Development of a Delft3D model for the Ayeyarwady delta, Myanmar

Part II: Data acquisition and model validation

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Disclaimer

Abstract

This report presents the development of a Delft3D model for the water system in the Ayeyarwady delta, located in the south of Myanmar. Problems in this delta are flooding and salt intrusion into the rivers and delta of Myanmar.

Understanding these phenomena is important since floods affect the safety of the people and salt intrusion impacts the quality of irrigation and drinking water. The main objective of this project is to develop a Delft3D model that can serve as a starting point for modelling these processes. This report will present the development of a 2D tidal model and validation of this model with locally measured data. Also, some preliminary results will be presented for 3D salt intrusion computations.

This report is the second part of the development of a Delft3D model. It is an addition to the work by Attema (2013), who developed the initial Delft3D model for the Ayeyarwady delta.

Acknowledgements

The development of this model partly took place in Yangon, Myanmar, and partly in Delft, the Netherlands. During my stay in Myanmar I've been accommodated by the governmental department of DWIR, for which I am really grateful. They provided me with workspace and assisted me in acquiring data and getting around in Myanmar. Special thanks go out to Mr. Sein Lwin and Mr. Htet Zaw Oo of DWIR, who both contributed greatly to my stay in Myanmar. Also, the governmental departments of DMH and MoAI are thanked for their cooperation and providing their data. To conclude, I would like to thank Deltares, and mr Tjitte Nauta in particular, for giving me the chance to work on this project in Myanmar.

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List of abbreviations

Throughout the report, various abbreviations are used frequently. This list gives an overview of the most frequently used abbreviations and their meaning:

DMH = Department of Meteorology and Hydrology, department of MoT, Myanmar

DWIR = Directorate of Water resources and Improvement of River systems, department of MoT, Myanmar

MoAI = Ministry of Agriculture and Irrigation, Myanmar

MoT = Ministry of Transport, Myanmar

MoU = Memorandum of Understanding

MPA = Myanma Port Authority, department of MoT, Myanmar

1 Introduction

This report is a part of the development of an Integrated Water Resources Management (IWRM) plan for Myanmar. It presents the results of the development of a Delft3D-model for the Ayeyarwady delta area, which focuses on modelling the intrusion of saline water in this region. Section 1.1 delineates the background of this report, and the circumstances under which the development of the model took place. In section 1.2 and 1.3 the current state of the model is discussed, as well as the objectives for this particular study. Section 1.4 gives an introduction into the modelling software used, Delft3D. Section 1.5 outlines the rest of the report.

1.1 IWRM in Myanmar

Myanmar has been virtually sealed off from the rest of the world for several decades. In the last three years, since 2011, the country has opened its borders and numerous cooperation with western countries have been started up. In the field of water resources management, a Memorandum of Understanding (MoU) has been signed between the Dutch Ministry of Infrastructure and Environment and the Myanmar Ministry of Transport. The goal is to develop an IWRM plan for Myanmar, to address its water-related issues. In turn, the Dutch government has asked Deltares and TU Delft to perform a preliminary study for the development of this IWRM plan. This preliminary study consists of the collection of relevant data on water resources and of the development of several computer models, which can be used as tools in the further development of the IWRM. The computer models and their current use are:

- Delft3D, focused on the hydrodynamics of the coast and Ayeyarwady delta
- Sobek, a 1D model for the Ayeyarwady and Chindwin rivers
- Ribasim, a water allocation model for the Ayeyarwady and Chindwin river catchments

It must be emphasized that these computer models can be useful tools when used appropriately, by skilled engineers. However, setting up and calibrating such a model requires a thorough understanding of the underlying physical processes and, next to that, a relevant dataset to calibrate the model with.

1.2 Problem definition

The Ayeyarwady delta area is one of the main agricultural areas of Myanmar, but in the dry season saline water protrudes far into the delta area, making river water unusable for irrigation- and drinking water purposes.

To protect this area, it is important to understand the phenomenon described above: when the main drivers of salt intrusion are understood, and how this impacts the river flow, it can be modelled using Delft3D.

As a first step, a Delft3D model of the Ayeyarwady delta has been developed at Deltares during the last three months of 2013. The following steps have been made in the development of this model over the past months:

- A model grid for the area of interest, the Ayeyarwady delta and the Andaman Sea, has been designed.
- The bathymetry of the Andaman Sea, the Ayeyarwady delta and its river branches, has been generated and coupled to the model grid.
- 2D-tidal conditions have been applied to this model, and simulated water levels have been compared with available observed water levels.
- A preliminary 3D-run to assess salt intrusion into Ayeyarwady delta has been carried out.

The current state of the model and the dataset that was used to develop the existing hydrodynamic model will be discussed in more detail in Chapter 3. However, during the preliminary 3D-run, it was found that the model output for salt intrusion did not match with the measured salinities in the delta area.

To model the salt intrusion correctly, data is required to correctly describe: river discharge, river bathymetry, measured salinity, sediment types in the Ayeyarwady and river outline. The question is whether this data is actually collected in the Ayeyarwady delta and if so, how this can be used to improve the model.

One aspect that could be estimated with the help from one of the other developed models is the river discharge, with the 1D-model Sobek. However, a link between the Sobek-model and the Delft3D-model has not yet been achieved.

1.3 Study objectives

The main objective of this research is to improve the Delft3D model, but since that objective is too broad, the objective has to be demarcated more clearly. From the problem definition, the following objectives can be distilled:

1. Data acquisition for salt intrusion model (and tidal model)

To properly calibrate the model and to assess model performance, more data is required. It will be part of the research to acquire this data and to process it, so it can be used to improve the model. This is mainly the case for the salt intrusion model, since the data deficiencies are the largest here. However, if there are water level observations available, that weren't used in the development of the 2D tidal model, these will be used to validate the 2D tidal model.

Moreover, this research can show how the data that is collected by Myanmar governmental departments can be used to set up and validate a numerical model. Next to that, with this research, possible gaps in knowledge and data collection can be identified, which can be used to improve the way in which data is collected.

Next to that, an inventory will be made of the available data.

2. Improvement tidal model where possible

If additional observation data indicates that the 2D tidal model needs improvement, this will be assessed and improved where it is possible.

3. Set up and calibrate a 3D model of the Ayeyarwady delta, to model salt intrusion

As has been stated before, a good understanding of salt intrusion in the Ayeyarwady delta is desirable, since salt intrusion influence water quality in the delta, which may have consequences for irrigation and drinking water quality. The preliminary run that has been done will be analyzed, and from that starting point, improvements are likely to be made.

4. Off-line link with SOBEK

An off-link with Sobek is to be established, to incorporate the results of the Sobek model into the Delft3D model. These results will be input into the Delft3D-model as upstream boundary conditions at the different river branches of the Ayeyarwady.

5. Sharing knowledge with Myanmar counterparts at the Directorate of Water resources and Improvement of River systems (DWIR) and the Department of Meteorology and Hydrology (DMH)

Not only should the model be developed, but the knowledge about this model should be shared with the Myanmar counterparts as well, so they can learn how the model works. This understanding is needed to independently interpret and analyze the results, and eventually develop the models by themselves.

1.4 Delft3D-FLOW modelling software

The Delft3D-FLOW software package is used in the project to model the Andaman Sea and the Ayeyarwady delta. This is a numerical modelling program, which can be used to simulate non-steady flows. Delft3D-FLOW incorporates the effects of tides, winds, air pressure, density differences (due to salinity and temperature), waves, turbulence (from a simple constant to the k-ε model) and drying and flooding. Delft3D-Flow covers curvilinear and rectilinear grids, full 2D and 3D hydrostatic flow, advection-diffusion module for salinity, temperature and substances, density driven flows, float (drogue) tracking, meteorological influences, on-line visualization and wave-current interaction. Delft3D-Flow also includes 3D flow and turbulence modelling. Delft3D allows you to simulate the interaction of water, sediment, ecology and water quality in time and space. (Deltares (2011))

Delft3D numerically solves the Navier-Stokes equation for incompressible free surface flow, under the shallow water- and Boussinesq-approximation. The N-S equations are discretized in both time and space, and yield an unique solution given a certain set of initial and boundary conditions. In space, the domain can be discretized using either a curvilinear or spherical grid. The grid should be orthogonal and well-structured. Delft3D utilizes the grid, for efficiency reasons, in a staggered approach, meaning that the velocities and water levels are not calculated at the same location. For the time discretization Delft3D uses the alternate direction implicit or ADI method. This method has the advantage that it imposes no time constraint for the stability of the model (unconditionally stable), although it is recommended, for accuracy reasons, to have a Courant-Friedrichs-Lewy number lower than 10.

The 2D tidal simulations in Delft3D are computed by using the depth averaged Navier-Stokes equations, meaning that the mass and momentum are integrated over the depth, so from the bed level to the water surface level. In the 3D simulations Delft3D uses a multi-layer model, which has the 3D Reynolds averaged Navier-Stokes equations as starting point.

For the transport of matter Delft3D uses a convection-diffusion equation, which is important in order to model the salt intrusion correctly. This convection-diffusion equation is influenced by user specified parameters and by the turbulence closure model.

There are several turbulence closure models available in the vertical direction, but for this project the k-epsilon model is used, since it is the most advanced model available in Delft3D. The turbulence closure model is used to calculate the eddy viscosity. This is needed because the space discretization is often too coarse and the time step too big to capture all the turbulent processes.

1.5 Report Outline

In this section, the rest of the report is outlined:

In chapter 2 the Ayeyarwady delta is described.

In Chapter 3 the preliminary dataset is discussed and possible improvements are identified

In Chapter 4, the additionally acquired data is presented and discussed.

In Chapter 5 the improvement of the 2D-tidal model is discussed.

In Chapter 6, the results of the 3D-salinity model are discussed.

In Chapter 7, concluding remarks and recommendations for future research and data acquisition are presented.

2 The Ayeyarwady delta

This chapter will give an overview of the system that is the Ayeyarwady delta. To do so, three different subsystems are defined, to give a proper description of the delta. These three subsystems are, ranked from up- to downstream:

- The Ayeyarwady river
- The Ayeyarwady delta
- The Andaman Sea and the Gulf of Murtaban

The distinction is made to provide a complete overview of the deltaic system, since the three subsystems mentioned above all have a great influence on how the delta evolves and it is necessary to describe all three simultaneously to get an understanding of the physical processes that are being modelled. For these subsystems, the relevant features are discussed. Besides that, this chapter should provide background about the geographical and physical features of the Ayeyarwady delta, such as the monsoonal climate. These features can help to understand the dynamic behaviour of the delta.

2.1 The Ayeyarwady river

The description of the Ayeyarwady river system is partly based on the report by Commandeur (2013).

The Ayeyarwady rises at 5900 m above sea level to the east of the eastern Himalayan syntaxis. It flows through the Central Burma Basin which stretches approximately 1100 km north-south between the Indo-Burma Ranges, including Rakhine (Arakan) Mountains to the west and the Sino-Burma Highlands, including the Shan Plateau, to the east (Bender, 1983; Varga, 1997). The Ayeyarwady catchment can be seen from Figure 2.1.

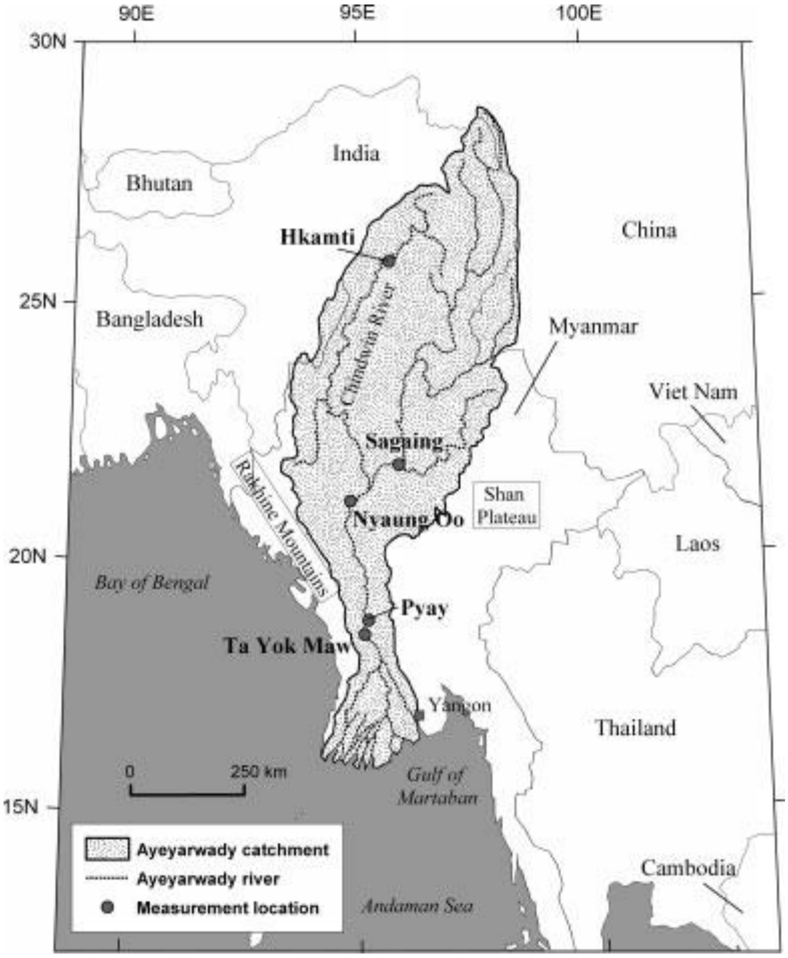

Figure 2.1: The catchment of the Ayeyarwady River. Figure taken from Furuichi et al (2009)

The Central Burma Basin was formed as fore-arc and backarc basins associated with subduction of the Indian Plate beneath the Eurasian (or Indochina) Plate (Bender, 1983). Most of the Central Burma Basin lies on thick sediments (23 000 m at the maximum) that have been deposited under marine and fluvial conditions throughout the Cenozoic. The basin contains alluvial plains, low-fold mountains and volcanic hills (Furuichi et al, 2009).

