing Wind Direction in 1961 - 1995 at Manila (Adapted from Fuji et al., 2002)

A.4 Water level estimation in Hagonoy during Pedring 2011

The last calculation used in chapter 2.5.2 is the conversion of the Manila South Harbour water levels to the estimated water levels at the Hagonoy coastline during Pedring 2011. The computation is separated in two independent components: tide and storm surge. The computation explained in chapter A.1 is used for the tide. The phase lag with an average of 52 min is rounded to one hour since the measured water levels are on hourly basis.. No correction for the peak difference is used, since there is no maximum peak difference on average and the small minimum peak difference is not relevant for flood modelling.

The conversion of the storm surge component of the water level is explained in multiple steps. First, the storm surge model of NOAH (2013) is used to estimate the surge level near the Hagonoy coastline during typhoon Pedring 2011 at both locations. The storm surge model is based on the linear shallow water equations and uses the finite difference method to solve these equations. The size of the grid is one arc minute and the Digital Elevation Model input data is two arc minute gridded data. The maximum water level according to the storm surge model in Manila South Harbour and Hagonoy Coastline is respectively 0.99 m and 1.48 m, see Figure A.7 the dotted lines for the storm surge levels and Figure A.6a for the model measurement. This makes a proportion in storm surge level between both locations of 1.49. The phase lag of one hour between both measurement locations also exists in the storm surge model.

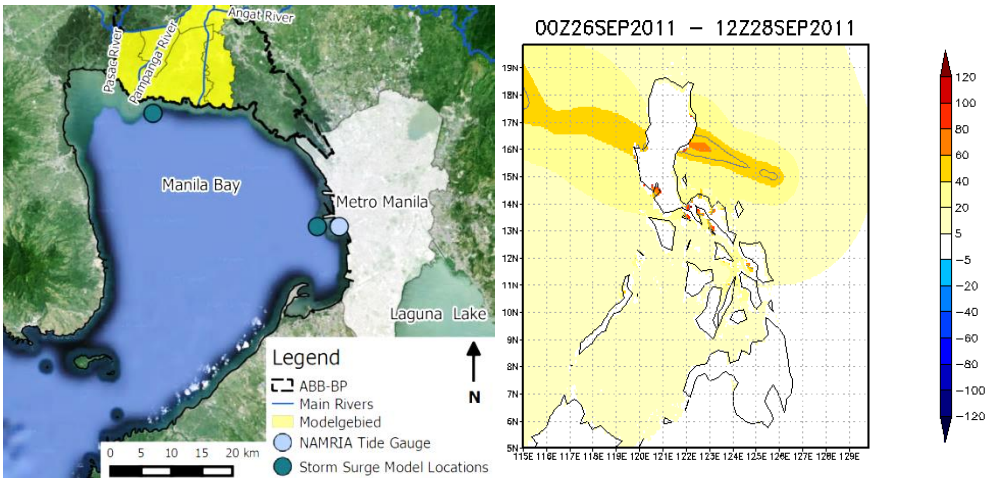

Figure A.6 – (a) Storm Surge Model and NAMRIA Tide Gauge locations (NAMRIA, 2014a; Google Maps, 2014); (b) Collated maximum surge level over the typhoon Pedring from NOAH's (2013) storm surge model

The assumption is made that the measured storm surge at Manila can be multiplied with the proportion found by the storm surge model for both the typhoon Pedring and Quiet. To separate the measured storm surge from the measured tide (NAMRIA, 2014a), the predicted water levels are used from WXtide. (Hopper, 2007) For this purpose, the average of the predicted WXtide is corrected based on the average water levels of both series from 12 to 25 September. By subtracting those water level series, the difference between the real tide and the measured tide is included in the result. This difference is in reality not amplified at the Hagonoy coastline and therefore a threshold of +8 cm is used to prevent the enlargement of the tide before and after the storm surge event. Using this information, the water levels at the Hagonoy coastline are computed with the following formula:

$$h_{hag,n} = h_{man,n-1} + \Delta h_{surge,man,n-1} \cdot 0.49$$

with $h_{hag,n}$ the estimated water level at the Hagonoy Coastline [m],$h_{man,n-1}$ the measured water level at Manila South Harbour [m], $\Delta h_{surge,man,n-1}$ the storm surge with a threshold of 8 cm at Manila South Harbour [m] and n increases with every interval step. The result of this formula is shown in Figure A.7.

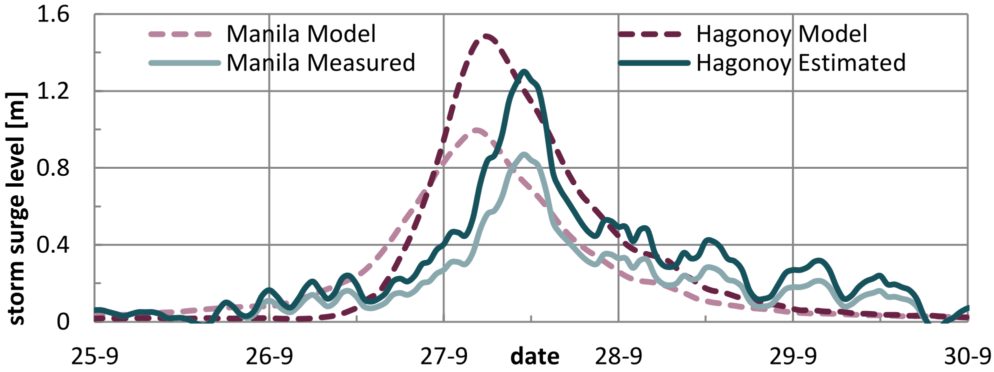

Figure A.7 – Results from storm surge model (NOAH, 2013) at Manila and Hagonoy, measured storm surge in Manila (NAMRIA, 2014a) and estimated storm surge in Hagonoy during Pedring 2011

Appendix B

Rainfall and Discharge

This chapter includes the analyses and calculations regarding rainfall and discharge in and upstream of the study area.

B.1 Discharge calculation summary

The calculation of the discharge through the Pampanga River and Candaba Swamp are summarised in this section.

B.1.1 Pampanga River

The Pampanga River has multiple water level measurement stations. For imaging, comparison and model purposes, the discharge in the Pampanga River is estimated by making use of a discharge-water level relation (or Q-H relation). 64 measurements are available with both the water level and the discharge. (PRFFWC, 2014b) A rating curve consisting of 3 parts is created. However, when applying this rating curve on the selected storms, see Appendix B.6, the discharge through the Pampanga River is much higher than the amount of rainfall. The most likely reason is the poor quality of 5 measurements with the slope-area method during the high discharges and therefor these and other poor estimated measurements are removed from the dataset.

For establishing a new rating curve, more measurements are needed, since the slope area method provided 5 of the 6 measurements above 1900 m^3/s. By combining two datasets with a daily interval step, PRFFWC (2014c) for water level and JICA et al. (2011) for the discharge, another 278 additional Q-H measurements are created. The 278 measurements consist of events with a high discharge between 1973 and 2001 and include both high as low discharges during the wet season. Using this dataset of 329 measurements, the following rating curve is developed:

$$Q = 9.00 \cdot [H - (-1.15)]^{2.30}$$

with Q the discharge in (m^3/s) and H the water level (m). The calculation method is explained in Appendix B.2. The result and the measurements are presented in Figure B.5.

Unfortunately, the Arayat station was not operational during typhoon Pedring, meaning that this rating curve cannot be directly used. The upstream stations Zaragoza and San Isidro cannot provide sufficient data to estimate the discharge at the Arayat station, since their rating curves are not reliable for high discharges. Therefore, the water level measurement station in the Candaba Swamp is used to estimate the water levels in the Pampanga River, since the shape of the flood wave is most comparable for this station in the PRFFWC reports (2011a, 2011b, 2012, and 2013) and it gives the best initial results for a rough calculation.

To estimate the water level at Arayat station, the two water levels of the stations are related with each other. However, the Candaba Swamp is a large retention basin and the response of this basin is much slower than the river itself. This is causing a slow response including a phase lag. Relating both water level stations is tough and the error could be quite large. An analysis is made about the volumes of the storms to estimate the size of the error, see sub-section B.1.3.

From PRFFWC (2014c), 8505 water level measurements for the Arayat and Candaba station are used to establish the relation between the two water level stations. The extensive explanation of the calculation can be found in Appendix B.3. These measurements are measured during the wet season between the month July and October of 2009 until 2013 and are above 3.5 m above MSL. This threshold is chosen because the start level of the Candaba swamp before the typhoon Pedring was also 3.5 m above MSL. Before the relation is formulated, is to estimate the phase lag of the Candaba station. This is done by a correlation analysis. For a phase lag of 25 hours, the correlation coefficient of 91% is the highest. Then, the assumption can be made that the water levels of both stations could be related by the same form as the rating curve. Using the 8505 water level measurements, the following relation and figure is created:

$$H_{arayat} = 1.57 \cdot [H_{candaba} - 1.98]^{1.12}$$

Combining both formulas, the rating curve and the relation between the two stations, the discharge during Pedring 2011 could be estimated. The peak discharge is estimated at 2,777 m^3/s that is comparable to a 10-year discharge event of 2,700 m^3/s according to JICA et al. (1982). After the peak the discharge slowly reduces. During the typhoon Quiel no clear increase in the water level is noticed, this could be a caused by the use of the Candaba station as input to calculate the discharge at Arayat. The discharges of the three inflows in the direction of the study area during Pedring 2011 are summarised in Figure B.1.

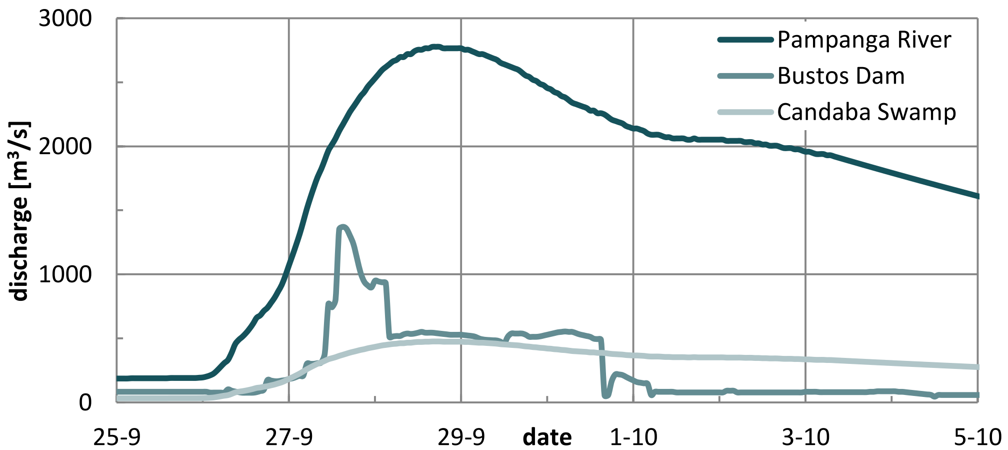

Figure B.1 – Discharges of the Candaba Swamp, Pampanga and Angat River during Pedring 2011 (PRFFWC, 2014b, 2014c; NIA, 2011)

B.1.2 Candaba Swamp

The water level is measured on the upstream side of the swamp. The only exchange between the Pampanga River and that point is the Candaba Floodway. For modelling purposes, also the discharge is estimated, since a water level boundary causes an unrealistic high discharge. Since no discharge measurements are available for the Candaba Swamp, the rainfall is used as input to estimate the water level. The relation between the rainfall that felt on the catchment above Arayat and Candaba station is 0.17, see chapter 2.5.1. For this estimation, the Candaba Floodway is ignored based on two arguments:

1. The estimated run-off compared with the expected run-off over the six selected events has an absolute error of only 6% and the events have a slightly lower run-off, including the storms with a water level lower than the threshold of the Candaba Floodway,.
2. The most important factor is total volume flowing into the system at the north side and not the location. Because there are multiple connections between those inflow points before reaching the study area.

Furthermore, the assumption is made that the phase lag of 25 hours is also applicable on the inflow at the Candaba Swamp, because the discharge depends on the time of concentration of the upstream area and that the water level responds slow due to the large area of the retention basin. The discharges of the three inflows in the direction of the study area during Pedring 2011 are summarised in Figure B.1.

B.1.3 Verification

The water level relation between the Candaba and Arayat station are verified based on the five remaining storm events, see Appendix B.4. The storm volume, one of the most important parameters for modelling flood events, shows a volume error of on average 12% for all storms and a volume error of on average 3% for the three largest storms. The maximum discharge is mainly underestimated due to the slow response of the Candaba Swamp. The discharge error for maximum discharges higher than 1000 m^3/s is below 10%. The complete calculation can be found in Appendix B.5.