The Ayeyarwady River has a total length of 2000 km and predominantly flows from North to South, discharging into the Andaman sea. The Ayeyarwady river has a drainage area of $0.413*10^6$ km^2 (Bender 1983). It starts in Myanmar at the confluence of the Nmai Hka and the Mali Hka streams. The north-western branch of the Ayeyarwady is known as the Chindwin river. The confluence of the Ayeyarwady and the Chindwin rivers occurs north of Naung Oo, which can also be seen in Figure 2.1.

2.1.1 Discharge and Monsoonal climate

With a total annual discharge of 440 ± 48 km^3/yr, which was calculated as a 10-year average annual discharge by Robinson et al (2007), the Ayeyarwady ranks as the 4th biggest river in South-East Asia, in terms of annual discharge, after the Yangtze, Mekong and Ganges-Brahmaputra. (Milliman and Meade, 1983)

Myanmar has three distinct seasonal periods, being the dry, wet and cold (winter) season. The climate of Myanmar is strongly influenced by the south-west monsoon, which causes heavy rainfall in the period from May till October. According to data from the Department of Meteorology and Hydrology (DMH), 92% of the annual rainfall actually falls in this period. The cold season spans from November to January, and shows a general drop in temperatures across the country. Finally, the dry season encompasses the months of February till April, with rising temperatures across the country.

Precipitation in Myanmar is influenced by its topography: the north-south alignments of the valleys and ranges divide the country into alternate zones of heavy and scanty precipitation. In the deltaic area the annual rainfall is around 2030 mm to 3050 mm, 2030 to 3810 in the north, even more in Rakhine and Tanintharyi State up to 5080 mm. The dryer areas receive only 760mm, which are situated in the central region of Myanmar. The spatial distribution of annual rainfall can be seen in Figure 2.2.

As a direct consequence of the monsoonal climate, the discharge of the Ayeyarwady River also shows a great seasonal variability. As was stated before, the monsoon 92% of the annual rainfall is recorded in the period from May-October. Subsequently, 81% of the annual discharge is discharged during the period July-October.

This large variability in discharge is one of the main reasons why saline intrusion can occur in the Ayeyarwady delta. During the month of March, which is believed to be the most critical month when it comes to saline intrusion into the branches of the Ayeyarwady delta, the average discharge at Pyay is 2613 ± 550 m^3/s. Pyay, formerly known as Prome, lies 90km north of the starting point of the delta. The month of March is the most critical, as the discharges have been low for the preceding months and together with February, the month of March has the lowest average discharge throughout the year. Because of the high temperatures during this month, the glaciers of the Himalayas will start to melt, and therefore there is a rise in discharges during the month of April, which counteracts the saline intrusion.

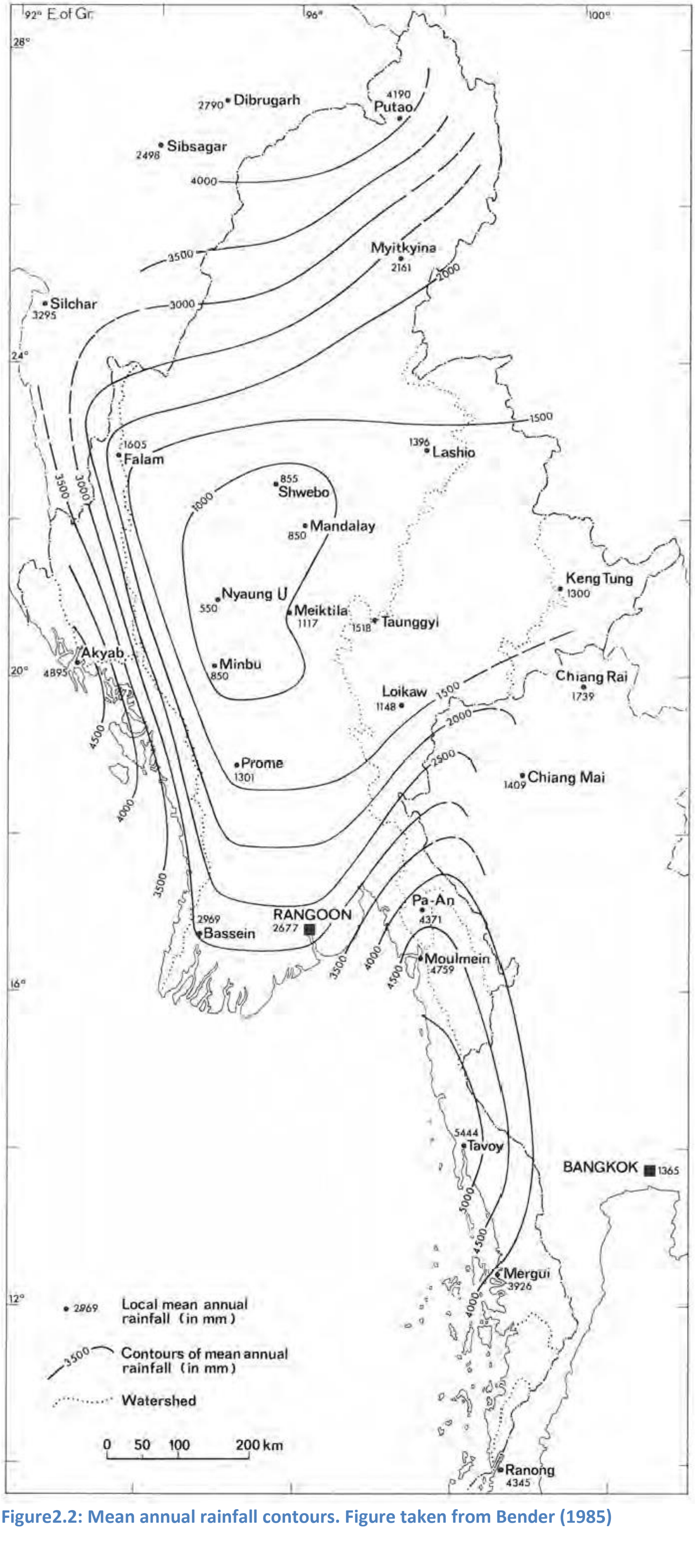

Figure2.2: Mean annual rainfall contours. Figure taken from Bender (1985)

2.1.2 Sediment properties

The Irrawaddy catchment rock types include Cretaceous to mid-Cenozoic flysch of the western Indo-Burman ranges, Eocene- Miocene and Quaternary sediments of the Myanmar Central Basin, and the Late Precambrian and Cretaceous-Eocene metamorphic, basic, and ultrabasic rocks of the eastern syntaxis of the Himalayas. Currently 56% of the Ayeyarwady catchment is forested (IUCN, 2003), and the catchment is unusual in that forest cover is predominantly in steep, mountainous areas on the periphery of the catchment while much of the central and southern lowlands are situated in a rainshadow region and hence are covered by comparatively arid shrubland and savanna (Blasco et al, 1996).

The Ayeyarwady transports 364 ± 60 MT/yr of sediment load. This number is based on the 19th-century data that was collected by Gordon (1883), and that has been reanalysed recently by Robinson et al (2007).

As with the river discharge, there is a strong seasonal variation: more than 90% of the annual sediment load is delivered during a part of the monsoon season, between mid-June and mid-November.

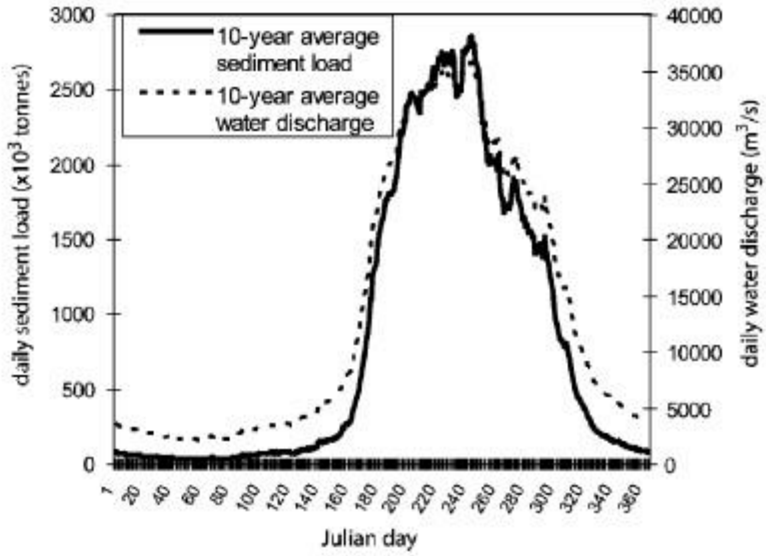

Figure 2.3: Sediment load at Pyay

Based on the amount of suspended sediments passing Mandalay (estimated to be 32 MT/year), Stamp (1940) suggested that 229 MT/year (88%) of the suspended sediment load at Ta Yok Maw is derived from the Central Dry Zone (he called it the ‘dry belt’), and that the Chindwin River carries about half of this (109 MT/year) and the other half (no less than 120 MT/year) comes from the non-perennial streams of the Central Dry Zone.

2.2 The Ayeyarwady delta

The Ayeyarwady delta starts at Kyangin, 380 km from the Gulf of Martaban, at an altitude of 15 m, and extends over an area of 31 000 km between the confining hills of the 1300 m Arakan Yomas in the west and the 900 m Bago Yomas in the east. The river fans out from its braided channel above Kyangin in a complex of tidal creeks which drain into the gulf by 12 major mouths extending over 260 km of coast.(Figure 2.4) The climate, topography and silty clay soils of the delta are ideal for rice production, and extensive development of paddylands has taken place since the 1850's (Brichieri-Colombi, 1987).