B.2 Rating curve for Pampanga River at Mount Arayat

First the general approach for creating a rating curve is shortly explained. Then, the two rating curves are described in more detail. The form used for developing the rating curve is:

$$Q = a(H - H_0)^b$$

with *Q* the discharge in (m^3/s), *H* the water level (m), H_0 is the water level at zero flow and *a* and *b* are constants. The constants a, b, H_0 are determined with the least square method. The assumption is made that the logarithm of Q and $H - H_0$ is linear. In short, the variable H_0 is chosen and the variables *a* and *b* are calculated with the least square method. With the created formula and the measurements the sum of the errors is calculated. A new value for H_0 is chosen and this iteration loop is repeated until the smallest achievable sum is found for two decimals.

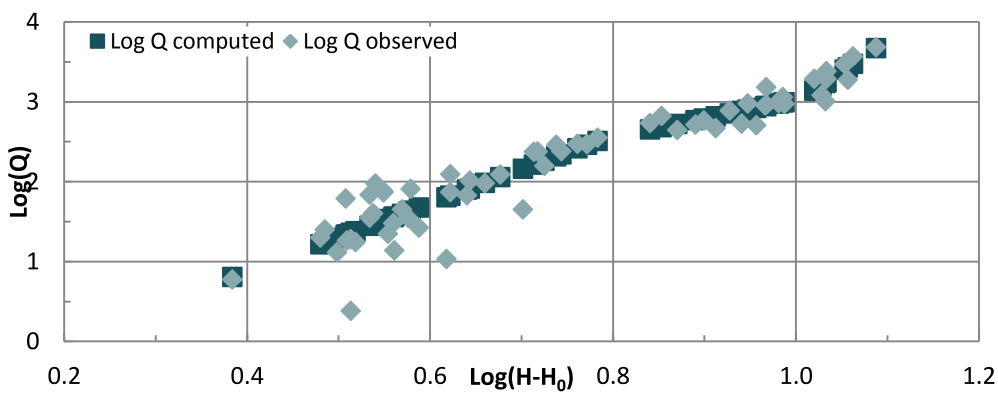

Figure B.2 – Logarithmic plot of the discharge *Q* and the discharge contributing water level *H-H₀* with the observed and calculated values for the first calculated rating curve (PRFFWC, 2014b)

The first created rating curve is based on 64 *discharge-water level* measurements of PRFFWC (2014b). First, it is checked if the logarithm of Q and $H - H_0$ is linear for the all the measurements. As can be seen in Figure B.2, there are three lines with a different slope and therefor for each part a different rating curve is created.

For the first formula H_0 is iteratively found according to the method described above. The water level at zero flow is known by then and is used as input for the other two parts of the measurements. The transition point is selected based on the intersection point of the neighbouring formulas. The following three formulas are computed and presented in the graph in Figure B.3:

$$Q = 0.147 \cdot [H - (-2.77)]^{4.264} \qquad H < 3.372$$

$$Q = 5.053 \cdot [H - (-2.77)]^{2.317} \qquad 3.372 < H < 6.815$$

$$Q = 7.750 \cdot 10^{-4} \cdot [H - (-2.77)]^{6.203} \qquad H > 6.815$$

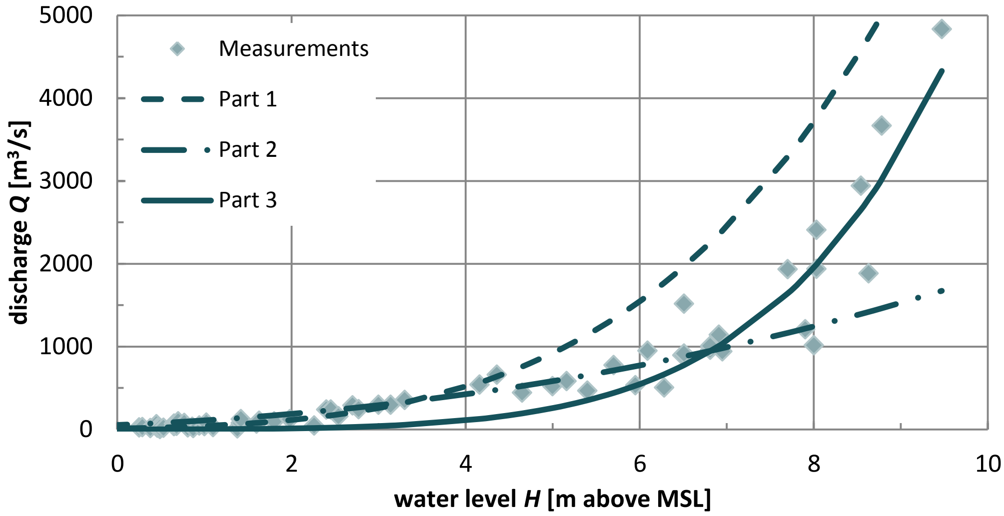

Figure B.3 – Rating curve for the Pampanga River at Mount Arayat consisting of three parts based on 64 measurements of the PRFFWC (2014b)

For the second rating curve, new values are gathered to compensate for the loss of the high discharge measurements by the slope area method. Two datasets with daily discharge or water level averages are used. The high discharge events are selected including a couple of days before or after a large event to include high, medium and low discharges. (JICA et al., 2011) In total 278 measurements are taken from the JICA et al. (2011) combined with PRFFWC (2014c) for the water levels to establish a new rating curve. The measurements are all taken in the wet season and are summarised in Table B.1. The measurements are fairly linear on logarithmic scale, so one rating curve is sufficient, see Figure B.4.

Table B.1 – Summary of the number of measurements from (PRFFWC, 2014b, 2014c; JICA et al., 2011)

Discharge (m^3/s)	Measurements (-)
0 - 500	126
500 - 1000	100
1000 - 2000	88
2000 - 3000	22
3000 - 5000	6
Total	**342**

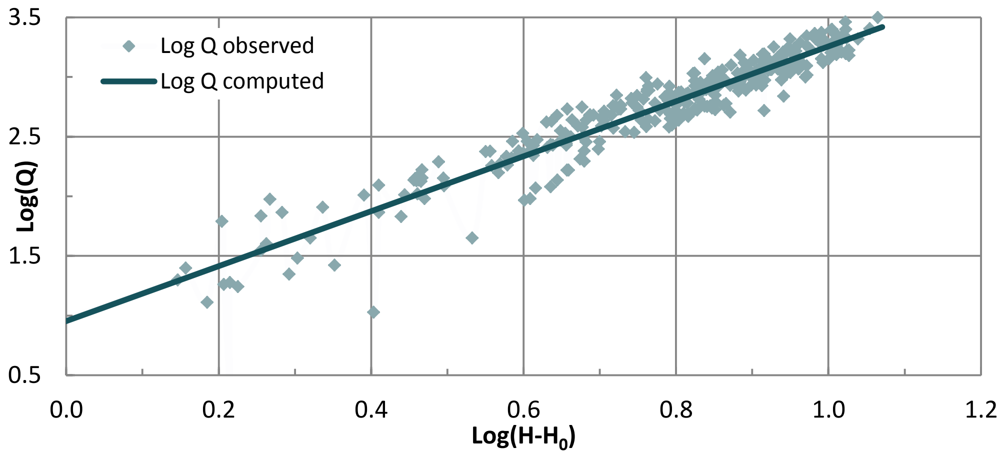

Figure B.4 – Logarithmic plot of the discharge *Q* and the discharge contributing water level *H-H₀* with observed and calculated values for the 278 measurements (PRFFWC, 2014b, 2014c; JICA et al., 2011)

By using the method described above, a new rating curve is generated in the following formula. The same formula is plotted together with the measurements in Figure B.5.

$$Q = 8.999 \cdot [H - (-1{,}15)]^{2{,}302}$$

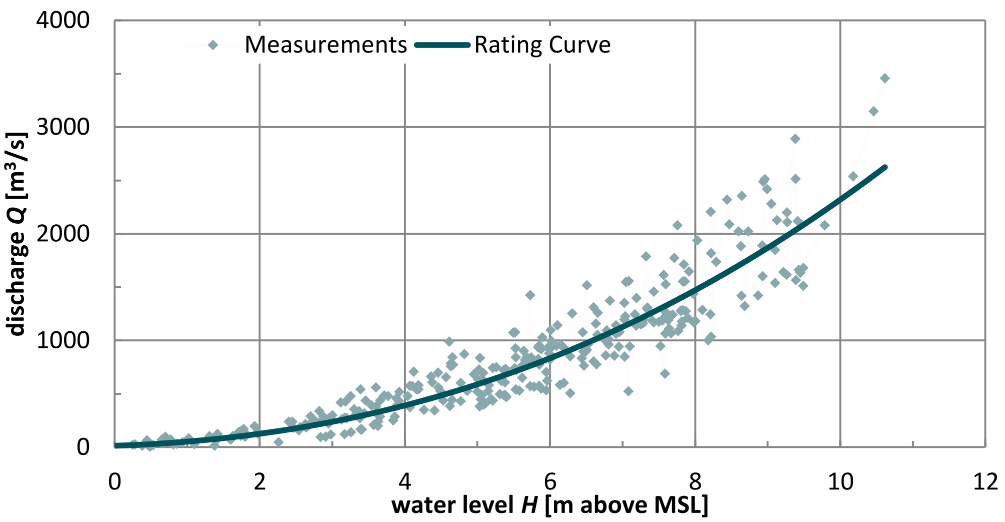

Figure B.5 – Rating Curve of the Pampanga River at Mount Arayat with measurements used for the development of the rating curve (PRFFWC, 2014b, 2014c; JICA et al., 2011)

B.3 Relation between Candaba and Arayat

By making the water level relation of Candaba and Arayat, the same approach is used as for the establishing the rating curves for Mount Arayat, because the assumption is made that the relation could be described using the same function:

$$H_{arayat,n} = a(H_{candaba,n+\gamma} - H_0)^b$$

with γ the phase lag between the Candaba and Arayat station and *n* the interval step. The phase lag is chosen based on the highest correlation coefficient by making use of the following formula:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_x \cdot \sigma_y}$$

with $\rho_{X,Y}$ the correlation coefficient, X and Y two random variables, *cov* the covariance, σ the standard deviation. The measurements are selected during the wet season between the month July and October of 2009 until 2013. Furthermore the measurements are selected with a threshold of 3.5 m above MSL because the start level of the Candaba swamp before the typhoon Pedring was 3.5 m above MSL. Due to the phase lag, only events that are longer than 28 hours above 3.5 m above MSL could be selected, making the total of 8505 water level measurements. The results of the correlation analysis are presented in Table B.2.

Table B.2 – The correlation between the water level measurements at Candaba with a certain phase lag and Arayat

Phase lag (hrs)	ρ
+28	0.9109
+27	0.9111
+26	0.9112
+25	**0.9112**
+24	0.9111
+23	0.9108

By using the method described above, the new relation could be presented in the following formula. The same formula is plotted together with the measurements in Figure B.6.

$$H_{arayat} = 1.567 \cdot [H_{candaba} - 1.98]^{1.121}$$

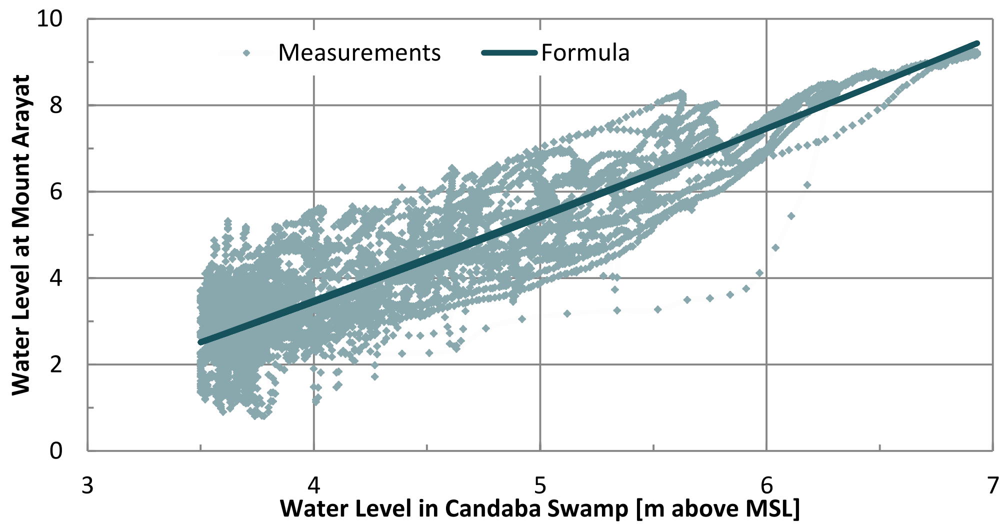

Figure B.6 – Formula relating the water level of the Pampanga River at Mount Arayat with the Candaba Swamp minus a phase lag of 25 hours with measurements used for the development this (PRFFWC, 2014c)