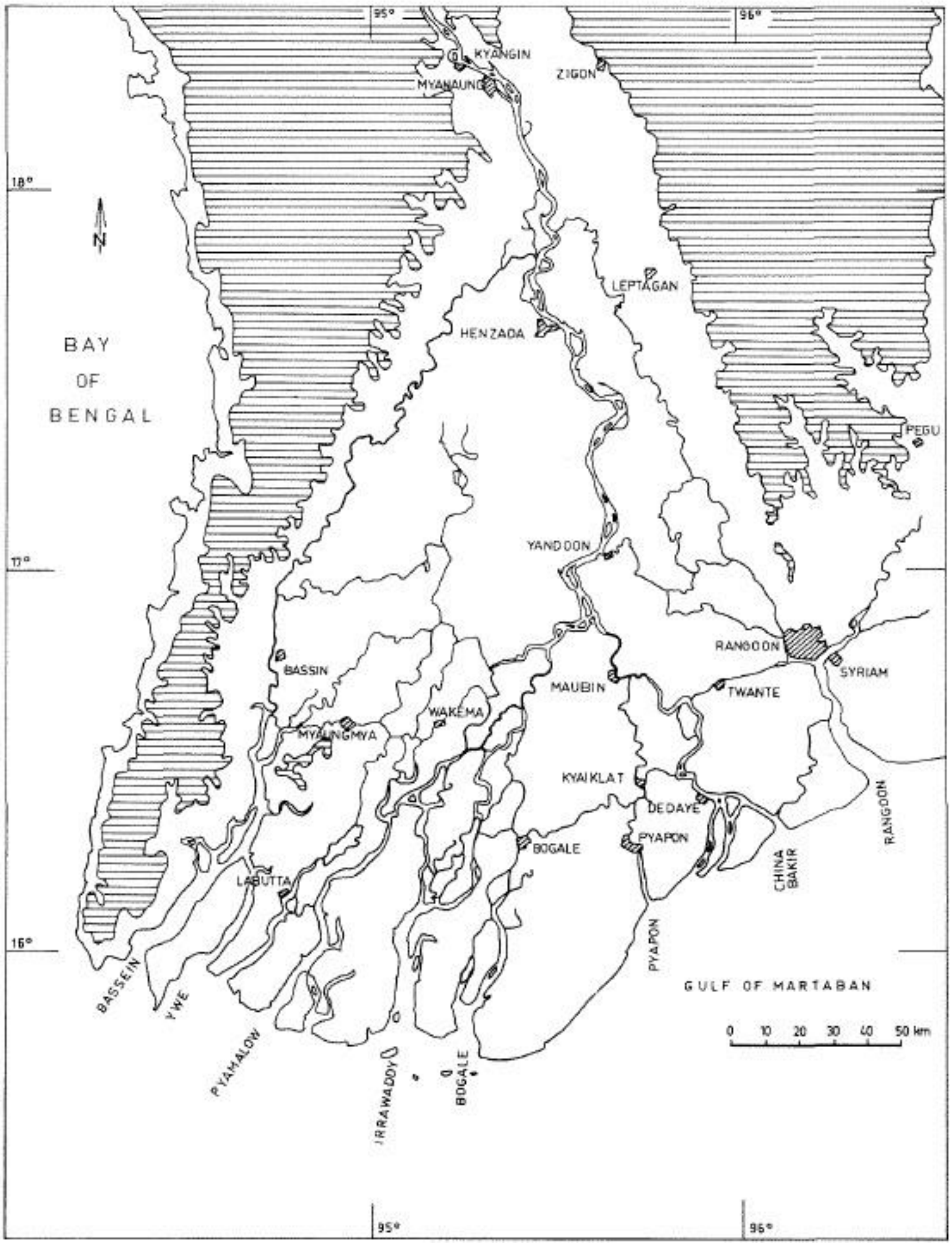

Figure 2.4: Ayeyarwady Delta, taken from Brichieri-Colombi (1987)

Fundamentally, deltas are regressive/prograding systems and estuaries are transgressive coastal depositional systems, according to the sedimentological definitions proposed by Boyd et al. (1992) and Dalrymple et al. (1992). In this definition, the Ayeyarwady is definitely a delta.

Until Kyangin, the Ayeyarwady can be seen (roughly) as a river with one main braided channel. Afterwards, it fans out into a complex of different rivers. These rivers are listed below, and are ranked from west to east. The river names displayed in Figure 2.4, are (in some cases) not up-to-date. As a reference, the new and old river names are both listed. In the remainder of the report, the current river names are used:

River (current name)	River (names from Figure 2.4)
Pathein/Ngawun	Bassein
Ywe	Ywe
Pyarmalot	Pyamalow
Ayeyarwady	Irrawaddy
Bogalay	Bogale
Pyapon	Pyapon
Toe	China Bakir
Yangon/Hlaing	Rangoon

Table 2.1: Previous and current names of river branches in the Ayeyarwady delta

In Myanmar, the Yangon and Pathein rivers are also called Hlaing and Ngawun River, respectively. These names are used by different governmental institutions (such as the ministry of Irrigation). However, in the remainder of this report, these rivers will be called Yangon and Pathein River, for reasons of clarity.

2.3 The Andaman Sea and the Gulf of Murtaban

The Andaman Sea, located south of the Ayeyarwady delta, is a part of the Indian Ocean. It is surrounded by the Bay of Bengal in the West and it narrows to form the straits of Malacca in the South-east. In between the Bay of Bengal and the Andaman Sea lie the Andaman and Nicobar islands, which are of volcanic origin. This resulted in rapid changes in the water depths there, with only a small depth of about 500 m in the area separating the two water bodies (Rizal et al. (2012)), allowing the tidal motion in the Andaman Sea to develop almost independently from the Bay of Bengal, and thus can the tidal systems be addressed separately.

The characteristics of the tidal systems are influenced by the position of the amphidromic point. The nearest amphidromic point influencing the tidal characteristic in the Andaman Sea is located south-east of Sri Lanka. This results in a counter clockwise tidal progression through the Bay of Bengal and the Andaman Sea. Within the vicinity of the amphidromic point small tidal amplitudes exist, but amplitudes are amplified in the Andaman Sea(Van Holland et al. (2000)).

The tidal type that is dominating in the Andaman Sea is the semi-diurnal tide, with the M_2-component as its main contributor. Other important contributors are the S_2-component, the N_2-component and to a lesser extent the O_1 and K_1 components. All semi-diurnal tides enter the Andaman Sea in a similar pattern, they enter from the Indian Ocean and bifurcate towards the strait of Malacca and the coastline of Myanmar, with increasing amplitudes in the shallow continental waters (Rizal et al. 2012)).

However not only the amplitude is amplified in the shallower areas in the northern part of the Andaman Sea, also the tidal currents associated with the M_2-component are stronger there. The currents of the M_2 semi-diurnal tide in these shallower continental waters are more than 10 cm/s oriented normal to the coastline, whereas it is less than 5 cm/s in the deeper parts.

Rao et al (2004), concluded, based on sediment distribution patterns in the Andaman Sea, that most of the suspended sediment that is transported by the Ayeyarwady and its branches, is transported eastward along the coast into the Gulf of Martaban where it is subjected to re-suspension by tidal currents before deposition in the gulf or transport to the deep sea through the Martaban Canyon. The dominant mechanism for the dispersal of suspended sediment is the tidal currents. Hence, it is expected that there is an alongshore current along the Myanmar coast in the direction of the Gulf of Martaban.

3 Preliminary dataset and model

This chapter will give an overview of the dataset which was available for the setup of the Delft3D-model that was developed by Attema (2013). The goal of this chapter is to identify where this dataset should be supplemented with local measured data. After these have been identified, the Chapters 4 and 5 will discuss the additional data that has been acquired and how this data is used to improve the Delft3D model.

It must be stressed that assessing numerical model performance with locally measured data is important to check the validity of the model results: numerical models can run and generate results, but checking these results with measured data is needed to see if reality is represented adequately by the numerical model.

3.1 Overview of different datasets

The datasets mentioned in this section have been used to set up the 2D-tidal model of the Andaman Sea and Ayeyarwady delta and the preliminary simulations of the salinity intrusion in the Ayeyarwady delta. Their benefits and drawbacks, with respect to this model, will be discussed in this section. The datasets that were used to set up the model are:

- IHO database for tidal data
- GEBCO 08 database for bathymetry
- ACE 2 for topography of land area
- Google Earth for land boundaries of model

The IHO tidal database and the GEBCO 08 bathymetry database will be discussed in Section 3.2 and 3.3, respectively. The latter two datasets, the ACE 2 dataset and the information obtained from Google Earth will be combined in section 3.4, since the main importance of these two datasets for the current research is to get an idea of the river outlines.

3.2 IHO tidal database

The International Hydrological Organisation (IHO) tidal data bank consists of over 4000 tide gauge stations scattered all around the globe, most of which are in coastal regions. For each of these tide gauge stations, a number of tidal constituents are available. The tidal signal for the different gauge stations can be obtained through DelftDashboard, a modelling tool of Deltares, in which the different constituents can be specified. From these constituents, a tidal signal can be obtained. For the Andaman Sea, data from 6 tidal gauge stations is available; which can be seen in Figure 3.1.

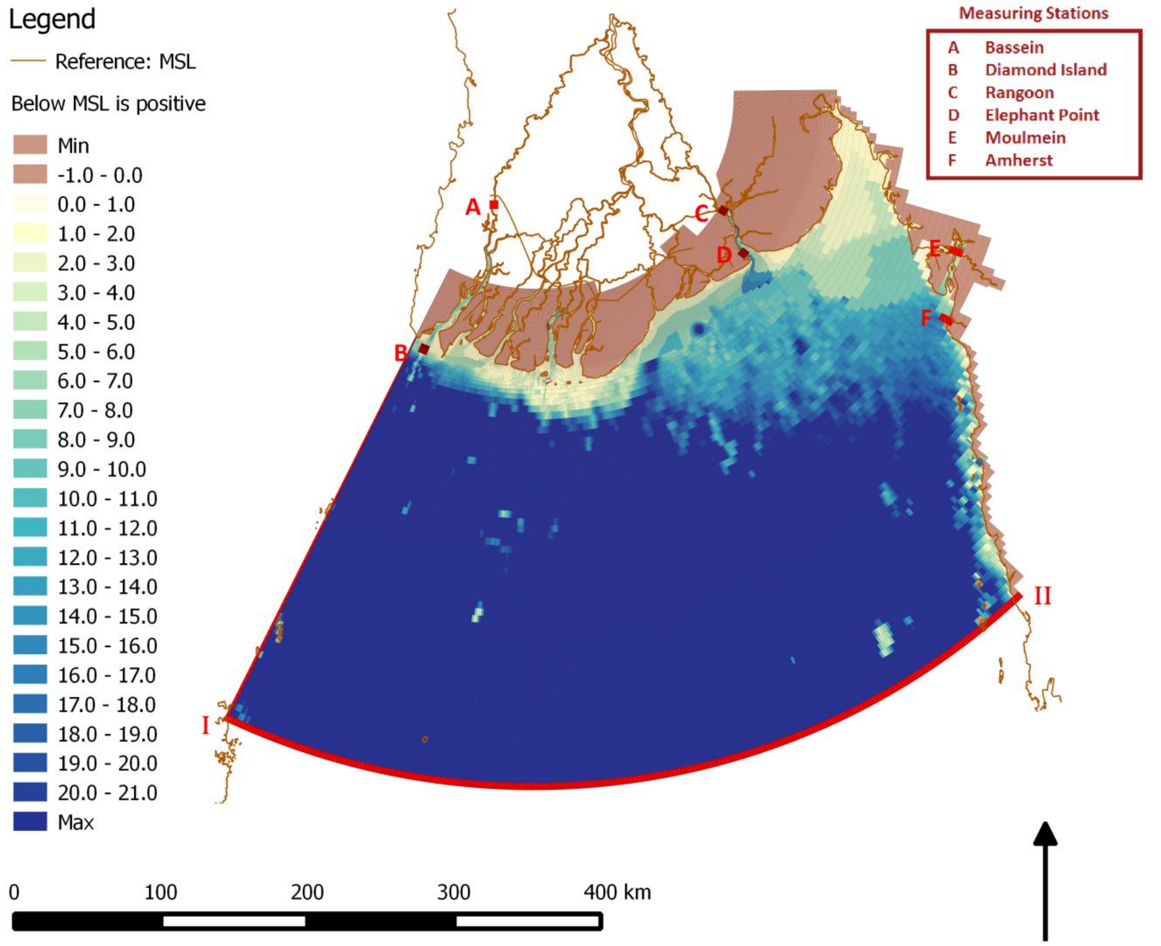

Figure 3.1: IHO tidal stations

The major drawback of the IHO tidal database is the fact that hardly any metadata is available for this database. During the process of setting up the 2D-tidal model of the Andaman Sea, it was assumed that the IHO tidal stations provide a virtual tidal signal, based on a set of estimated components. However, the paper by Qi (2012) suggests that this database consists of actual measurements. Hence, it still remains unclear how well the water levels provided by the IHO database correspond with the actual water levels.

Together with the lack of metadata, there is one other big drawback when using this dataset. The number of tidal stations that actually lie in the area of interest, being the Ayeyarwady delta, is limited. Only the tidal stations at Elephant Point, Rangoon and Diamond Island can be considered to be in the area of interest. The tidal stations at Amherst and Moulmein lie on the Eastern side of the Andaman Sea and the station at Bassein is so far upstream of the river mouth that it is questionable how well the tidal motion can be represented by the model at this location. Besides that, Diamond Island and Bassein are located quite close to the Western boundary of the model, which might influence the model outcome for these two locations.

So, this dataset can provide a good estimate of overall behaviour of the tidal model in the Andaman Sea. However, the performance of the model in the Ayeyarwady delta, where it should be able to give a representation of the tidal motion, remains to be seen. To check this, additional data should be acquired and the model should be verified with this data. This will be discussed in more detail in Chapter 4.