B.4 Storm events

Between 2010 and 2013, the Pampanga River Flood Forecasting Warning Centre (PRFFWC, 2011a, 2011b, 2012, 2013) made four post flood reports of the most severe storm events during this period for the Pampanga River Basin. Next to these four storm events, two less severe storm events are selected for comparison and analyses purposes. In addition, the storm Habagat 2012 from August 6 till August 21 is divided, since the last part of the monsoon has the largest precipitation and discharge measurements are available for Bustos Dam during this period. This makes a list of six storm events with the Philippine and international, between brackets, names of the typhoons and the duration:

1. Typhoon Juan (Megi) from 18 till 24 October 2010
2. Severe tropical storm Falcon (Meari) from 23 till 27 June 2011
3. Typhoons Pedring (Nesat) and Quiel (Nalgae) from 26 September till 4 October 2011
4. Habagat (southwest monsoon), tropical storm Gener (Soala) and Helen (Kai-Tak) from 20 July till 21 August 2012
    - Part I from 20 July till 6 August 2012
    - Part II from 6 August till 21 August 2012
5. Habagat (southwest monsoon), tropical storm Maring (Trami) from 18 till 29 August 2013
6. Typhoon Santi (Nari) from 11 till 18 October 2013

In summer, the temperature of the Asian continent is high which is causing wind circulation patterns from Indian Ocean to China due to the low pressure area that arises above the continent. For the Philippines, this means a dominant southwest wind that is causing frequent heavy rainfall due to its warm and humid character. (Bosboom and Stive, 2013) This phenomenon is called southwest monsoon internationally or Habagat in the Philippines. Tropical cyclones arise on the Pacific Ocean and are moving into the direction of the Asian Continent. Five of the eight tropical cyclones during the six selected storm events made land fall on land at North or Central Luzon, the other three passed over the Pacific Ocean at considerable distance, see Figure B.7. (International Best Track Archive for Climate Stewardship, 2014)

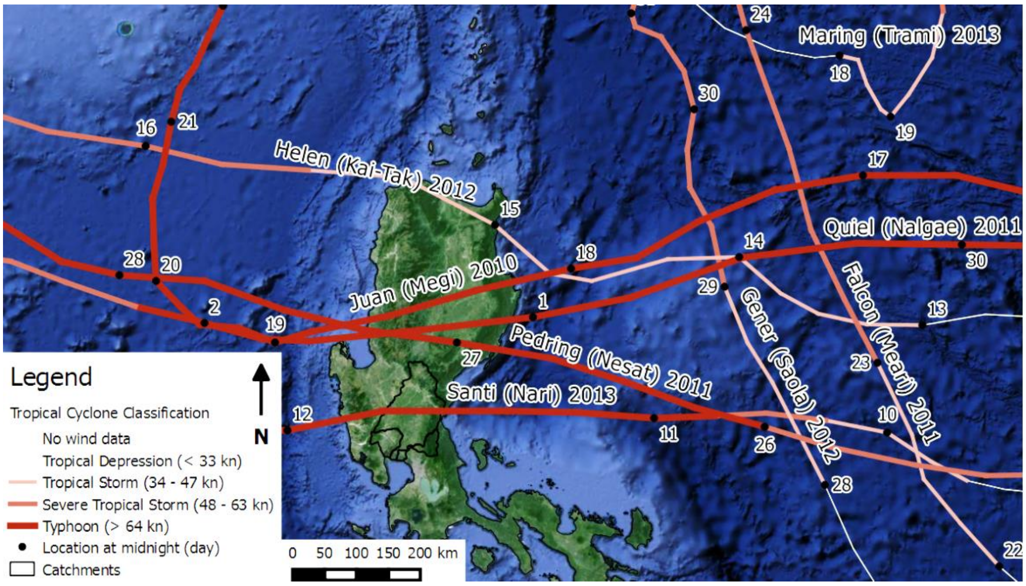

Figure B.7 – Eight tropical cyclone tracks between 2010 and 2013 used for analyses with classification based on the RSMC Tokyo (International Best Track Archive for Climate Stewardship, 2014; World Meteorological Organization, 2012; Google Maps, 2014)

The damage during various storm events is quantified in numbers and costs and is presented to get a feeling with the severity of the different storm events. The Provincial Disaster Risk Reduction Management Office of Bulacan made flood reports of the six events as described in Table B.3. The numbers in this table are for the whole province of Bulacan, including the Municipalities of Calumpit, Hagonoy and Paombong.

Table B.3 – Summarised flood reports of the Provincial Disaster Risk Reduction Management Office of Bulacan (2014); No data is available for the cells with a dash

Event	Affected People (x1000)	Killed Wounded Missing	Damaged Houses Partly	Damaged Houses Severly	Damaged Infrastructure (mil ₱)	Damaged Agriculture (mil ₱)	Aid (mil ₱)	Total (mil ₱)
Juan 2010	-	-	-	-	9	363	0	372
Falcon 2011	479	2	-	-	-	136	17	153
Pedring 2011	766	36	4423	1375	268	2,529	62	2,859
Habagat 2012	880	9	-	-	64	543	40	646
Maring 2013	971	-	-	-	54	142	19	215
Santi 2013	103	2	1660	1070	84	765	1	849

B.5 Verification of water level relation

The water levels found by the formula that relate the water levels of the Candaba and Arayat station are verified by the five remaining events. With both the water levels of Candaba as Arayat, the total volume and maximum discharge in the Pampanga River at Mount Arayat of the storm is calculated by making use of the rating curve of Arayat and the water level relation between Candaba and Arayat, see Table B.4 and Table B.5. Remarkable is that the error decreases as the storm volume increases. For storms large than 1 billion m^3 the volume error is on average 3%, while the error for all storms is on average 12%.

Table B.4 – Comparison between estimated storm volume in the Pampanga River at Mount Arayat based on the water level measurements of the Candaba and Arayat measurement station

Storm Event	Storm Volume [mil m^3] WL Arayat	Storm Volume [mil m^3] WL Candaba	Volume Error
Juan 2010	640	459	28%
Falcon 2011	846	949	12%
Pedring-Quiel 2011	-	2,310	-
Habagat 2012	3,354	3,103	7%
Habagat Part II 2012	2,118	2,062	3%
Santi 2013	759	934	23%
Maring 2013	1,215	1,216	0%

The maximum discharge is underestimated by using the Candaba measurement station to estimate the Pampanga River discharge. This can be explained by the damped response of the Candaba Swamp. The discharge error for maximum discharges higher than 1000 m^3/s is below 10%. Both errors are acceptable for the usage of the Candaba measurement station to estimate the water levels at Mount Arayat during Pedring 2011.

Table B.5 – Comparison between estimated storm volume in the Pampanga River at Mount Arayat based on the water level measurements of the Candaba and Arayat measurement station

Storm Event	Discharge [m^3/s] WL Arayat	Discharge [m^3/s] WL Candaba	Discharge Error
Juan 2010	980	595	39%
Falcon 2011	1612	1457	10%
Pedring-Quiel 2011	-	2790	-
Habagat 2012	1971	2056	4%
Santi 2013	1776	1651	7%
Maring 2013	1619	1504	7%

B.6 Verification based on ratio discharge - precipitation

In this chapter, the inflow discharges are calculated and this section is used to show the reliability of this estimation. The reliability is checked based on two parameters: volume over the storm and the ratio between discharge and precipitation, summarized as run-off coefficient. For this analysis, 22 precipitation measurement stations are used, see Figure B.8. The method used by Nippon Koei (2011) is the rational method with the addition of a saturated rainfall. The run-off coefficient captures the precipitation that is flowing into the downstream rivers during the storm event. When the precipitation depth exceeds the saturated rainfall threshold, Nippon Koei (2011) assumes that all the remaining precipitation is run-off.

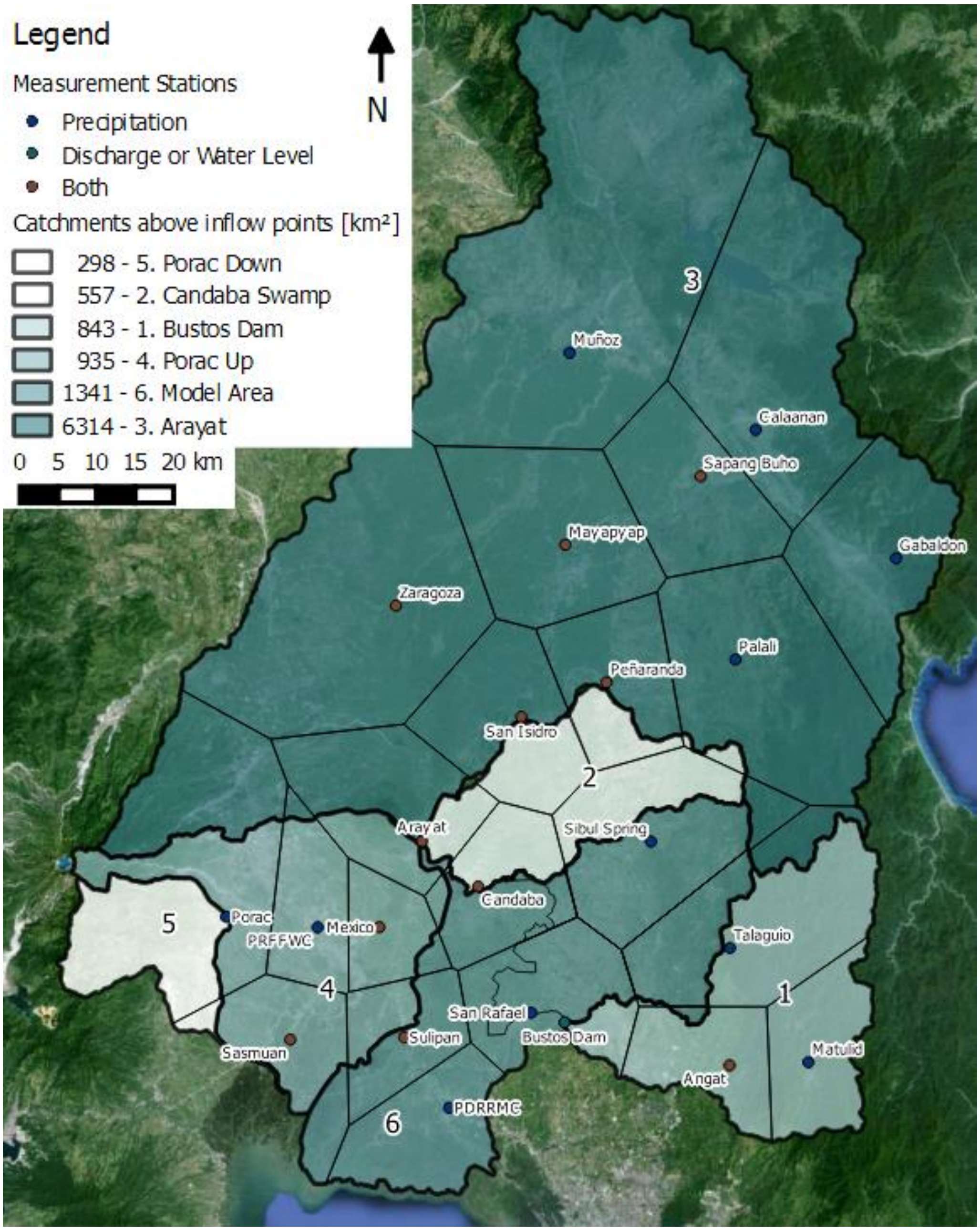

Figure B.8 – Map with the 23 precipitation and/or water level measurement stations and the location of Bustos Dam; Voronoi diagrams for the 22 stations; Catchments above the nearest reliable inflow points for the study area (PRFFWC, 2014a; Google Maps, 2014)

The Thiessen method is used for an estimation of the areal rainfall, see Figure B.8 for the Voronoi diagrams. The area of the Voronoi diagrams is multiplied with the precipitation over the whole storm. By combining the storm volumes, see section B.5, with the precipitation volumes, a run-off analysis is made. For comparison, according to Nippon Koei (2011) is the run-off coefficient 0.5 and the saturated rainfall 200 mm for the Agno and Angat River Basin. (Nippon Koei, 2011) The Agno River basin borders the Pampanga River basin on the northwest side. The run-off coefficient for the Pampanga River measured at the Arayat station is 0.56 without taking into account the saturated precipitation. (JICA et al., 2011) Making use of the precipitation depth of the storm, the run-off coefficient is calculated based on the values of Nippon Koei (2011). The analysis is summarised in Table B.6 for the Pampanga River at Mount Arayat and Table B.7 for the Angat River at Bustos Dam.