3.3 GEBCO 08 bathymetry map

The starting point for the model bathymetry was the GEBCO 08 (General Bathymetry Chart of the Ocean, version 2008) map. The GEBCO 08 bathymetry map is a database with a spatial resolution of 30 arc-seconds (approximately 900 meters) and has relatively good bathymetry data for the deeper parts of the oceans, but the dataset becomes less reliable for the shallower parts. For this reason, the bathymetry was augmented in the shallower parts of the Andaman Sea, close to the shore, by using nautical charts where available. Besides, the bathymetry of the Yangon and Pathein rivers were obtained from navigational charts, for the harbours of Yangon and Pathein respectively.

The details of the specific nautical charts used can be found in the report by Attema (2013).

For the other rivers, a uniform depth of 5m (for all rivers) was chosen. By obtaining additional bathymetric charts, actual data can be applied rather than the assumed depth. The adjustment in the bathymetry in the rivers is expected to improve the model outcome. However, the number of grid cells across the river branches is very limited, even close to the coast. Hence, the effect of improving the model bathymetry may well not be that significant.

3.4 Model outline and topography

The starting point for the model is the land boundaries and river outlines of the coastline, delta and rivers of Myanmar. The coastline has been obtained from a global data set and the river outlines have been extracted from Google Earth by drawing polygons of the outlines by hand. However, these river outlines might vary from season to season and may shift, hereby influencing the cross-sectional area of the river. Since it is uncertain when the satellite images of Google Earth were taken, this adds to the uncertainty in the model and model outcome. In Section 2.1, it was already stated that the majority of the discharge occurs during the monsoonal period (81% of the annual discharge is discharged during the period July-October) and it is likely, that in this period, the river cross-section will also increase. If the satellite images were collected during the monsoonal period, the river cross-section will be overestimated, and hence, will lead to an underestimation of the flow velocities.

One of the goals when setting up the model was making it suitable for the mapping of floods due to storm surges. To make sure the model can be used to model floods, it is required that the topography of the Ayeyarwady delta is also fed as input into the model. The topography is obtained from the ACE 2 database and has a spatial resolution of 3 arc-seconds, approximately 90 meter. The accuracy of this dataset is around 1 meter for most of topography in the Ayeyarwady delta according to the quality matrix of the data.

3.5 Preliminary model setup

The general settings of the model, as it was set up by Attema (2013) at Deltares, are presented here. These settings will be used as a starting point for further model development. During the process of developing the model, adjustments have been made to these initial settings. When changes have been made, a motivation for these changes will be given. This is mainly described in Chapters 0 & 5.

Timeframe

The period selected for comparing the model results to the IHO tidal measurements is the month of March in the year 2010. The reason for selecting the month March has already been explained in Section 2.1.1, which is the fact that it is the most critical month for salt intrusion. The year 2010 is selected because of the availability of UHSLC tidal measurement data for the measuring station of Moulmein (Attema, 2013).

Processes

The physical process that is further investigated by using Delft3D is salinity intrusion, as has been mentioned before. The intrusion of salt water also influences the flow pattern in the river. However, two remarks should be made about this:

1. The impact of salinity intrusion on the flow pattern is caused by the density difference (mainly) between the salt and the fresh water. This is an effect that needs to be studied in 3D. If it is studied in 2D, the focus will mainly lie on the dispersion of salt throughout the system, which, in itself, can be quite useful to investigate whether the flow pattern is represented adequately in 2D.
2. When vertical accelerations at the freshwater-saline front are large compared to the horizontal velocity gradients in the x/y direction, this might lead to a non-hydrostatic situation. However, one of the assumptions underlying the Delft3D code is the hydrostatic pressure assumption and one has to verify whether this is still valid. Next to that, the choice for the vertical coordinate system (either σ- or Z-layers) has an effect on how far the saline water intrudes into the rivers.

Roughness

An attempt was made to relate the value for the roughness coefficient to the type of sediment on the seabed and to its effect on the model results is a function of the depth and geometry as well. In general it is evident that a higher roughness, or a bigger influence of the roughness due to the shallow depths, damps the amplitude and slows down the tidal propagation speed. In this case, Manning's roughness coefficient will be used to define the roughness coefficient. This value has been set equal to 0.015 $s/m^{1/3}$ for the rivers, delta and part of the coastal area. This value is chosen because literature suggests that the soil of the river and delta is mainly composed of fine sediment, which would lead to a relatively smooth bottom.

For the deeper parts of the Andaman Sea, this coefficient has been set to 0.024 $s/m^{1/3}$.

Turbulence coefficients

The Delft3D-Flow manual addresses how turbulence can be incorporated in the hydrodynamic model:

"Delft3D-FLOW solves the Navier-Stokes equations for an incompressible fluid. Usually the grid (horizontal and/or vertical) is too coarse and the time step too large to resolve the turbulent scales of motion. In other words, the turbulent processes are 'sub-grid'. Filtering the equations lead to the need for appropriate closure assumptions."

The 2D part is associated with the contribution of horizontal motions and forcings that cannot be resolved ("the so-called sub-grid scale turbulence") by the horizontal grid. The 3D part is referred to as the three-dimensional turbulence and is computed following a turbulence closure model" (Delft3D–FLOW (2013))

When the model was set-up, as a first estimate the relevant parameters, being the horizontal eddy viscosity coefficient ν_H and eddy diffusivity coefficient D_H, were set to ν_H=1 m^2/s and D_H= 10 m^2/s. For the 3D turbulence, the k-ε closure model is used. It is thought however, that the horizontal turbulence parameters could be much larger due to the relatively large grid cells which are used in this model (even in the area of interest).

Discharges

At the upstream end of the model, river discharges are imposed. As a first estimate, the long-term average discharge at Pyay was taken and divided over the different river branches. The gauging station at Pyay lies 90 km north of the starting point of the delta, and lies 330 km upstream from the river mouth of the Ayeyarwady river.

This division was made by taking the ratio of the particular river width to the combined river width. This resulted in the following river discharges for the model period(Table 3.1):

River	Discharge [m3/s]
Pathein	380
Ywe	234
Pyarmalot	217
Ayeyarwady	417
Bogalay	359
Pyapon & Toe	359
Yangon	417

Table 3.1: First estimate of river discharge in model period

4 Additional acquired data

One of the main findings when setting up the Delft3D model was that additional data had to be acquired to validate and improve the hydrodynamic model.

During the period January 2014-March 2014, data has been supplied by governmental departments in Myanmar. This data includes:

- Bathymetric charts, by the Directorate of Water Resources and Improvement of River Systems (DWIR) and Myanma Port Authority (MPA)
- Discharges, by the Department of Meteorology and Hydrology (DMH)
- Water levels, by the Department of Meteorology and Hydrology (DMH)
- Salinity measurements, by the Ministry of Agriculture and Irrigation (MoAI), Hydrology Branch

The MoU signed between the governments of the Netherlands and Myanmar foresees sharing gathered data. However, the data is not available for other purposes. Therefore, it will not be discussed in the publicly available version of this report. If one wishes to access the data and wants to be informed about the data acquisition, please contact the relevant authorities or the author.

In the following sections the additionally acquired data is discussed briefly, to give an indication of the data available for calibration of hydrodynamic models.

4.1 Bathymetric charts (DWIR & MPA)

Bathymetric charts are provided by the Directorate of Water Resources and Improvement of River Systems (DWIR) and the Myanma Port Authority (MPA). DWIR has mainly supplied CAD-files, since they try to archive all the new maps as CAD-files. The maps provided by MPA are hardcopy files. An overview of all bathymetric charts can be found in Appendix A.

4.2 River Discharges (DMH)

Time series of river discharges have been supplied by the Department of Meteorology and Hydrology, which gather meteorological and hydrological data throughout Myanmar. In the Ayeyarwady region, hydrological data is collected at the following stations (Table 4.1):

Station	River	Data type measured	Observation type	Start date	Elevation (m)
Hinthada	Ayeyarwady	Water levels	Staff gauge	1968	13.5
Za Lun	Ayeyarwady	Water levels & discharge	Staff gauge	1985	13.7
Ngathinggyaung	Pathein	Water levels & discharge	Staff gauge	1985	13.4
Maubin	Toe	Water levels & discharge	Staff gauge	1950	3.0
Myaung Mya	Pathein	Water levels	Staff gauge	1976	1.8

Table 4.1: Hydrological measuring stations DMH in Ayeyarwady region

The location of the hydrological stations in the Ayeyarwady delta can be seen from Figure 4.1.

Figure 4.1: Location of hydrological stations in Ayeyarwady region

4.3 Salinity measurements (MoAI)

For the past years, the hydrology branch of the Ministry of Agriculture and Irrigation (MoAI) has been measuring salinity in the different river branches of the Ayeyarwady delta. The goal of these measurements is to measure the 1-ppt isohaline in the different rivers when spring tide occurs in the month of March (as was stated before, this is the most critical month for salinity intrusion). The 1-ppt isohaline is measured to give an indication whether the river water at a certain location is suitable for irrigation or not.

5 2D tidal model

The first part of improving the Delft3D-model of the Ayeyarwady delta is mainly concerned with how the tide propagates into the rivers. Since the tidal motion is one of the main drivers of salt intrusion, it is important to make sure this is represented well in the model and especially in the different river branches. If the tide is represented adequately, this model can be used as a starting point to model other processes taking place in the delta, since the tide plays such a large role in these processes.

5.1 Measured tidal data

In section 3.2 it was concluded that based on the preliminary data, it is not possible to determine if the tidal propagation into the river branches is represented adequately. Hence, there is a need to acquire data from gauging stations located in the delta itself.

This data has been provided by the Department of Meteorology and Hydrology (DMH), which have 11 gauging stations at different locations in the delta area. An overview of these gauging stations can be seen in Figure 5.1.

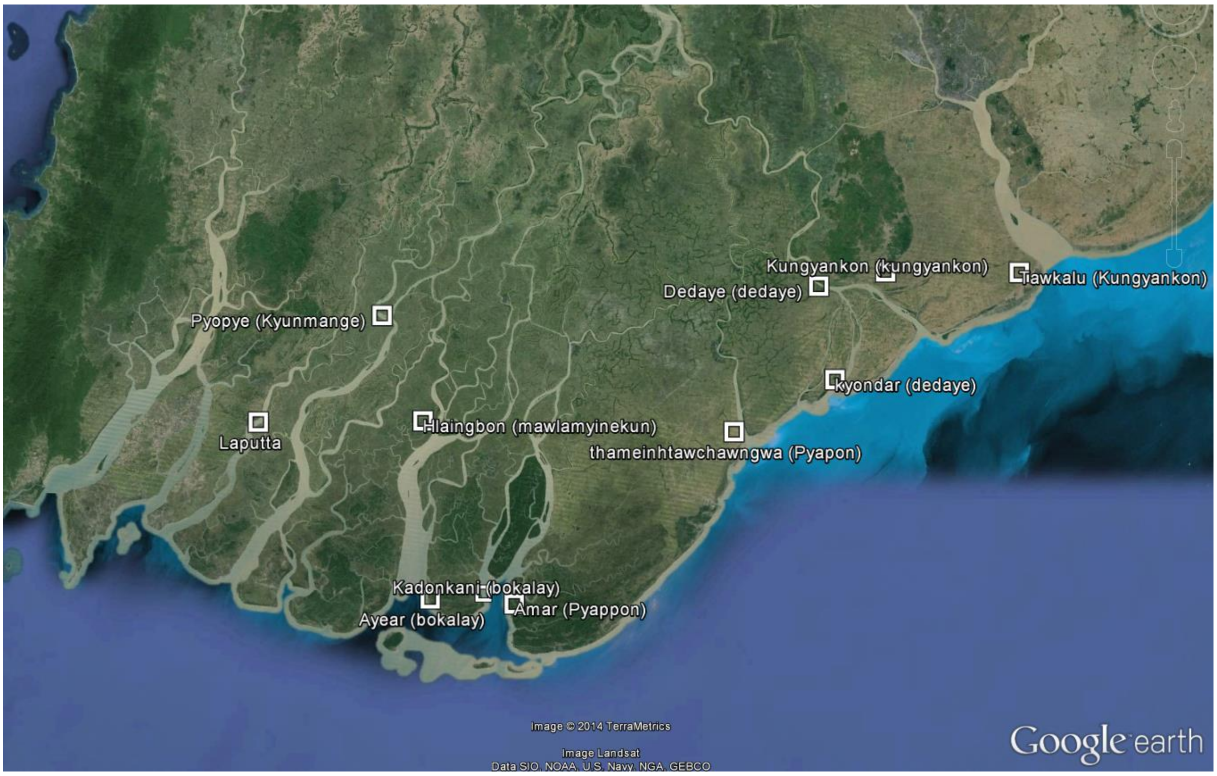

Figure 5.1: DMH gauging stations in Ayeyarwady delta

When the location of these gauging stations is compared with the location of the IHO tidal stations (Figure 3.1) it becomes clear that the data from these gauging stations could prove to be very valuable when assessing the propagation of the tide into the river branches. Whereas the IHO tidal stations are mainly located on the outer edges of the delta area, most of the gauging stations from DMH are located in the centre of the delta.