Table B.6 – Comparison of the run-off coefficient based on the rating curve and the run-off coefficient calculated based on the rainfall and the run-off coefficient and saturated precipitation of Nippon Koei for the Pampanga River at Mount Arayat (2011)

Storm Event	Precipitation depth [mm/storm event]	Run-off coefficient by Rating Curve [-]	Run-off coefficient by Nippon Koei [-]
Juan 2010	199	0.50	0.54
Falcon 2011	212	0.63	0.62
Pedring-Quiel 2011	512	0.71	0.80
Habagat Short 2012	362	0.92	
Habagat 2012	634	0.83	0.84
Santi 2013	160	0.74	0.55
Maring 2013	296	0.64	0.67
		Average absolute error	**0.06**

This comparison is a way to check the reliability of the rating curve, since the rating curve determines the discharge and thereby the measured runoff coefficient. At least, the runoff coefficient needs to be between 0.5 and 1, since during storms it is not likely that the runoff coefficient is below the average runoff coefficient and that more water is flowing out than precipitates. For the first rating curve based on 64 measurements, see Figure B.3, the runoff coefficient is calculated between 0.48 and 1.34 with an average absolute error of 0.23. A unrealistic run-off coefficient of 1.34 is calculated for Pedring 2011. The values for the second rating curve based on 329 measurements are given in Figure B.5. The runoff coefficients stay within the limits of 0.5 to 1 and the average absolute error reduces to an acceptable value of 6%. For the typhoon Pedring, the volume error based on the two estimations of the run-off coefficient is around 11%, which is comparable to the error in the water level relation for all storms of 12%, see Table B.4.

Table B.7 – Comparison of the measured runoff coefficient and the runoff coefficient calculated based on the rainfall and the runoff coefficient and saturated precipitation of Nippon Koei (2011) for the Angat River at Bustos Dam

Storm Event	Precipitation depth [mm/storm event]	Measured runoff coefficient [-]	Runoff coefficient by Nippon Koei [-]
Pedring-Quiel 2011	763	0.50	0.87
Habagat Short 2012	534	0.49	0.81
		Average absolute error	**0.34**

The runoff coefficient for Bustos Dam is regulated by the three dams. The runoff coefficient should be a lot higher since an error is measured of 0.34. It could mean that the discharge measurements of the dam are incorrect; however, it is more likely that other reasons are causing a lower runoff coefficient. Angat Dam is rising from 206.5 to 213.9 m during Pedring

2011 and from 201.6 to 213.1 m during Habagat Short 2012. This means that respectively 51% and 33% would be retained by Angat Dam, while the water level at Bustos Dam is still around the same level. (Nippon Koei, 2011) The calculated inflow based on the four rain gauges are probably an under estimation during Pedring 2011 when compared to the real inflow of Angat Dam. (National Power Cooperation, 2014)

Appendix C

Model DEM layer

This appendix describes the generation of the Digital Elevation Model (DEM) layer for the model, see sub-section 3.2.1.The input used for this layer are three Digital Terrain Model layers of NOAH (2013) with a resolution of 1 x 1 m, an ocean bathymetry map of GEBCO-BODC (2008) with a resolution of 1 x 1 km and cross-section measurements of the three large rivers for approximately every kilometre. (De Vos et al., 2014, DREAM, 2012)

C.1 Digital Terrain Model

The first step is the creation of one Digital Terrain Model (DTM) related to mean sea level (MSL) from three DTM layers of the downstream part of the Pampanga and Angat River Basins. The overlap of the three sets is used to mosaic the layers together to the same height. The large two layers of the area, pam7 and pam8 in Figure C.1, are already at the same height, the average error in the overlapping area is 6 cm for Light Detection And Ranging (LiDAR) measurements taken at different moments in time. This error is attributed to the changing water elevation of the fishponds. The Hagonoy River is used as border to mosaic these two sets together to prevent sharp edges. The smaller layer, pam8add in Figure C.1, along the coastline is not at the same height as the other two layers. The error measured in the overlapping area with pam7, is around 26 cm. On the north side of the layer, one flight band has a visible higher elevation than the rest of the layer. The difference for this area, compared with the overlapping area with pam7 and pam8, is on average 55 cm. Both errors, for the whole data set of pam8add and the flight band, are corrected and all three layers are mosaicked together.

The mosaicked DTM layer is clearly not related to MSL. Therefore, 70 benchmarks are used to snap the DTM to mean sea level. (56 from NAMRIA, 2014b; 9 from Hydroterre Consultants, 2006; 4 from Hagonoy, 2014) But, many benchmarks only have a drawn map of the location of the benchmark and not exact GPS locations. The location could be estimated, since they are close to the road and the difference in elevation from the main road is given. Three type of errors are included in the difference between the benchmark and the original map; offset from original location with different height, processing error to get the DTM from the Digital Surface Model and the real error in height. The difference is calculated for the three original layers and the layer pam8, see Figure C.1, shows the lowest standard deviation in the error and is also based on the most benchmarks. Therefore, the 58 benchmarks on the layer of pam8 are used to snap the DEM layer to MSL. The average difference of the layer is 1.805 above MSL and the standard deviation is 29 cm.

The last step to create the DTM is to interpolate the small gap in the Candaba Swamp and to remove the North Luzon Expressway, since this expressway is on piles. For both interpolations the method Natural Neighbour is used.

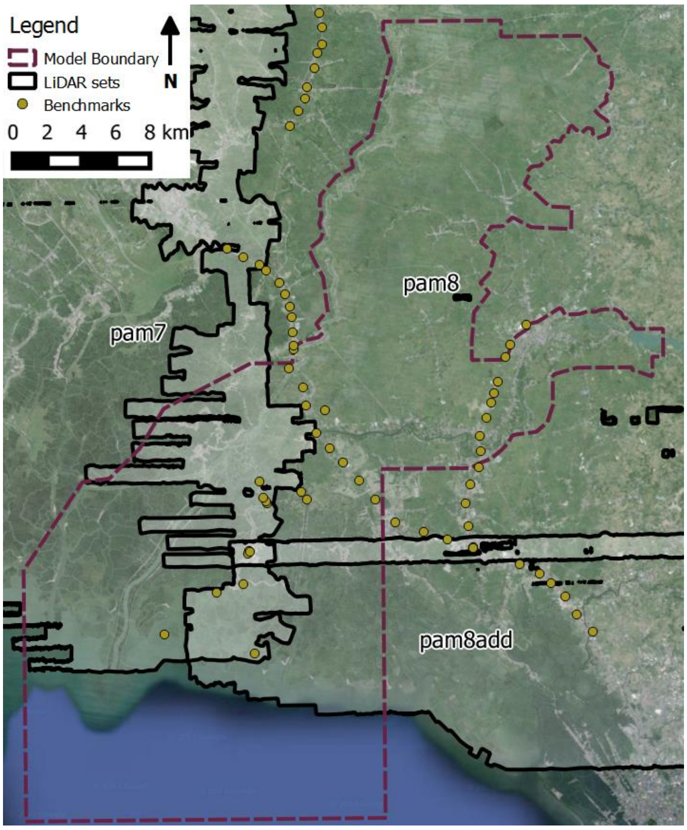

Figure C.1 – The extends of the three DTM of Bulacan and Pampanga with the locations of the benckmarks (NOAH, 2014; NAMRIA, 2014b; Hydroterre Consultants, 2006 Hagonoy, 2014; Google Maps, 2014)

C.2 River bathymetry

River bathymetry is added to the DTM, since the LiDAR measurements of NOAH (2013) reflects on the water. De Vos et al. (2014) measured cross-section data in the San Esteban Diversion and Labangan Channel, Pampanga, Angat, Old Pampanga and Bagbag River. Cross-section measurements of DREAM (2012) are added for the upstream part of the Pampanga River. In Figure C.2, the location of the cross-section measurements are plotted.

The cross-section measurements cannot easily be interpolated to get the river bathymetry, since the river is curved and the cross-sections measurements are only once per kilometre. With the help of the method described by Merwade et al. (2005), a method is created to interpolate the bathymetry over the centreline of the river. This method is shortly described in this chapter.

The first step is to correct the depth measurements for the tide. For this correction measurements at the mouth of the Pampanga River and Sulipan are used (De Vos et al., 2014), see Appendix A.2. For the Pampanga River, both measurement stations are used to correct for the tide and for the other rivers the water level measurements of the river mouth are used. Since the phase lag of the tidal wave determines the tide elevation at a certain moment in the river, the travel speed of this wave is calculated to compensate for the distance from the river mouth. The travel speed of the tidal wave is 0.26 km/min. The travel speed is calculated by dividing the phase lag of the two measurement stations with the distance along the centreline of the river.

The second step is the interpolation process between the cross-sections over the centreline. The main step is to use a coordinate system that moves along the river. Therefore, all the cross-section point are converted from Cartesian coordinates (x,y) to orthogonal curvilinear coordinates (s,n) with the s-direction, the centreline of the river and the n-direction, perpendicular to the centreline, see Figure C.3.

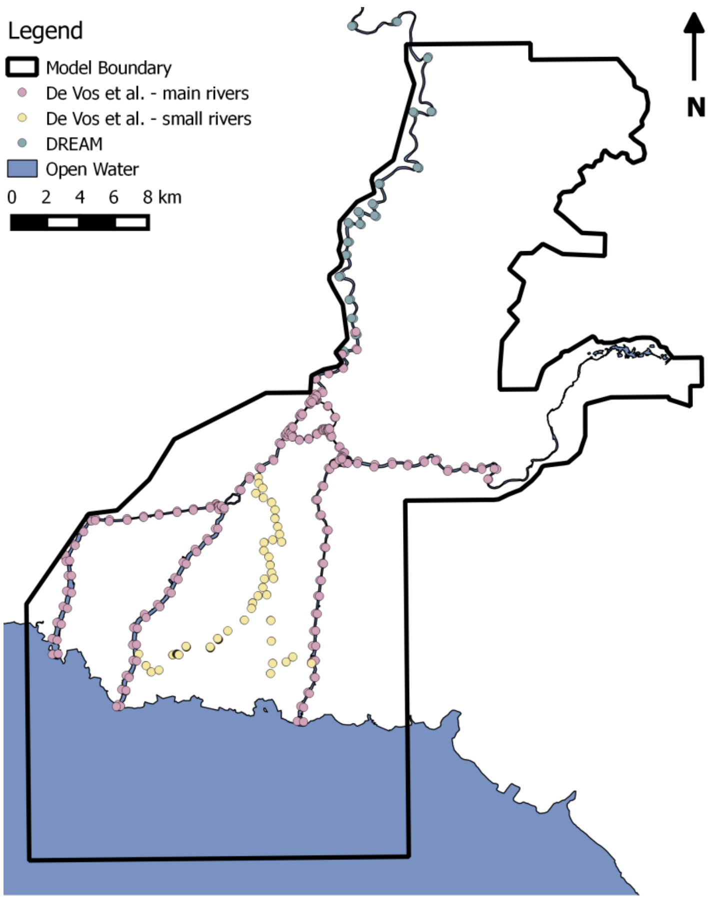

Figure C.2 – Cross-section measurements of De Vos et al. (2014) and DREAM (2012)

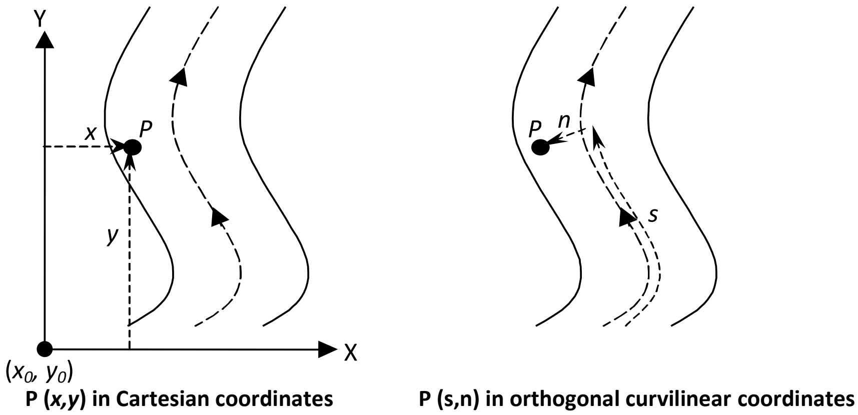

Figure C.3 – Conversion from Cartesian coordinates to orthogonal curvilinear coordinates over the centreline of the river (Merwade, 2005)

Station points are created every 10 m over the centreline of the river. Perpendicular on the centreline (n-direction), 15 points on equal distance are created on both sides of the centreline between the river bank and the centreline. This creates 31 points in total, including one centre point and 15 point on both sides. This means that the left side of the river could have a smaller distance between those points than the right side if the centreline is not exactly in the middle. A grid of bathymetry points is created that fits exactly into the river because the river boundaries are followed.