At these gauging stations, the water level is measured three times a day: at 6:00 AM, and at two varying times, when the maximum and minimum water level are reached. There are two things to note about the measured data:

- The gauges are referenced to Mean Sea Level (MSL). However, it is not clear how reliable the datum of these gauges is. Since no actual measurement has been done of these gauge datums in this report, we have adjusted the local datums to match the computed water levels.
- The times indicated for the maximum and minimum water levels are given in a 24-hour format. However, for some gauges this would mean that water level measurements were done in the middle of the night. Since these aren't automated gauges and the locations of these gauges are quite remote, it is unlikely whether this is actually the case. It is also unclear for which gauges a 12-hour format has been used to denote the time at which the measurement was done.

So, there is some uncertainty involved about the time at which the measurements were taken and the reference level of the measured water levels. To be able to use this data to improve the model, first a selection is made of the different available gauging stations. Only stations that have data for the specific timeframe of the model, which is March 2012, are included. Next to that, a first check has been carried out to see whether the data is reliable. The results of this first selection are presented in Table 5.1. When a gauging stations is omitted, the reason is also specified:

Name	River	Selected	Motivation
Amar	Bogalay	Yes	
Ayear	Ayeyarwady	No	Data unreliable
Dedaye	Toe	Yes	
Hlaingbon	Ayeyarwady	Yes	
Kadonkani	Bogalay	Yes	
Kungyankon	Kadonkani	Yes	
Kyondar	Toe	Yes	
Laputta	Ywe	Yes	
Pyopye	Pyarmalot	Yes	
Tawkalu	Toe	No	No data for model period
Thameinhtaw	Pyapon	No	No data for model period

Table 5.1: Selected gauging stations for analysis

The data from the selected gauging stations has been compared with the output generated by Delft3D. In the following sections, the results of two Delft3D runs are presented. In Section 5.2, the initial model results are presented (only minor adjustments are made to the model, compared to the model that was developed by Attema (2013)). In Section 5.3, the results after the Delft3D model has been adjusted are presented. These adjustments will be discussed in the same section.

5.2 2D Tidal model – Run 1

This is the base case. The only differences with the model as it was developed by Attema (2013) are listed below:

- Model time: this is now March 2012
  The month of March will still be used for the analysis because it is the most critical month for salinity intrusion. Since the data from the gauging stations along the coast is only available for the year 2012, this year was chosen for the modelling work.
- Diffusion coefficients: horizontal eddy viscosity and diffusivity are set to 50 each. These values are adopted because of the coarse grid and the 2D approach.
- River discharges:

River	Discharge [m3/s]
Pathein	384
Ywe	234
Pyarmalot	217
Ayeyarwady	417
Bogalay	359
Pyapon & Toe	359
Yangon	417

Table 5.2: Discharges imposed on river boundaries

However, it is thought that adjusting these parameters has a minimal influence on the simulated water levels. In fact, adjusting the model time to match with the time for which measurements are available is quite important when comparing these water levels. (due to the astronomic boundary conditions) As for the river discharges; since it is the dry season these river discharges are quite low and it is believed that the water levels at the gauging stations are completely governed by the tidal forcing, since these gauging stations are all in the vicinity of the coast.

The analysis of the simulated water levels at these gauging stations for the base case, mainly focuses on comparing the tidal range of both the measured and simulated water levels. Absolute level comparison is not appropriate due to the uncertainty about the vertical datum of the gauging stations.

The simulated and measured water levels can be found in Appendix B.

When the simulated water levels are compared with the observed water levels, the following remarks can be made(the selected gauging stations are addressed in alphabetical order):

Amar: during spring tide, the tidal range of the model results is +/- 2 m, whereas the observed water levels suggest a tidal range of 3m. The simulated ebb water levels are lower bounded(at h=-0.5m), this could probably be caused by (too) shallow bathymetry. Since the specific bathymetry for the coastal area and the rivers is lacking, this is a parameter which can be adjusted in subsequent model runs. It is also possible that a slight offset of the measured water levels is needed to improve the fit with the model results.

Dedaye: for this gauging station, the tidal range already seems to match quite well, the simulated tidal range underestimates the actual tidal range by 0.5 m during the spring tide. For this gauging station, it is questionable whether the measured minimum water levels actually represent the daily minimum water levels. This will be investigated in the next runs.

Hlaingbon: this gauging station is relatively far from the coastline, being 40 km upstream of the Ayeyarwady river mouth. At first sight, it seems that the simulated spring-neap cycle is out of phase with the measured water levels. Here, the simulated tidal range is also 1m smaller than the measured tidal range. For this gauging station, it is also likely that too shallow bathymetry at the river mouth and in the river itself damp the minimum tidal water levels.

Kadonkani: Again, it seems that the spring-neap cycle is out of phase with the measured water levels. However, what is different from the previous gauging station is that this gauging station is at the mouth of the Bogalay river. Besides to the phase of the spring-neap cycle, the simulated minimum tidal water levels do not correspond with the data.

Kungyankon: for this gauging station, the simulated tidal range seems to match quite well with the measured water levels already. The reference level of this gauging station seems to differ from the model.

Kyondar: here, the simulated water levels for the gauging station already predict a larger tidal ranges than has been actually measured. However, it is questionable whether the measured minimum water levels actually represent the daily minimum water levels, since the measured minimum water levels hardly show any variation for the entire month while it is expected to see some variation. (due to spring-neap tide cycle)

Laputta: for this gauging station, the main issue seems to lie in the fact that the reference level for the simulated and measured water levels do not coincide. The tidal ranges seem to match quite well.

Pyopye: this gauging station is the station which is upstream the furthest from its river mouth (in this case the Pyarmalot river) and besides that, according to the supplied coordinates, just behind a confluence between two river branches. It could be possible that this river branch will therefore experience some backwater effects. The tidal range is underestimated by the model by about 1m.

5.3 2D Tidal model – Run 2

As could be seen in the previous section, for the delta region the overall water levels computed by Delft3D already match quite well with the measured water levels in the delta. However, a couple of aspects could be improved. The main uncertainty in the delta region, which has a direct influence on the model output, is the bathymetry of the coastal zone and the rivers. This has been adjusted by:

- schematising the bathymetry charts supplied by DWIR (Section 4.1), for the river branches where they were available.
- Iteratively adjusting the water depth in the river branches for which no bathymetry charts were available.

By iteratively adjusting the water depths the presumption is made that for the Andaman Sea the tidal model already performs as it should and that a mismatch between the measured water levels in the delta and the simulated water levels is mainly caused by local conditions which influence the model output.

The following changes have been made to the model in the process:

<u>Adjusted river depths</u>

For most river branches, the depths have been adjusted, based on:

- bathymetric charts

- comparison between measured and simulated water levels

As for the bathymetric charts, these have been schematised. (same width and cross-sectional area)

For all the river branches, Table 5.3 indicated whether changes have been made in the bathymetry and based on which information this has been done:

River	Depth adjusted	Based on
Pathein	No	No additional bathymetric charts or measured water levels available
Ywe	Yes	Bathymetric charts at Laputta
Pyarmalot	Yes	Tidal range at Pyopye gauging station
Ayeyarwady	Yes	Tidal range at Hlaingbon gauging station
Bogalay	Yes	Tidal range at Kadonkani and Amar gauging stations
Pyapon	Yes	Bathymetric chart at Pyapon channel
Toe	Yes	Bathymetric chart at Dedaye and tidal range Kungyankon and Dedaye
Yangon	No	Verified with additional Bathymetric charts from MPA and tidal range at Yangon and Elephant point (IHO stations)

Table 5.3: Changes in model bathymetry for 2D model run 2

On the next pages, these changes in bathymetry are shown in plots generated with QUICKIN, a tool of the Delft3D suite, with which bathymetry can be linked to a computational grid, and which can be used to alter the bathymetry. The plotted figures display the change in depth between the initial bathymetry and the adjusted bathymetry.

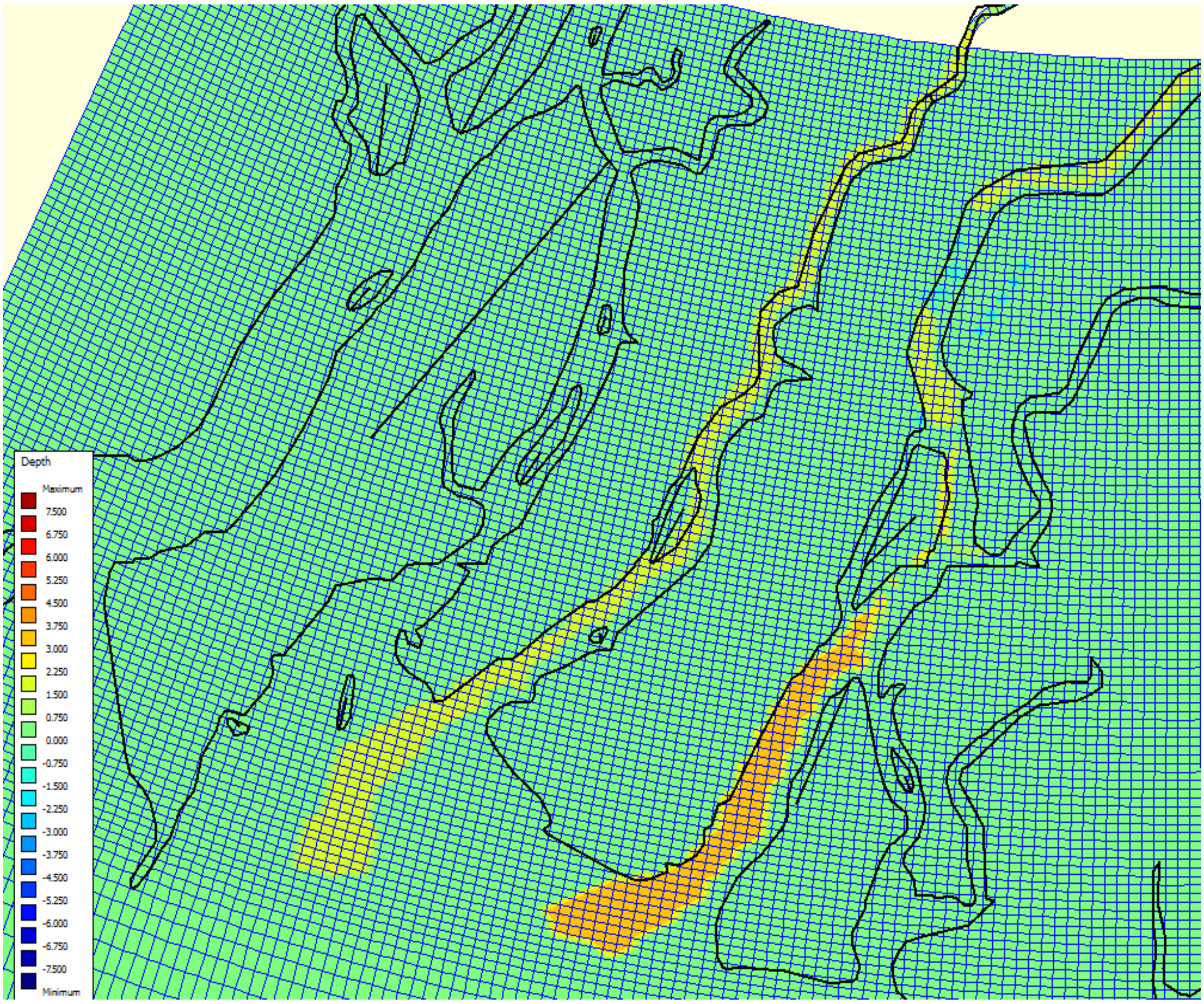

Figure 5.2: Changes in depth between initial bathymetry and adjusted bathymetry for the Ywe (middle) and Pyarmalot (right) river. Positive depth means an increase in depth between previous and current bathymetry.

Starting on the western side of the delta, the bathymetry of the Ywe river has been augmented by schematising the bathymetric chart of the Laputta channel. The resulting depth at this point in the river, a depth of 6m, has been extended to both the river mouth and roughly 20 km upstream from Laputta. Laputta is roughly 30 km upstream of the river mouth. The changes in bathymetry can be seen in Figure 5.2.