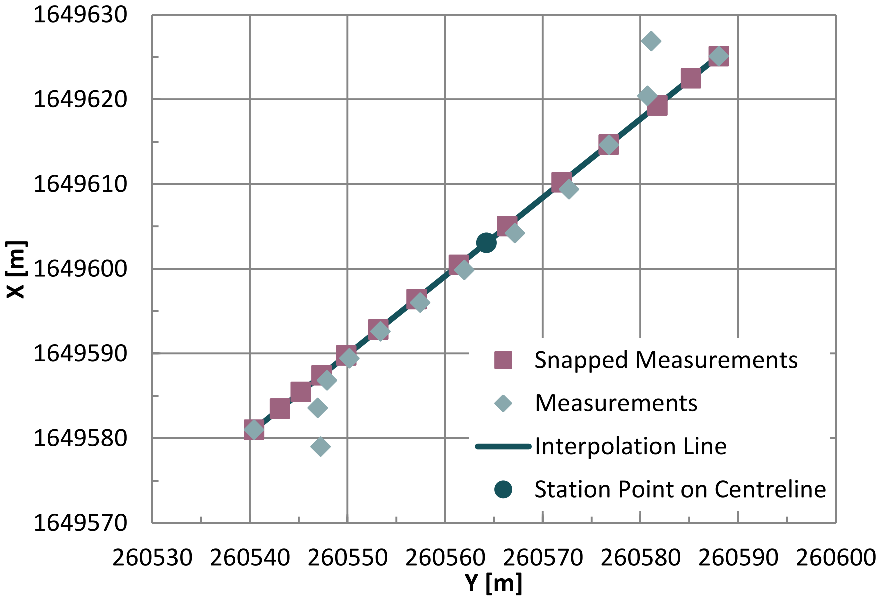

Figure C.4 – Example of snapping of the measurements to the line over which is interpolated

All the cross-sections are linked to the closest station point on the centre line and then all the cross-section measurement points are snapped to the line between the two river bank points. Then, the snapped measurements are interpolated over 31 points that are created based on the method described above. For all cross-sections in the river are now 31 cross-section points available and the distance to the next cross-section is known. With this information all the created bathymetry points are filled with linearly interpolated bathymetry data. For example, looking in the river direction (s) and starting at the one river side, the interpolated cross-section points along the river bank (row 1 in n-direction) are interpolated over all created bathymetry points along the river bank (row 1) and the interpolated cross-section points, row 2 just next to the river bank, are interpolated over all created bathymetry points at row 2 in n-direction, and so on until all 31 rows are completed. All the create bathymetry points are interpolated to a 1 x 1 layer with the natural neighbour method to make it compatible with the DTM.

This method gives a fairly accurate method to interpolate the bathymetry. Though, one could notify that the thalweg, the line through the deepest point in s-direction of the river, switches from one to the other side. This method fades out the deep section of the river on one side and fades in the deep section on the other side. Furthermore, one could notify that in case of multiple bends between two cross-sections, the deep point of the bathymetry is the inside of the bend instead of the expected outside of the bend. A method to improve this is to assume a thalweg instead of the centreline. On the other side, one could say that the data is not accurate enough, since with more cross-sections, of at least one per bend, both methods work.

Appendix D

Measure Selection

This appendix provides more information about the measures presented in Section 5.1. The information is presented per measure in the following order: measure information, conceptualization, effects, benefits, reasoning for not selecting.

D.1 Flood Forecasting & Early Warning

A popular reactive measure in the Philippines is flood forecasting and early warning. Both the Pampanga and Angat River have their flood forecasting and warning centre. For the Pampanga River this is executed by the *Pampanga River Flood Forecasting and Warning Centre* (PRFFWC) which is an office centre of the weather institute *Philippine Atmospheric, Geophysical & Astronomical Services Administration* (PAGASA). This office, with experience since 1973, has the task to monitor the rivers, to forecast and provide flood warnings for the Pampanga River Basin. For example, in 2011 the centre made 58 Flood Advisories and Bulletins for 10 storm events. Another task of the centre is to provide trainings, lectures and presentations to improve flood disaster awareness and for other related topics.

The dam operations are the most important factor for the flood forecasting and warning system for the Angat River, therefore the two agencies regulating the three dams have implemented this flood forecasting and warning system since 1983. In 2009, a large project started with the help of a large Japanese consultancy team (Nippon Koei, 2010) called “Flood Forecasting and Warning System for Dam Operation”. The system provides flood warnings for the downstream area of the Angat and Bustos Dam almost up to the border of the municipality of Calumpit.

The measure is not selected for further modelling, since it is reactive and does not reduce the flood. Furthermore, the quality of the flood forecasting and warning systems is high and many studies have been done in the Philippines on this topic. The advices given are to expand the cooperation between the two offices to improve dam operation, see “Improved Dam Operation” in Subsection 5.2.1, and to include the coastal municipalities in the warning area of the flood forecasting and early warning system.

D.2 Convert fishpens into fishponds

The municipal engineer of Hagonoy notified that several fishponds are converted into fishpens. The difference between a fishpond and a fishpen is that instead of levees, nets are used to prevent the fish from swimming away. This conversion has an effect on the hydraulics of the system, since flow through fishpens is possible, while flow through fishponds is limited. The roughness of the system decreases a lot due to the more or less open connection with the bay, making the reduction in the amplitude of the tidal wave less. This causes a larger tidal range in the upstream area. Furthermore, the bottom of the former fishponds could more easily be eroded, creating an even more open system. This also has a positive effect on the fluvial floods, since the drainage to the bay becomes easier. By converting the fishpens into fishponds again, the roughness is increased again and the process is counteracted.

This measure is *not* selected for modelling since the effects are small and negative towards the fluvial floods. When the area is prevented from upstream floods, the conversion of fishpens into fishponds becomes most beneficial.

D.3 Dredging

A common applied technology in flood mitigation is regular dredging of the rivers. Dredging enhanced the flow capacity of the river, which normally contributes to a reduction in floods upstream of the dredging activities, even up to the extent that solely dredging could prevent floods in the area. This statement is widely believed in the study area and is popular with politicians who are eager to win votes for the next election cycle and prefer short-term attractive solutions. They pretend that they can solve the floods without making sacrifices. One should take into account that dredging is a temporary solution, since maintenance dredging is required to keep the river in its unbalanced state. This measure is especially included to show that dredging does not solve the flood.

Still, dredging could have a positive effect on the reduction of the fluvial floods in the study area, because the flow capacity of the rivers is increased. However, one should take into account that dredging could also have a negative influence on river deltas, because it can even increase the tidal floods. When the river is dredged and the spill is moved out of the river, the average depth over the cross-sectional area is increased. This increase in depth leads to a higher wave celerity and a lower tidal velocity. The tidal range is controlled by the size of the river mouth. Meaning that the tidal range could be increased by, for example, removing a sill near the mouth. Both effects are pointing to a decrease in friction due to deepening. This decrease in friction could lead to either a reduction in the tidal damping or an (further) amplification of the tidal wave leading to higher tidal water levels in the study area (Savenije, 2012), see Figure D.1 for an example of the Scheldt. (Cai, 2012) The current tidal amplification of the Pampanga River is around one.

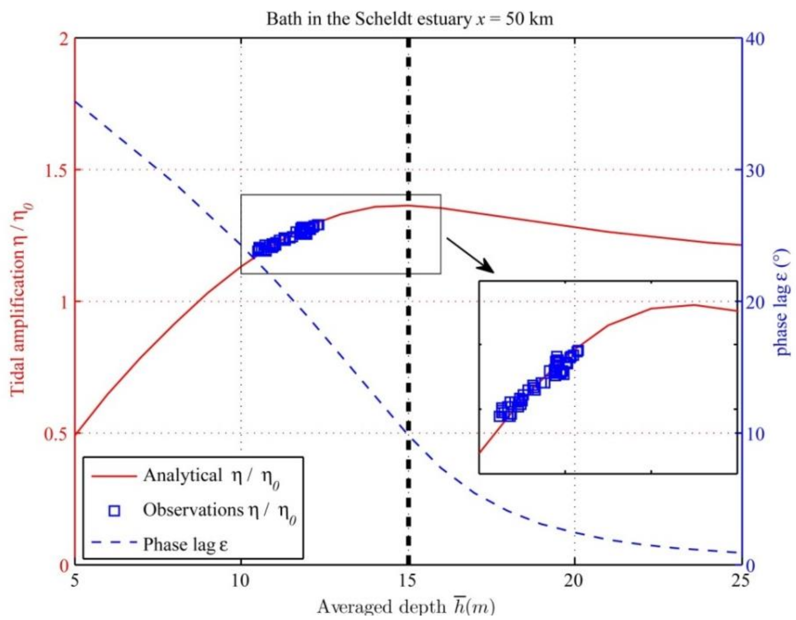

Figure D.1 – Example for relation between tidal amplification and average depth for the Scheldt Estuary (Cai, 2014b)

That dredging does not solve the floods in the Pampanga River Delta shows Figure D.2. In this example, all the main rivers are dredged with 3 m over the full width. The effect of this measure is still visible in the model results. The dredging activities are causing an improved flow at the upstream side of the study area causing a water level reduction in the Pampanga and Angat River of around 30 to 35 cm. Between these two rivers, the water reductions reduces from + 20 cm to a negative effect in downstream urban area of Hagonoy and Paombong of - 10 cm. On the west side of the Pampanga River the negative effect is even larger to an extend of - 40 cm. The dredging activities are causing a reduced damping of the tidal peak. For example, the water level due to the storm surge enhanced tide at 27 September 2011 14:00 increases with 15 cm in the area between the Pampanga River and Labangan channel. The benefits of this measure are only 11 million pesos over the study area, see Appendix E for the calculation method. This measures is *not* selected as potential measure because the effect is minimal for fluvial floods and negative for the tidal floods.

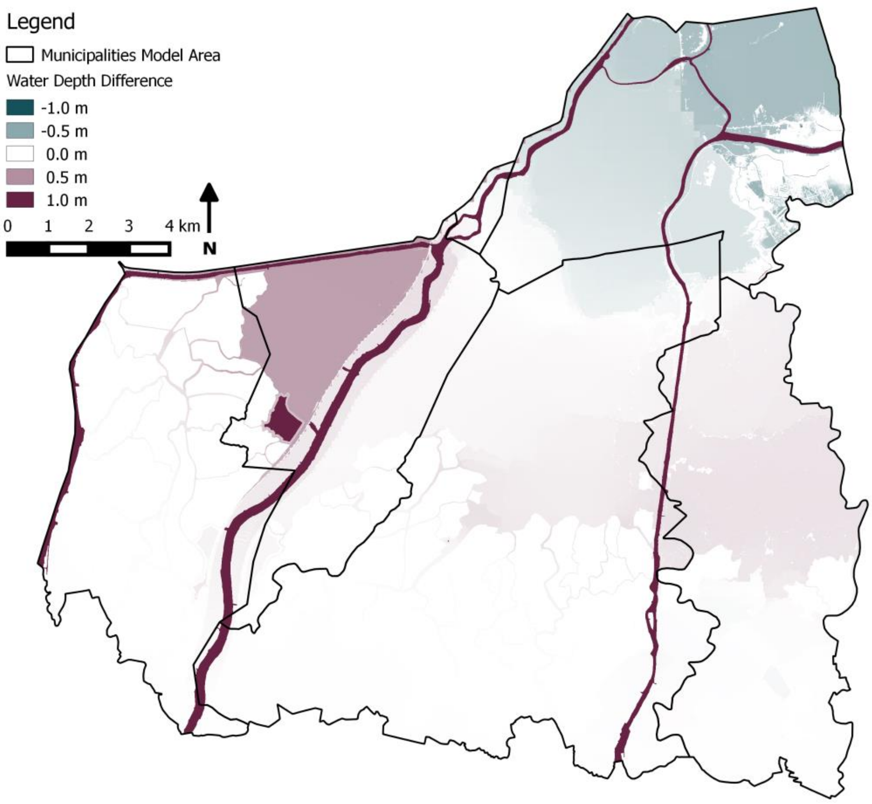

Figure D.2 – Water depth difference for the dredging scenario

D.4 Measures on small scale

An option for the government is to stimulate people to invest in building a stone house (on piles). There are various financial structures, like loans or funds that lower the threshold for starting these kind of projects. Building a house of stone with multiple floors increases the strength of the house and the option to start living on the second floor during floods. In Sagada, Masantol, 50% of the people are not evacuated but simple live on the second floor or the roof of their house. This is a safe way of dealing with floods, if the inhabitants have food security up to three weeks. Building houses on piles is another common method used to deal with floods and is already often applied in the study area.

Other measures, which start on small scale, deal with waste and education in a proper way. The government could set up a solid waste management system, e.g. the municipality of

Macabebe desires to set up such a system in the next 10 year, but the people need to take the effort to use this kind of system. A proper solid waste management system could solve the multiple clogged creeks and small channels. The same holds for education that needs to be implemented properly, to make it effective. Both measures are for the long run. These measures are *not* selected because the flood reduction is small or negligible.

D.5 Tidal Flood Control Hagonoy

The municipal engineer of Hagonoy (2014b) proposed a combination of a revetment dike or sheet pile walls along the coast and four tidal gates. The tidal gates have a width of 56, 65, 75 and 50 m for number one to four respectively, as seen in Figure D.3. The purpose of this tidal flood control system is to prevent the tide going into the urban area of Hagonoy, while the rivers can still function as drainage network for the fluvial floods. The costs of this project should be smaller than the costs of the Hydroterre Consultants Project (2008) according to the municipal engineer. But, the Tidal Flood Control Project of Hagonoy does not complete close all the rivers connecting the bay with the centre of Hagonoy, meaning that this project only results in a small reduction of the tidal amplitude when the flood gates are operational.

Figure D.3 – Tidal Flood Control system for the municipality of Hagonoy with 4 flood gates and a revetment dike or sheet pile wall (Hagonoy, 2014b)

In the tidal flood control scenario, the water still enters the area behind the flood gates by using other channels or even by the setback of the tide via the Hagonoy River or the side entrance via the Labangan Channel according to the model. The flood gates do have the effect of reducing the tidal peak, but the effect is limited without complete or almost complete closure of the area behind the gates due to this setback. Therefore, this measure is not selected as potential measure. Nevertheless, this measure could be combined with smart road elevation measure or PDDP phase II project to get the desired effect.

D.6 Hagonoy Flood Mitigation

In 2008, Hydroterre Consultants, made a report for the municipality of Hagonoy including a mitigation project on both fluvial and tidal floods. Hydroterre consultants proposed two schemes with as main objective to make the city flood prove. Both schemes contain 6 tidal gate units. for both schemes. For example in the first scheme, one tidal gate is placed at the crossing of Pampanga and Hagonoy River, two gates are placed along the Labangan Channel and one is located downstream of the urban area of Hagonoy in the Hagonoy River, see Figure D.4. Both schemes assume that either a revetment is constructed or that the flood only travels through the channels. For scheme one, the municipality of Hagonoy needs to cooperate with the municipality of Calumpit. (Hydroterre Consultants, 2008)

The costs of such schemes are high, approximately 1.5 billion pesos or 25 million euros respectively, since the same number of tidal gates needs to be constructed. The maintenance is around 1.3 million pesos or 22 thousand euro per year. (Hydroterre Consultants, 2008) The benefits for such schemes are almost zero in the future scenario due to two reasons. First, only one tidal gate structure is placed in the Hagonoy river, while there are multiple connections leading to Hagonoy through the crisscross of the channels between the Pampanga River and Labangan Channel. Second, in the future scenario the floods bypasses the gates with overland flow without the construction of embankments like in the PDDP project due to the large subsidence rates. Therefore, this measure is not selected as potential measure.

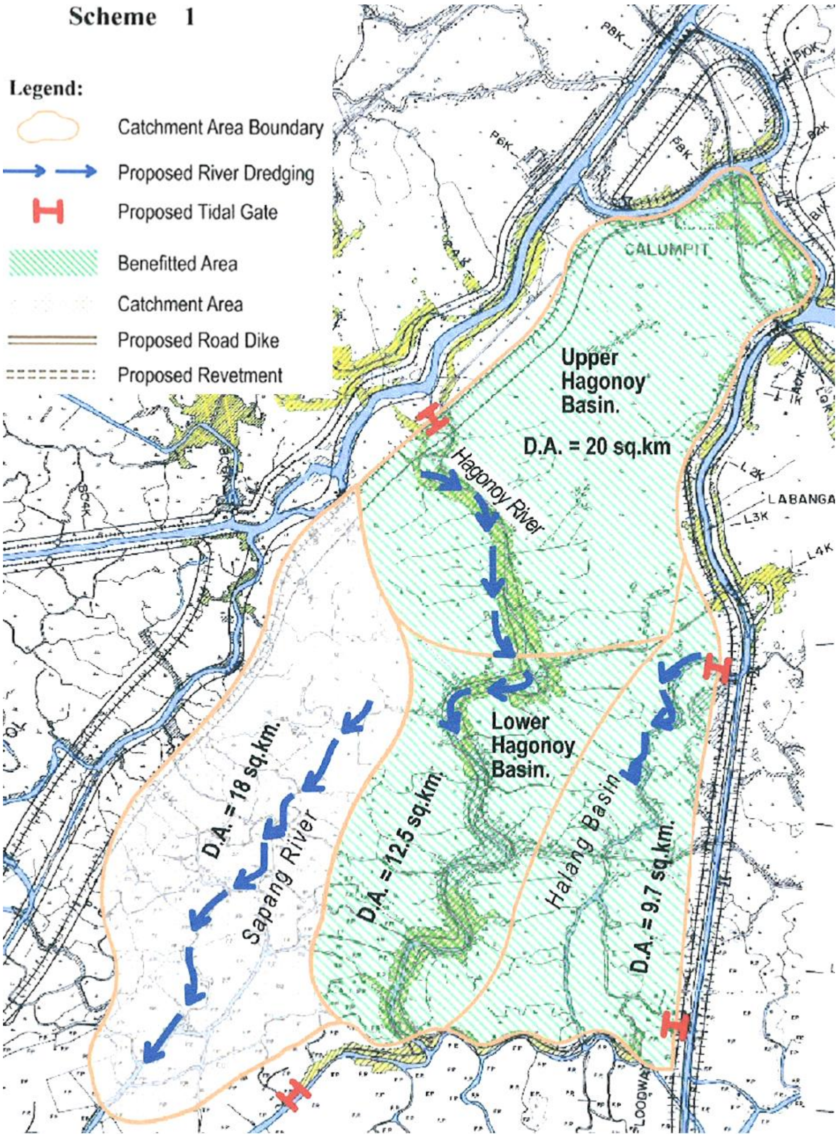

Figure D.4 – Two proposed schemes of Hydroterre Consultants (2008) for flood mitigation of the urban area of the municipality of Hagonoy; scheme one called "Control inflow from Pampanga River" (Hydroterre Consultants, 2008)

D.7 Community-Based Disaster Risk Reduction Program

Gaillard (2008) states that there should be more focus on improving the strength of the social networks and livelihoods in countries with regular floods. The Filipinos have a large capacity to adjust their lives to the regular happening floods. For example, they are used to save food or to save money in case of a large flood event. Even if the problems get to heavy, people could rely on their relatives, friends, small businesses or neighbours for loans or food (called “pagkikipagkapwa”). Another example of the importance of the community is that it is a duty to help in case of emergency preventive actions, for example raising a fishpond dike or securing furniture (called “bayanihan”).

The measure proposed by Gaillard (2008) is to change from the current reactive disaster management system to Community-Based Disaster Risk Reduction (CBDRR) program. The goal of the CBDRR program is to involve the local inhabitants in the process to create a (more) sustainable way of dealing with the current floods. By involving the local inhabitants, the needs are clearer for the government and the situation of the inhabitants can be improved by self-developed and culturally acceptable ways of dealing with floods. An example of an activity in the CBDRR program is participatory 3D mapping, which creates a platform for the community to discuss their situation in a visible way. (Cadag & Gaillard, 2010) Another activity, in line with this participatory 3D mapping, would be making a model available on barangay level, e.g. with a touchtable, to create more awareness of the current situation or to involve the inhabitants in the creation of potential (structural) measures. The latter could also contribute to create more political support for potential measures to reduce floods. This measure is not selected in this study, but is advised to implement since it enhances awareness of floods, political support and acceptability of the by the, in the end, government implemented measures.

D.8 Smart Road Elevations

Main roads are generally higher than the surrounding area, because road elevations are a common method to deal with increasing floods in the study area. The roads can be used for evacuation during high floods and prevent disruption of the society during low floods. The measure is popular with the local and regional politicians eager to put their names on the project. Surprisingly, road constructions are even accepted when it results in a wall in front of the house that has to be climbed with a ladder. The budget available for road elevations is higher than the budget available for civil projects despite the projects coming from the same department, namely Department of Public Works and Highways (DPWH). Combining the acceptability of road elevation, the favour of the politicians and the budget coming along, the road elevation projects have a much higher feasibility than normal civil works.

This report proposes road elevation at smart locations to make the road act as levee. This requires higher roads than normal, resulting in a higher elevation differences between the houses and the roads. On the other hand, the main advantages of this measure compared with a real levee are that there is another budget source and no households need to be relocated. By choosing more roads to be elevated, ring levees can be created that prevent the surrounded area from flooding. The height of the roads could be based on the preferred optimum between the difference in elevation with the surrounding area and the return period of the flood. In this report, the roads are designed on the typhoon Pedring 2011.

The effects of smart road elevations are shown based on one example of applying these road elevations. The PDDP project phase II shows another example, which could also be achieved with smart road elevations, see Section D.10. In the example scenario, the multiple roads along the Labangan Channel, Pampanga, Old Pampanga, and Bagbag River are elevated to reduce the floods downstream of the levees, see Figure D.5. In this example, the roads are elevated up to 2.5 m above MSL which is not enough to prevent overflow. The average heightening is 1.2 m and the maximum heightening is 2.9 m. This is a high, but common road elevation in Pampanga and Bulacan.

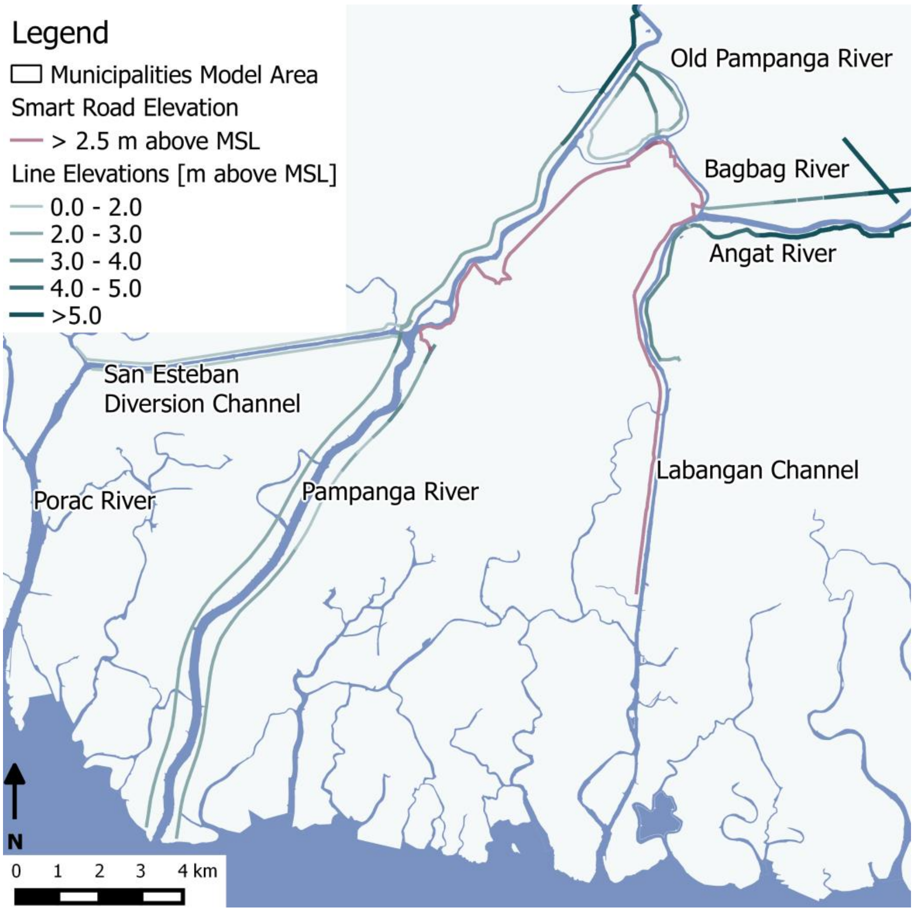

Figure D.5 – Smart Road Elevation starting at the Pampanga Delta Development Project and ending at the end of the road or small levee along Labangan Channel via the Old Pampanga and Bagbag River with a height of 2.5 m above MSL

The example scenario cause a water level reduction behind the elevated roads of around 40 cm at the upstream area and 25 cm at the downstream area, see . These effects are measured in the area between the Pampanga River and the Labangan Channel. The reduction increases for road elevations up to 4.0 m with water depth reductions of around 80 cm in the upstream area and a minimum of around 35 cm in the downstream area. The implemented smart road elevations are also offering protection against the storm surge. For example, the water level due to the storm surge enhance tide between the Pampanga River and Labangan channel at 27 September 2011 between 14:00 and 16:00 decreases with 25 cm in the downstream area and even 40 cm in the upstream area.