The bathymetry of the Pyarmalot river has been augmented by iteration, by comparing the measured water levels at the Pyopye with the simulated water levels for the same location. However, because of the location of the Pyopye which was discussed in Section 5.2, this gauging station might not be the best to compare measured and simulated water levels. However, this is the only information available for the Pyarmalot river. The depth of the Pyarmalot river is now set to 7m for the first 50 km upstream from the river mouth.

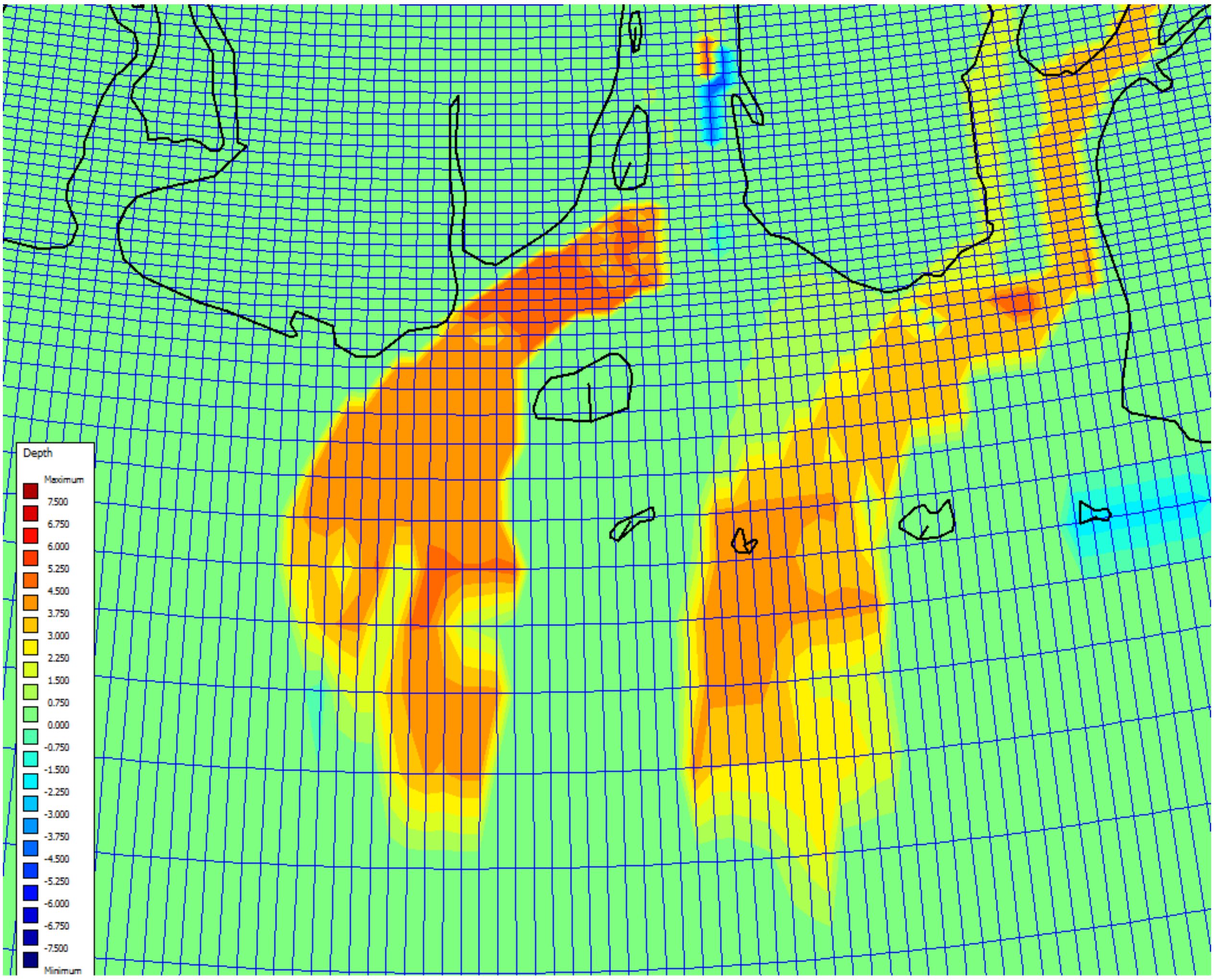

Figure 5.3: Changes in depth between initial bathymetry and adjusted bathymetry for the mouth of both the Ayeyarwady (middle) and Bogalay (right) river. Positive depth means an increase in depth between previous and current bathymetry.

Moving eastwards, the bathymetry of the Ayeyarwady and Bogalay rivers has been adjusted as well. Starting with the river mouth, which was very shallow in the initial model (depths of 1-2 meters over whole width of both rivers. This resulted in some sort of drying in this river, which can be deduced from the simulated results for the Amar (Bogalay river, Figure B.1), Kadonkani (Bogalay river, Figure B.4) and Hlaingbon (Ayeyarwady river, Figure B.3) gauging stations for run 1 of the 2D tidal model.

The depth has been increased by about 4-6 meters for the mouth of the Ayeyarwady river and by about 3-5 meters for the mouth of the Bogalay river(. By increasing the depth it should be possible for the tide to propagate into the river. Or, to be more precise, to allow the transport of water from the river into the sea during ebb.

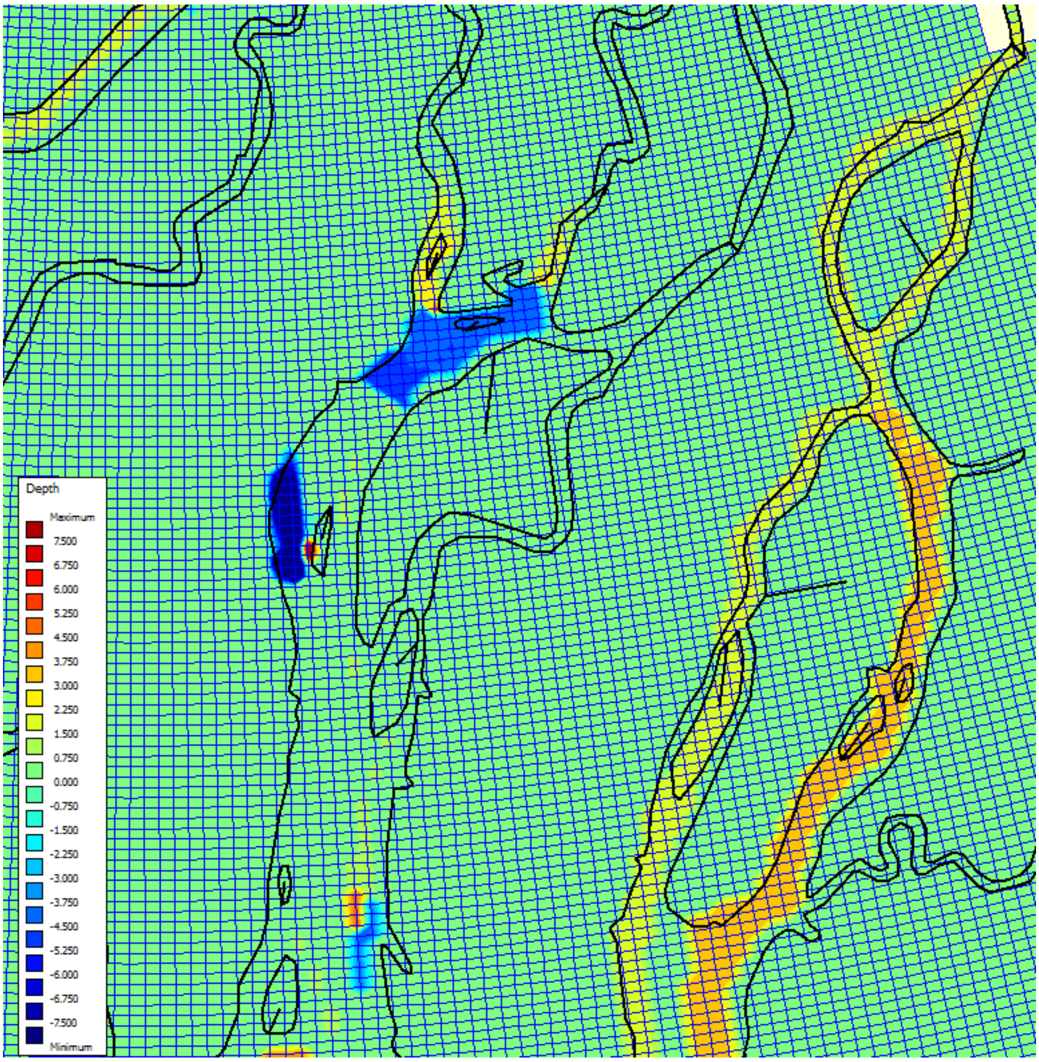

Figure 5.4: Changes in depth between initial bathymetry and adjusted bathymetry for the Ayeyarwady (middle) and Bogalay (right) river. Positive depth means an increase in depth between previous and current bathymetry.

Further away from the river mouth, the Ayeyarwady was schematised to be very deep in certain parts of the river (depth of +/- 15 m) .The decrease/increase in river depth can be seen in The main branch of the river has been given a uniform depth of 7 meters for the first 40 kilometres upstream from the river mouth. The sections of the river further upstream have a uniform depth of 5 meters but the effect of a bottom slope has been incorporated in setting the depth of the river section. Further details about how the depth was set for the most upstream part of the model, in which the river is modelled using one grid cell for the total width, can be found in Attema (2013).

The Bogalay river has been made deeper (as it was very shallow in the first version of the model, with a depth of only 3m!). Here, the river has a uniform depth of 6 meters for the first 40 km of the river upstream from the river mouth.

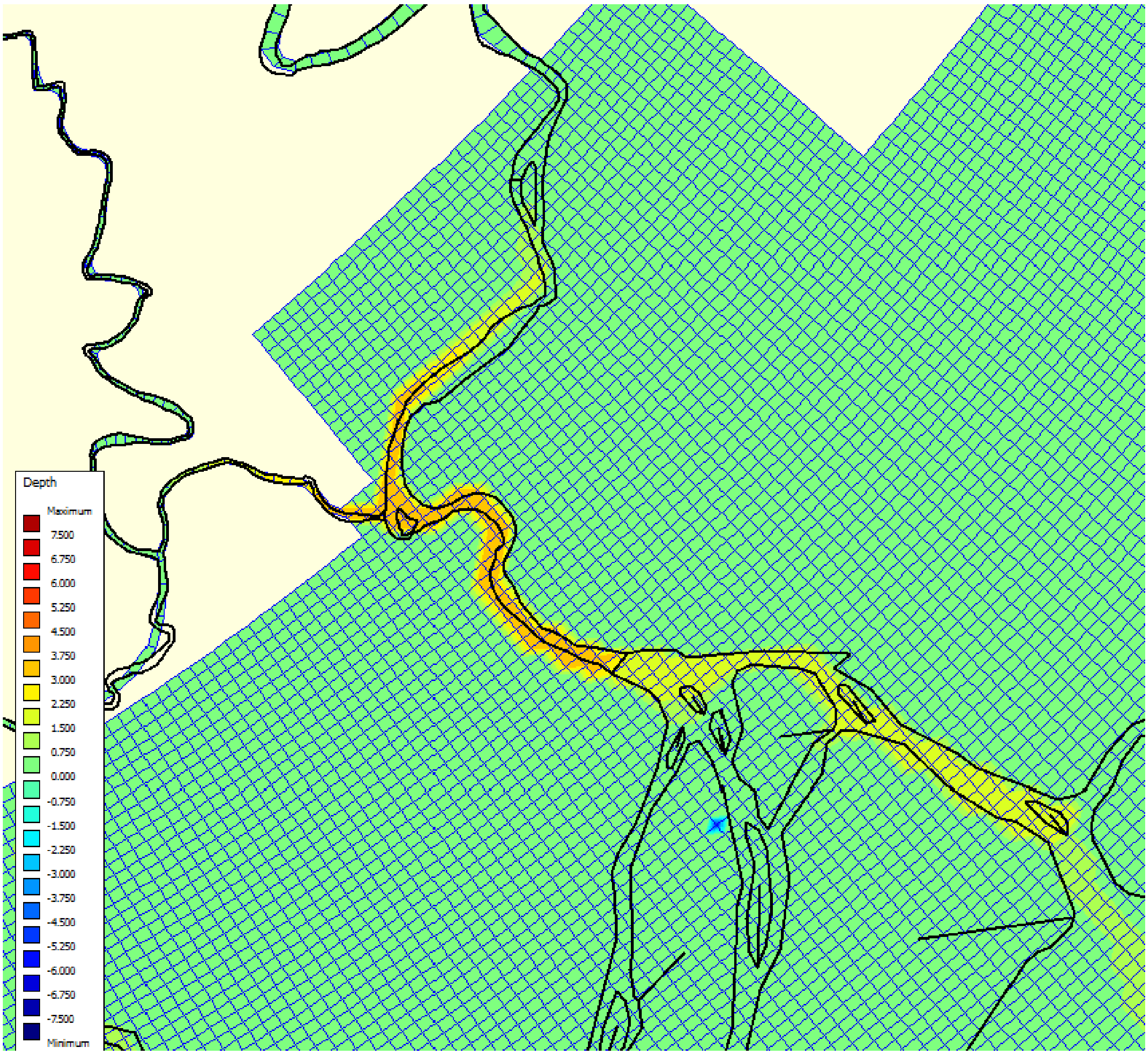

Figure 5.5: Changes in depth between initial bathymetry and adjusted bathymetry for the Toe river. Positive depth means an increase in depth between previous and current bathymetry.