The counter effect of this measure is that the road elevation has a negative effect on the municipality of Paombong with a water level rise up to 15 cm and on the municipality of Calumpit with a water level rise up to 75 cm. In other words, the road elevation scenarios are moving the problem to another area. Therefore, the benefits remain small with a maximum of 60 million euros for all smart road elevation scenarios, see Appendix E for the calculation method. The example scenario has damage reduction of only 4 million euros. Therefore, the smart road elevations are not selected as potential measure. Nevertheless, this measure could be combined with tidal flood control gates to get the desired effect, see Section D.5.

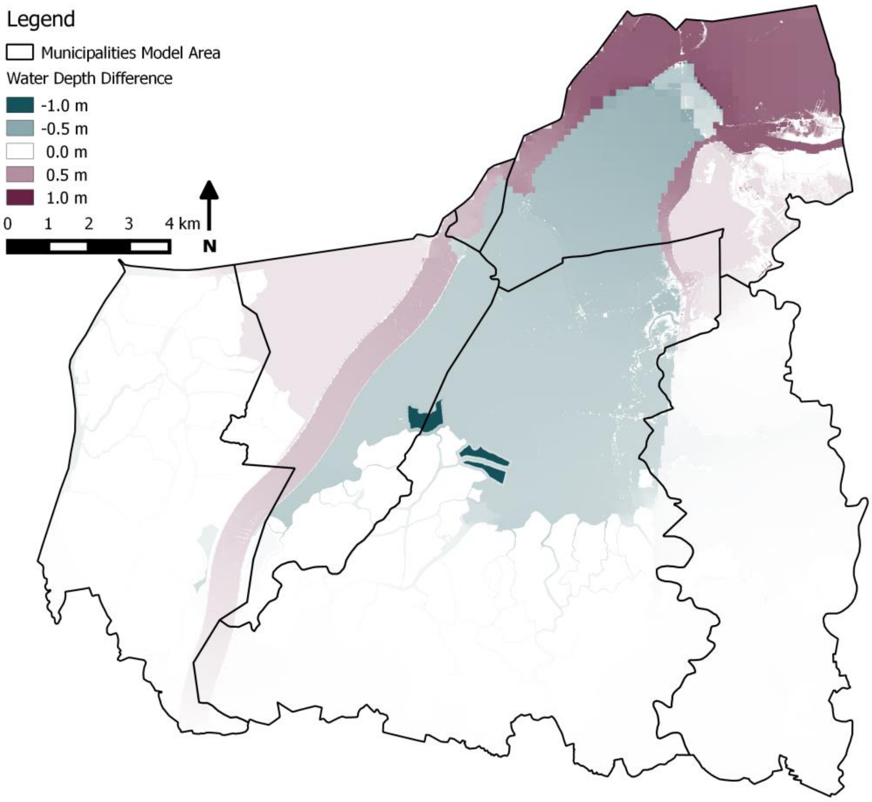

Figure D.6 – Water depth difference for the smart road elevation scenario with road elevations up to 2.5 m above MSL along the Pampanga River and Labangan Channel

D.9 Reforestation

Deforestation is a common cause for the increase of peak flows which results in more frequent river floods. Timber extraction is usually performed with heavy machinery that compact the top soil layer causing a drastic reduction in the soil infiltration capacities (Ziegler et al., 2006) and increase the generation of surface run-off. Paap (2014) showed that peak flows become 83% higher, if a healthy forest with an infiltration capacity of 50 mm/h is converted into pasture with an infiltration capacity of 5 mm/h and lower evaporation rates. The higher stream flows cause higher water levels in the river. The main problem for the Pampanga River Delta during storm events is that these higher water levels cannot be handled by the current river bed which increases the flood depth.

Reforestation is one of the mid to longer term solutions implemented by the provincial and national government. According to Paap (2014), reforestation does not solve the problem immediately, since the structure of the soil is heavily damaged and the root system of the trees is gone. However, the soil does not need to recover completely to reduce the increased surface run-off. If the infiltration capacity is restored to 20 mm/h, the surface run-off is almost reduced to its initial value. The time for this restoration is in the order of years and depends on the environment conditions and the type of trees planted. (Zimmermann et al., 2010)

The effect of reforestation could be large for the study area and is worth investigating. However, since reforestation is only applicable upstream in the catchment, it requires a different study area. Without a detailed study about the upstream area, the peak discharge reduction is hardly quantifiable. Therefore, this measure is not selected for further investigation.

D.10 Pampanga Delta Development Project – Phase II and III

After finishing multiple dike project in the seventies, the largest project undertaken in the downstream part of the Pampanga River Delta was initiated by JICA, which is a part of the Japanese Government. In 1982, JICA initiated the Pampanga Delta Development Project (PDDP) in cooperation with the Department of Public Works and Highways (DPWH). One of the development goals of this project is to improve the flood conditions in the Candaba Swamp and the coastal area of the Pampanga River Delta. The project consists of three phases to protect the Pampanga River Delta: two phases protect the Pampanga and Angat River Delta and one phase to convert the Candaba Swamp into a retention basin. The first phase of the project was finished in 1993 and included the widening of the Pampanga River between the river mouth and Masantol, see Figure D.7. The capacity of this part of the river with a length of 14 km was improved from 500 to 4,300 m^3/s. The dikes on both side of the channel were designed to deal with fluvial floods with a return period of 20 years. The total cost was around 2.9 billion pesos (around 50 million euros). (JICA et al., 1982, 2011)

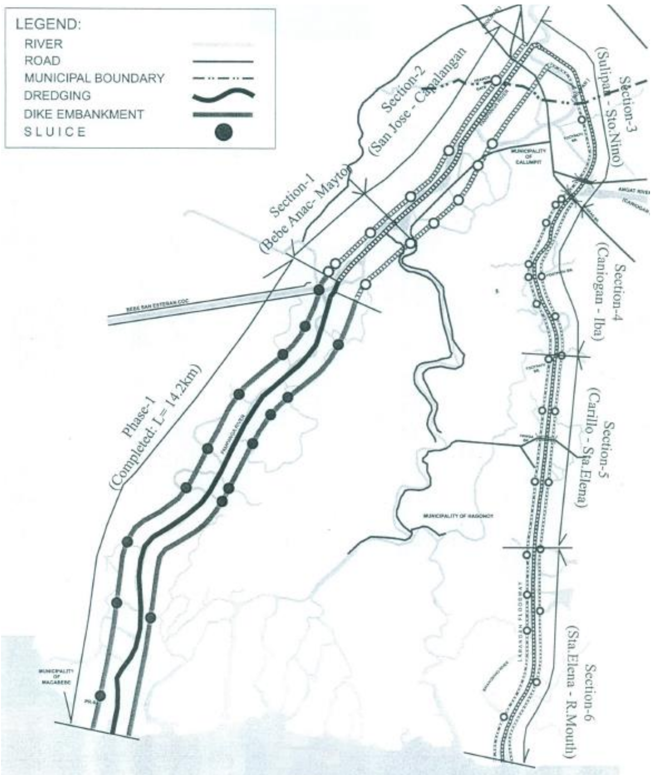

Figure D.7 – PDDP Phase I and II including new levees and channels (Nippon Koei, 2003)

After the first phase was finished, none of the other phases were started, due to strong opposition of the local community, including the local government. The main reason was that the second phase required a relocation of 6,700 houses to be able to construct the dikes along the rivers. (JICA et al., 2011) On top of that, even if the government was willing to help, it was often not able to resettle the illegal occupants, due to an insufficient budget. (Rodolfo, 2006)

The objective of the third phase of the PDDP is to construct a dike along the South Candaba Swamp to make a controlled detention pond with control structures. Because, this is the third phase of the PDDP detailed plans are not yet available. The effect can be large if the large area is controlled wisely. To get an impression, the flooded area of this part of the swamp during Pedring 2011 is around 100 km^2 according to the satellite image taken on 3 October (NOAH, 2011), see Figure 3.10. However, the Candaba Swamp plays a key role in the natural environment, especially for migratory birds during the wet season, and changing this environment could have a large effect on both animals and vegetation. (JICA et al., 2011)

D.10.1 Effects of PDDP Phase I

The levees as presented in Figure D.7 are elevated high enough in the model to withstand the fluvial flood. This does not prevent the area behind the levees from flooding because the tide can still enter the area via the many small channels along the coast. In the most upstream part of Calumpit below the Old Pampanga and Bagbag river, the flood is prevented. In the remaining area between the two main rivers, the flood is reduced from 1.1 m to 0.4 m. On the other side of the Labangan Channel, the water level is reduced from 25 cm upstream to 40 cm downstream.

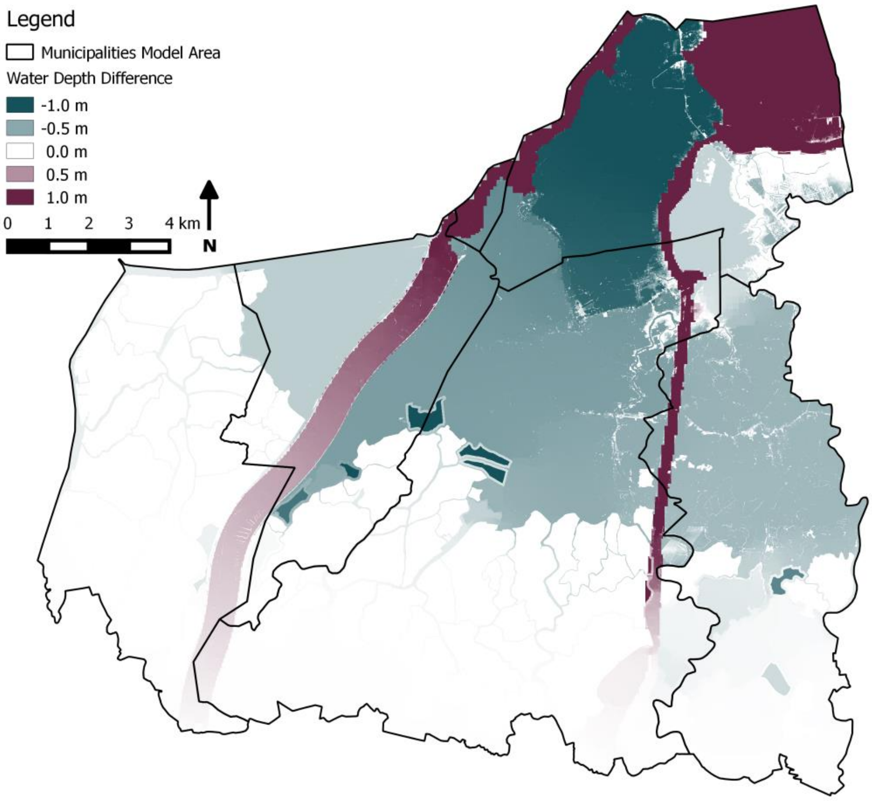

Figure D.8 – Water depth difference for the PDDP phase II scenario

The levees until the Labangan Channel Mouth are offering a increases the protection against the storm surge compared to the smart road elevation project, see Figure D.5. For example, the water level due to the storm surge enhance tide between the Pampanga River and Labangan channel at 27 September 2011 between 14:00 and 16:00 decreases with 45 cm in the downstream area and even 75 cm in the upstream area. The effect is almost double compared to the smaller smart road elevation projects.

The flood gate, constructed in the connection between the Pampanga River and San Esteban Diversion channel, reduces the water level at the west side of the Pampanga River with 30 cm. But, the area is not protected against the (storm surge enhanced) tidal floods. To protect the city centres, it is advised to include maintenance of the San Esteban Diversion dike in the PDDP project phase II for the 50 year subsidence scenario.

For a rough design of the height of the levees for the PDDP project phase II, the following data could be used. Pampanga River Dike needs to be raised at Sulipan to 4.1 m and at the diversion point with the diversion channel to 2.5 m above mean sea level (MSL). The Labangan Channel needs to be raised at Bagbag river to 4.2 m above MSL. At the Labangan Channel mouth, an levee height of around 2.2 m is sufficient. This measurement requires the highest levees due to the closure of the Old Pampanga River, the closure of the connection to the San Esteban Diversion Channel, the movement of the East Pampanga River Dike in Calumpit and the extension of the Labangan Channel Dike to the channel mouth.

The PDDP Phase II projected is not selected as potential measures, because the benefit-cost ratio is low and the similar project *combination of measures* offers more potential. The main reason is that this measure does not prevent tidal floods in the area which reduces the benefits of this expensive measure drastically. The benefits over the study area are 290 million pesos during typhoon Pedring, see Appendix E for the calculation method. The costs are estimated at 8.8 billion pesos according to JICA (2011).

D.10.2 Effects of PDDP Phase II

The sensitivity of a proper use of the Candaba Swamp as retention basin is high. This could be based on the three modelled scenarios for the Candaba Swamp. The key features of these scenarios are:

1. elevation downstream of 4.5 m above MSL;
2. elevation downstream of 6.0 m above MSL plus a gap at the largest creek flowing out of the swamp;
3. elevation downstream of 6.0 m above MSL without a gap at the largest creek flowing out of the swamp.

To make fully use of the retention basin, it should be used at the flood of the peak. To make this effective for every event, the inflow or outflow of the retention basin need to be regulated in the same way as the dams in the Angat River should be regulated. Then, for every event the flood could be reduced.

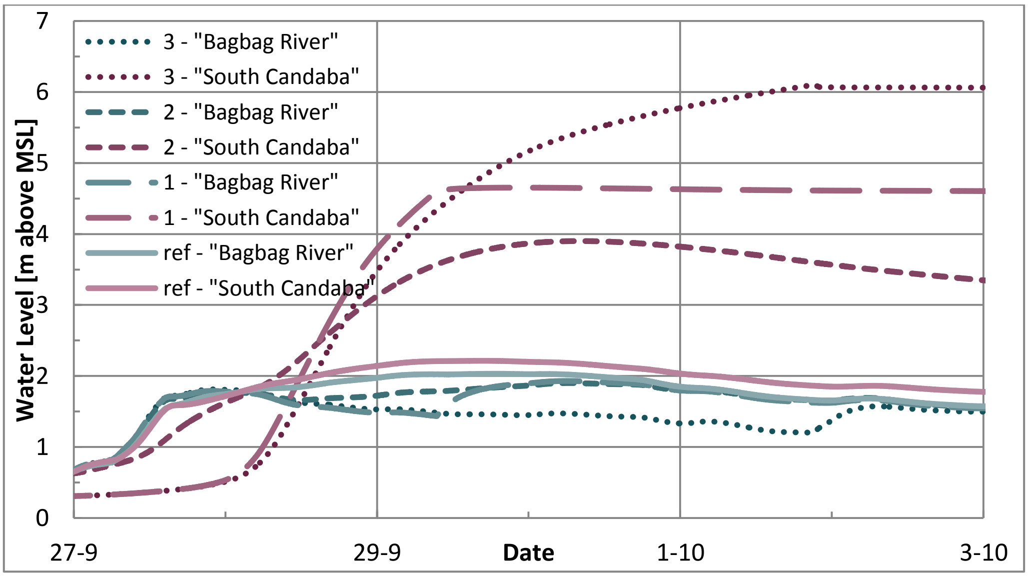

Figure D.9 – Water levels in the South Candaba Swamp and the Bagbag River at the crossing with Angat River for the three retention basin scenarios of PDDP phase III and the reference scenario.

By applying the retention basin the water levels increased largely in the retention basin, see Figure D.9. All the scenarios show a reduction in the water level. The first scenarios do not capture the full peak of the event, still resulting in a large peak before the event. The second scenario show that the swamp is already filled by the storm surge and is too open since not the complete reservoir volume is used. The last scenario is the best and shows that the peak of the event is topped off and for the measurement point the storm surge wave becomes dominant due to the fast response of the rivers. Nevertheless, the water level remains high due to the discharges from Angat and Pampanga River, causing floods downstream.

An argument against the Candaba Swamp as retention basin is the large increase in the flood extent including populated area, see Figure D.10. Even compared to the PDDP phase II measurement with the largest water level rise due to the construction of the levees, the Candaba Swamp has a large increase in flood extent.

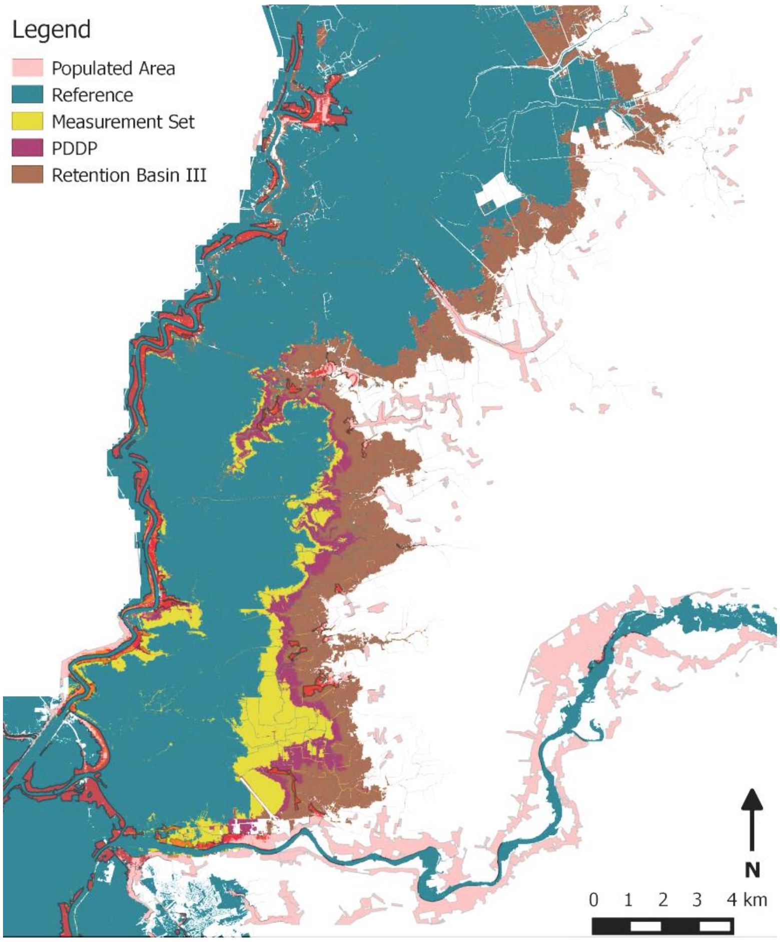

Figure D.10 - Comparison of the flood extent on the Candaba Swamp for the reference, combination of measures, PDDP phase II and retention basin no. 3 scenario; the light yellow area is the populated area.

To conclude, this measure is *not* selected because the benefits are small compared to the cost of the project, the sensitivity of the operation and environmental impact on the Candaba Swamp. The benefit of the best retention basin scenario is only 57 million pesos for Pedring 2011, see Appendix E for the calculation method. An increase in water depth in the Candaba Swamp could have adverse environmental effects. For example, the bird migration could be hindered when the flood does not subside fast enough. The sensitivity of the operation is high and active operation is required.

D.11 Building with nature

Mangroves can help in the protection against the tidal floods, because mangroves offer an open barrier for waves, storm surge and tide, especially along the coastline. For the tide, the mangroves increase the roughness, causing a reduction in the tidal amplitude. This measure is not selected since the main effect is on wind waves instead of floods and the benefits could not be estimated with the 3Di model. Nevertheless, this project is worth investigating to restore the environment.

Between 1994 and 2005, 77% of the mangroves disappeared in the provinces Bulacan and Pampanga (JICA et al., 2011) The removal of mangrove forests along the coast does not only cause further tidal intrusion, but also erosion of the coastline. The waves directly hit the coastline, causing a large increase in impact on for example the fishpond dikes. One measure to restore the mangroves is to build small dams made of prunings in front of the coastline. During the tidal movement, sediment settles down behind the small dams creating a basis for natural mangrove reforestation and other nature recovery. If the process is accelerated by dredging other muddy parts of the bay, the coastline could be restored in five years. The involvement of the local inhabitants or government is important for this kind of structures, since they need to maintain or even upgrade the dams to make the project work. (Didde, 2014)

Appendix E

Cost – benefit analysis

The underlying assumptions and calculations for the cost – benefit analysis, which is presented in section 5.4 and summarized in Table E.1, are explained in detail in this appendix.

Table E.1 – Results of the Cost – Benefit analysis for the five modelled potential measures plus the creation of fishpond flood channel from Hagonoy towards the coastline; the benefits only represent the damage reduction of typhoons with a return period of 10 years; the benefit-cost ratio is determined over 50 year; the last column represents the flood prevention of the city centres of Macabebe and Masantol (City Centres M&M)

Measure	Initial Cost [mil ₱]	Yearly Cost [mil ₱/yr]	Benefit [mil ₱/yr]	Benefit-Cost ratio [-]	City Centres M&M
Improve Dam Operation	-	1	18	21	
Fishpond dike height regulation	707	75	113	1.1	
Fishpond Flood Channel	84	25	-	-	
Levee maintenance	-	17	-	-	Yes
Groundwater extraction regulation	-	145	35	0.2	
Combination of measures	5,411	66	95	0.3	Yes

E.1 Cost

The cost are estimated by making use of unit prices, see Table E.2. For all the structural projects, the costs are multiplied with 1.15 to include the costs for equipment and general items, 1.1 to include contingency and 1.2 to include consulting services and project administration. (Nippon Koei, 2003)

Table E.2 – Unit Price for Cost Analysis (Nippon Koei, 2003; Hagonoy Water District, personal communication, May 21, 2014)

Type	Price	Unit
Embankment	521	₱/m^3
Road	8,000	₱/m^3
Large Tidal Gate	107,442,000	₱/structure
Small Tidal Gate	17,935,000	₱/structure
Bridge	104,606	₱/m^2
Resettlement Area	1,000,000	₱/ha
Lot Acquisition	6,310,000	₱/ha
Employee	420,000	₱/employee/year
Change to Bulk Water Supply Project	12.85	₱/m^3

The assumption is made that two extra employees are needed for the *improved operation* of the dams in the Angat River Basin. It could be expected that some additional training is needed. A training is not included in the estimated cost.

The *fishpond dike height regulation* and *fishpond flood channel* could be divided into two types of expenses: structures and wages. First, the current fishponds need to be adapted to just above spring tide level. The volume change is estimated for all the fishpond dikes by making use of the difference between current height and new height, assumed as 1.25 above mean sea level. The cost are estimated by making use of the unit price of embankment. It is expected that the measure requires continuous maintenance due to man-made and natural changes in the fishpond dikes which means that every 10 years the project needs to be renewed. Second, one employee needs to be assigned for all the municipalities to regulate and monitor the height of the fishpond dikes and to monitor if the gates of the participating fishponds are opened during a fluvial flood.

For the *groundwater extraction regulation* measure, the current water use is estimated for the five municipalities by extrapolating the total capacity of the pumps in Hagonoy. The total capacity is 280 lps. The assumption is made that the pumps are using 80% of the capacity and that at least 50% of the total extraction needs to be replaced by another water source.

The cost of the *combination of measures* could be distinguished in embankment, roads, bridges and gates, improved dam operation and resettlement and lot acquisition. The volume needed for the embankment is estimated based on the increase in elevation compared with the 50 year scenario minus the road thickness of 0.2 m for local roads to 0.3 m for provincial roads. Next to the road elevation, the system is closed with 26 small and 11 large gates with bridges. For creating enough space for the construction of the elevated roads, it is assumed that on average 5 m is needed on both sides of the roads that needs to be acquired and relocated. Lastly, the costs of the improved dam operation are included. The yearly costs for maintenance are assumed to be the same as 50% of the initial costs spread over 50 year.

E.2 Benefit

The benefit of the measures are based on the change in the flood damage by using the land use, increase in water depth and flooded area. The increase in flooded area is estimated by extracting the flood extent at the start of the event from the maximum flood extent during the typhoon. The flood extent is multiplied by a land use dependent constant for estimating the damage costs. For the non-populated area, it is assumed that the damage does not change when the water depth increases. For the populated area, it is assumed that the flood damage linearly increases with the increase in water depth.

The damage constants of the non-populated area are estimated at 60,000 ₱/ha for cultivated area; 45,000 ₱/ha for fishponds and 135,000 ₱/ha for populated area. The constant for the populated area is calibrated on the detailed damage report of Municipality of Hagonoy. The damage constant are assumed to be constant over the modelling period of 50 year. (Hagonoy, 2012; Provincial Disaster Risk Reduction Management Office Bulacan, 2014)

E.3 Present value

The present value of the cost and benefit are calculated to make them comparable. The yearly cost and benefits are discounted to the present value by dividing them by the interest of 4%. The yearly benefits are calculated based on a return period of ten year of typhoon Pedring. The benefit-cost ratio can then be calculated by dividing the benefit through the initial and yearly costs.