The depth of the Toe river has been increased, based on the bathymetric chart at Dedaye and by analysing the simulated water levels at Kungyankon and Dedaye with the measured water levels at these gauging stations. Again, some sort of drying seemed to occur during the first model run. This can be seen from Figures B.2 and B.5 for the gauging stations of Dedaye and Kungyankon, respectively) The depth of the river is now set to 5m for the first 40km upstream from the river mouth.

Adjusted discharges

Besides adjusting the bathymetry, some changes have been made to the river discharges. These are based on a couple of sources:

- The daily mean discharges measured at the Ngathinggyaung station for the 2002-2013 period.
- A research paper on the Yangon river by Nelson (2001) stating that in the dry season, of which March is the penultimate month, only 150 m^3/s is discharged through Yangon river. It is unclear on which information this figure is based. However, as it is the only available source giving an estimate for the discharge in the Yangon river during the dry season this value is adopted.
- Based on the same paper by Nelson(2001), a small discharge is imposed on the Northern boundary of the Bago river. The Bago river isn't one of the branches of the Ayeyarwady river, but it confluences with the Yangon river just south of the city of Yangon and might influence the salinity intrusion. Nelson states that the discharge in the Bago river falls to only 10 m^3/s in the dry season.
- Based on the distance over which saline water intrudes into the Toe river during the dry season, which is relatively small, and the fact that large discharges are measured at the Maubin gauging station (see Section 4.2) the discharge through the Toe river is believed to be higher than was assumed before.

These insights lead to the following adjusted discharges. To compare with, the previously used discharges are displayed as well.

River	Previous discharge [m3/s]	New discharge [m3/s]
Pathein	380	375
Ywe	234	200
Pyarmalot	217	200
Ayeyarwady	417	400
Bogalay	359	325
Pyapon & Toe	359	600
Yangon	417	150
Bago	-	10
Total	2383	2260

Table 5.4: Discharges applied during 2D tidal model run 2

It must be noted there is still a considerable difference between the long-term averaged discharges at Pyay and the actual imposed discharges on the northern model boundary.

The specific results for the second run can be found in Appendix B. This time, two plots are made for each gauging station. The first plot shows the measured daily minimum and maximum water levels, whereas the second plot shows these measured water levels as well as the water levels measured at 6.00 AM (measured water levels as discussed in Section 5.1). Besides that, the first plot per gauging station displays the simulated water levels vs the simulated water levels for the entire month. The second plot per gauging station shows a specific 5-day period for the month of March 2012. This can be seen both from the axes in the plots and the caption that accompanies it.

General remark: simulated water levels are shifted 6.5 hrs as the the time zone of the model was set to +0 GMT, while Myanmar is in the +6.5 GMT timezone.

As was discussed in Section 5.1, it is unsure whether the given datum for each gauging station is correct. Therefore, an adjustment to the measured water levels is made by shifting the measured water levels over a certain height, which is indicated both in Table B.2 and in this section. The adjustments made are mainly intended to show that the tidal forcing applied to the model is working quite well, but that an improvement would be to actually verify the datum for the different gauging stations, as it is suspected that some of the gauging station datums are incorrect. However, it must be kept in mind that the results as shown in Appendix B are only a possible result.

The adjustments lead to the following qualitative analysis for the 2D tidal model for the selected gauging stations.

Amar: measured water levels offset +0.3m

Tidal range of simulated and measured water levels seems to be both approx. 3m. Measured water levels indicate that tide may be more asymmetric than is currently simulated (see Figure B.10) which would have impact on the computed velocities. This could be of importance when using this model to simulate sediment transport as sediment transport is largely determined by flow velocity. Tidal asymmetry leads to differences between ebb and flood velocities. (as flood and ebb periods are different) Besides, a proper validation of the computed velocities would be required when trying to model sediment transport.

Dedaye: measured water levels offset -0.3m

For this gauging station, the tidal range already matched quite well in Run 1. There seems to be a small phase difference for the tide, but besides that, results computed for this period seem to be good. It cannot be said whether the measured minimum water levels actually represent the daily minima. For the water levels plotted in Figure B.12 this is the case, but this isn't the case for the complete month.

Hlaingbon: measured water levels offset +0.5m

The simulated spring-neap cycle is still out of phase with the measured water levels. However, the adjustment of the water depth at the mouth of the Ayeyarwady and the first 40 km upstream have a noticeable impact on the simulated water levels. Simulated water levels give a better fit with the measured water levels (Figure B.13). Besides that, the tidal period matches quite well (Figure B.14).

Kadonkani: measured water levels offset +0.2m

The spring-neap cycle is out of phase with the measured water levels. Adjusting the depth of the mouth of the Bogalay river affected the simulated low water levels. However, there is no clear fit between the simulated and the measured water levels. This is remarkable, as the fit for the simulated and measured water levels is quite good for the Amar gauging station, which is just across the river.(the river at this point is 5 km wide, but for the tidal motion, this isn't a relevant lengthscale) It might be wise to check the measured water levels for both the Kadonkani and the Ayear gauging station, as also the measured water levels at the Ayear gauging station didn't prove to be useful for this analysis (see Figure 5.1: DMH gauging stations in Ayeyarwady delta for location of both gauging stations).

Kungyankon: measured water levels offset -1.0m

Measured water level offset is quite large. However, when this is offset, the results are good. Tidal range differs with max. 0.2m. Phase and tidal asymmetry seem to be represented adequately.

Kyondar: measured water levels offset -0.3m

No significant changes in depth, and thus, the simulated water levels aren't significantly different from the results of Run 1. When examining Figure B.20, again, one can question whether the measured minimum daily water levels are actually the daily minimum water levels. Besides the fact that they hardly vary during the month of March, the simulated water levels actually match quite well with the measured water levels for the specific time at which they were measured.

Laputta: measured water levels offset +0.7m

By adjusting the bathymetry for this gauging station, the main issue seems to lie in the fact that the reference level for the simulated and measured water levels do not coincide. The tidal ranges seem to match quite well.

Pyopye: measured water levels offset -0.2m

This gauging station is the station which is upstream the furthest from its river mouth (in this case the Pyarmalot river) and besides that, according to the supplied coordinates, just behind a confluence between two river branches. It could be possible that this river branch will therefore experience some backwater effects. The tidal range is underestimated by the model by about 1m.

5.4 Concluding remarks about 2D tidal model

From the 2D tidal model analysis, the following conclusions can be drawn:

- the results of the 2D tidal model seem to be quite reasonable when they are compared with the measured water levels in the Ayeyarwady delta in a qualitative manner.
- The measured water level data provided by the Department of Meteorology and Hydrology(DMH) proved to be very useful when trying to calibrate the model. Again, it is stressed that validating a numerical model with measured data is of great importance when setting up a numerical model.
- the bathymetric charts provided by the Directorate of Water Resources and Improvement of River Systems (DWIR) proved to be a useful guidance when adjusting the bathymetry of the different river branches.

However, a couple of remarks about the current state of the model have to be made:

- Adjusting the bathymetry has a significant impact on the simulated water levels. However, for large parts of delta, depths are still unknown. Even if bathymetric charts are available, model resolution requires that these are schematized to be input into the model.

- To further improve 2D tidal model one should take more frequent measurements at specific locations to be able to further investigate tidal asymmetry and phase differences between simulated and measured water levels. It is advised to narrow down the area of interest, as the analysis for the 8 different river branches proved to be quite extensive. But even more important, collecting data with a higher frequency than the available data requires narrowing down the area of interest, as it does not seem to be realistic to collect a detailed dataset of measured water levels for the entire Ayeyarwady delta

- Uncertainties in both model output and available data still exist, which makes it difficult to perform a quantitative analysis of the model output and the measured data. For instance, an improvement of the measured data would be to check the datum of the gauging stations and to align it with the reference level of Delft3D.

- It is useful to vary the discharges at the upstream boundary, to see its impact on the model output. The main goal of varying the upstream river discharges would be to verify the measured discharges at the Zalun and Maubin hydrological measuring stations. (see Section 4.2 for more details about the provided discharge data)

6 3D salt intrusion model

The second part of improving the Delft3D-model of the Ayeyarwady delta is concerned with the salinity intrusion into the Ayeyarwady delta. As was said before, the Ayeyarwady delta area is one of the main agricultural areas of Myanmar, but in the dry season saline water protrudes far into the delta area, making river water unusable for irrigation- and drinking water purposes. This is why, for the past years, the hydrology branch of the Ministry of Agriculture and Irrigation (MoAI) has been measuring salinity in the different river branches of the Ayeyarwady delta.

During these measurement campaigns, the 1-ppt isohaline in the different rivers was measured at the occurrence of spring tide in the month of March (as was stated before, this is the most critical month for salinity intrusion). The 1-ppt isohaline is measured to give an indication whether the river water at a certain location is suitable for irrigation or not. (See Section 4.3 for details about the measurement campaign and the acquired data)

In this chapter, the results of the 3D salt intrusion model are discussed. First, the model setup is presented. Afterwards, the model output and the measured data are compared. Finally, some concluding remarks are made about the current model state and chances for future development.

6.1 Model setup

The 3D salt intrusion model is based on the 2D tidal model, but in this case, the model is no longer depth-averaged. This means that depth gradients in, for instance, velocity and salinity are also considered. The relevant model parameters are listed below:

Parameter	Value
Timeframe	4 february 2012 till 31 March 2012
Time step	60 sec
Processes included	Salinity
Initial conditions	Based on map file results preliminary 3D model
Roughness method	Manning
Roughness	0.018 (Ayeyarwady delta) 0.024 (Andaman Sea)
Vertical layers	10 (σ-layers)
Horizontal Eddy Viscosity	20 m2/s
Horizontal Eddy Diffusivity	20 m2/s
Vertical Eddy Viscosity	10^-6 m2/s
Vertical Eddy diffusivity	10^-6 m2/s
Turbulence closure model	k-ε model

Table 6.1: Model setup salt intrusion model

The bathymetry is the same as was used for the second 2D tidal model run. The discharges applied at the upstream boundary can be found in Table 5.2. As is stated in Table 6.1, the initial conditions for the model are taken from the results obtained during the preliminary model runs performed by Attema (2013). A remark about the horizontal eddy viscosity and diffusivity coefficients is that these are calibration parameters for numerical models. As there is not sufficient data available such a calibration has not been performed, but these values are chosen such that they account for the relatively coarse numerical grid that is used for this numerical model. Therefore, these values are both set to 20 m2/s.

6.2 3D salt intrusion model results

As salt intrusion is a phenomenon that varies both in time and space, both the time and location of model output and measured data must be specified. In this case, the location is (of course) the front of the saline intrusion and the dates for which the results are displayed are when measurements were gathered in the Ayeyarwady delta by MoAI. For March 2012, these dates were 9 March 2012 and 24 March 2012. Some remarks about the results:

- Water is well-mixed over the vertical.

When the results are examined for the delta area, it is found that the concentration of salinity barely varies over the vertical, i.e. the different river branches are well-mixed. When doing further work on the model, it is advisable to do some calculations to see whether one would expect the river system to be well-mixed or stratified. (where there is a distinct density gradient over the water column) The tidal range in the delta varies from 3-5 meters, whereas depths in the western Ayeyarwady delta are estimated to be around 5-7 meters (at the river mouth). Hence, the tidal range is quite large when compared to the river depth and thus, a well-mixed water column is plausible. . Another explanation could be that because of the coarse grid, small differences in salinity are averaged out over the particular grid cells and therefore a well-mixed water column is generated as output. However, the best way to verify whether the system is well-mixed or stratified is by taking measurements over the full water depth

- As measurements were taken close to the surface, model output is displayed for layer 1

The salinity measurements were taken approx. 1m below the water surface. This fact, combined with the fact that the water column appears to be well-mixed, leads to the fact that model results will be displayed for the upper layer of the water column, numbered layer 1. (as a numerical model discretizes space, the vertical is divided in 10 layers, where numbering starts at the top)

For the 9th of March 2012, the maximum salt intrusion is displayed in Figure 6.1 and Figure 6.2. In these figures, the salinity (displayed in ppt) ranges from 0 to 1 ppt. This is done because the 1-ppt isohaline has been measured by MoAI. This isohaline is plotted in red in both figures. One remark that must be made is that the isohaline has not been measured for the Pyarmalot river, and the isohaline in that location is merely a interpolation between the location of the 1-ppt isohaline in the Ywe and Ayeyarwady river.

Overall, the figures show that the saline intrusion is represented quite well by the model. Especially the Ayeyarwady, Bogalay and Yangon rivers show a good fit with the measured isohaline. One detail deserves some extra attention: the saline water seems to intrude far into the Toe river (Figure 6.2). However, this salty water mainly comes from the Yangon estuary, and flows through the Twante canal (west of Yangon) into the Toe river. This is because the Yangon estuary is quite salty (with values of up to 15 to 20 ppt in Yangon harbour) and the Twante canal forms an easy passage to the Toe river.

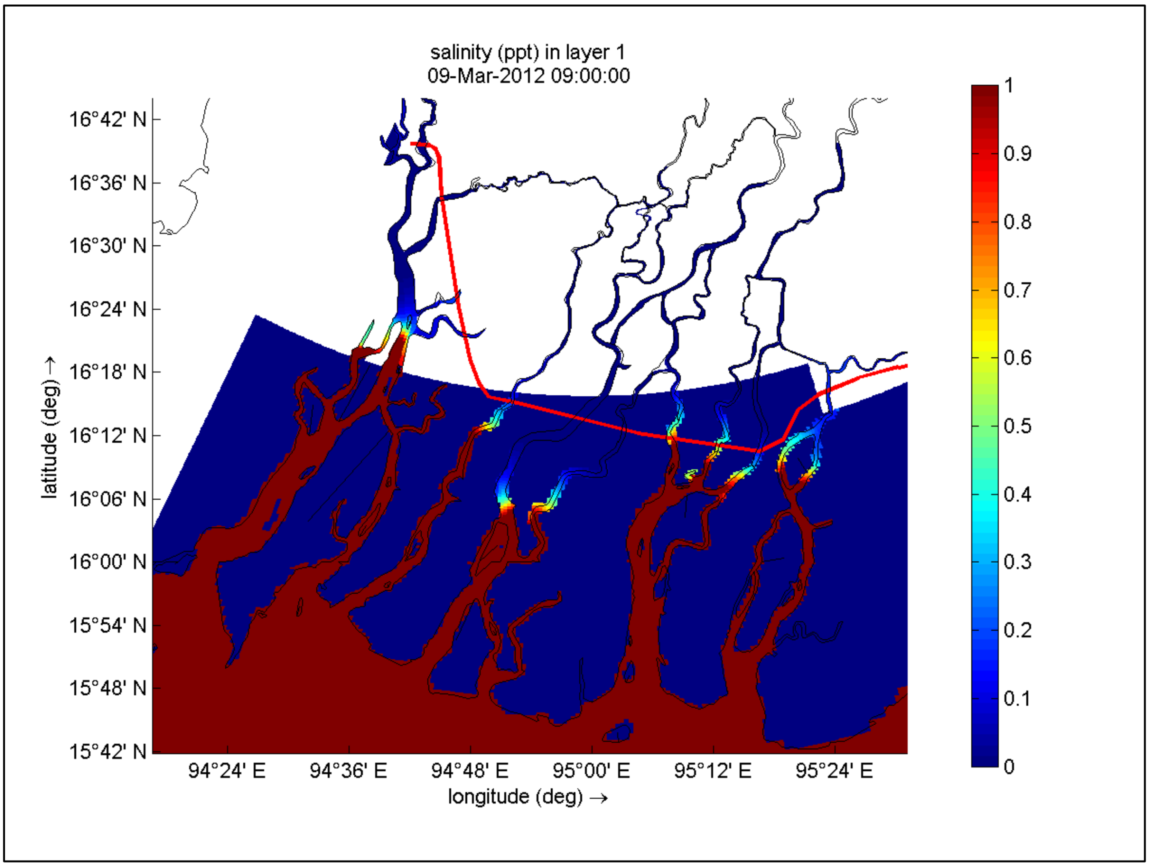

Figure 6.1: Salinity in western Ayeyarwady delta on 9 March 2012.

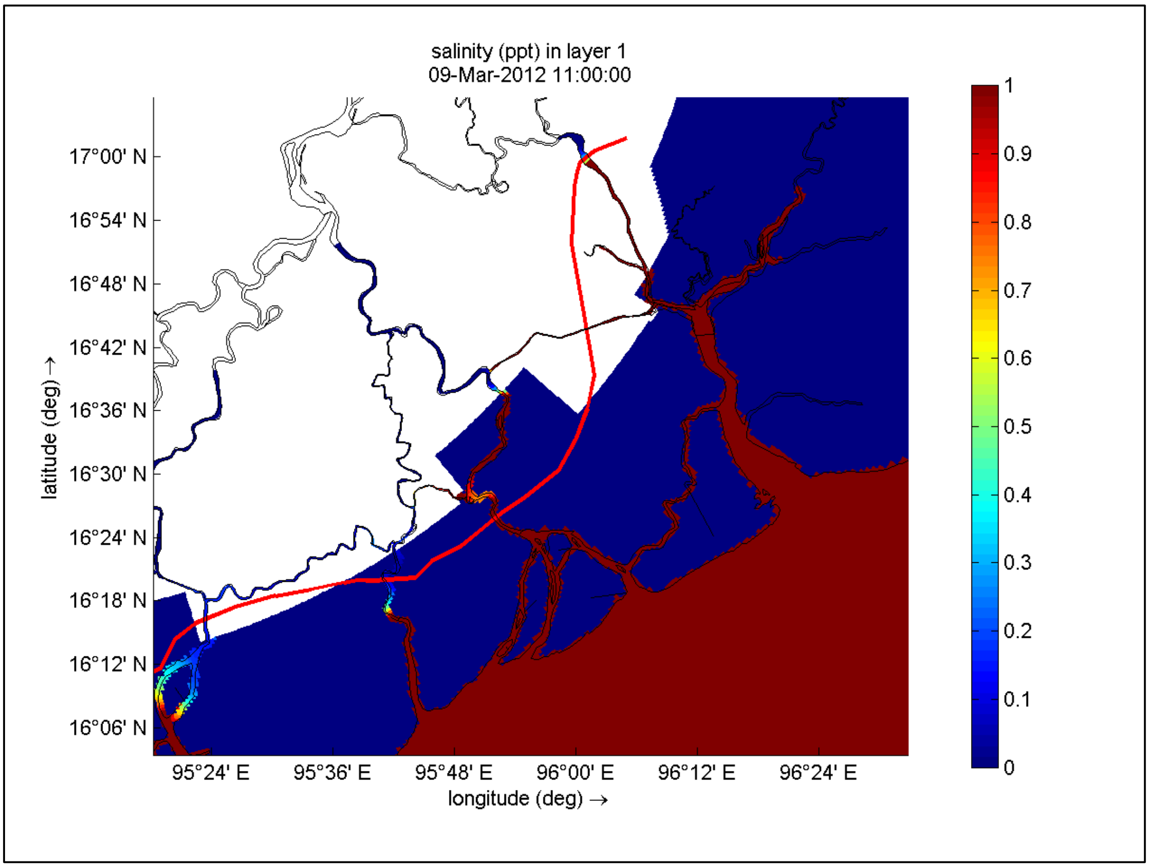

Figure 6.2: Salinity in eastern Ayeyarwady delta on 9 March 2012.

This can also be seen from Figure 6.3. Here, a plot is made of salinity a couple of hours before Figure 6.2. What can be seen clearly, is the fact that the more saline water in the Twante channel that flows into the Toe river. Here it will mix with the fresher waters in the Toe river. The main conclusion from this result is that it might be useful to sample water in the Twante channel, to see if it becomes saline during the dry season. The model result gives an indication that this might actually be the case.

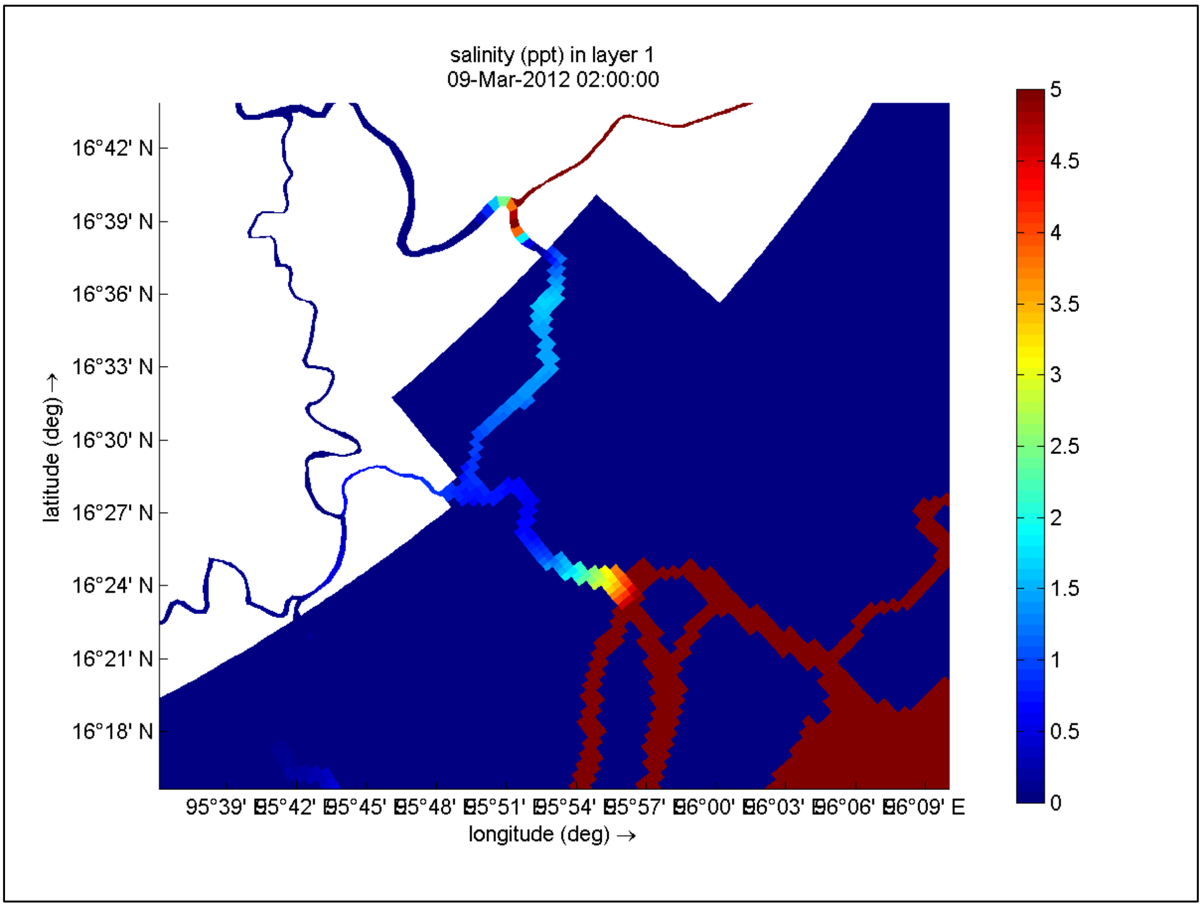

Figure 6.3: Salinity in Toe river and Twante channel on 9 March 2012. Note the range in salinity from 0 to 5 ppt

The salinity is also plotted for the 24th of March 2012, and the results are presented in Figure 6.4 and Figure 6.5.

Again, quite a good fit for the Ayeyarwady, Bogalay and Yangon river between measured and simulated salinity intrusion. Also, the length of the salinity intrusion in the Pyapon river matches quite well with the measured 1-ppt isohaline. For the Yangon river it is noted that the saline water protudes almost up to the upstream boundary. When doing further investigation on the Yangon river it could be wise to extend the model grid in the upstream direction, as to avoid boundary effects.

Again, the influence of saline water from Twante canal in the Toe river is noticed. As a last remark, it is noted that for both the beginning and end of March, the simulated salinity intrusion for the Pathein river is 20/30 km shorter than what was actually measured in the field. This could be due to the proximity of the western model boundary for the Pathein river.

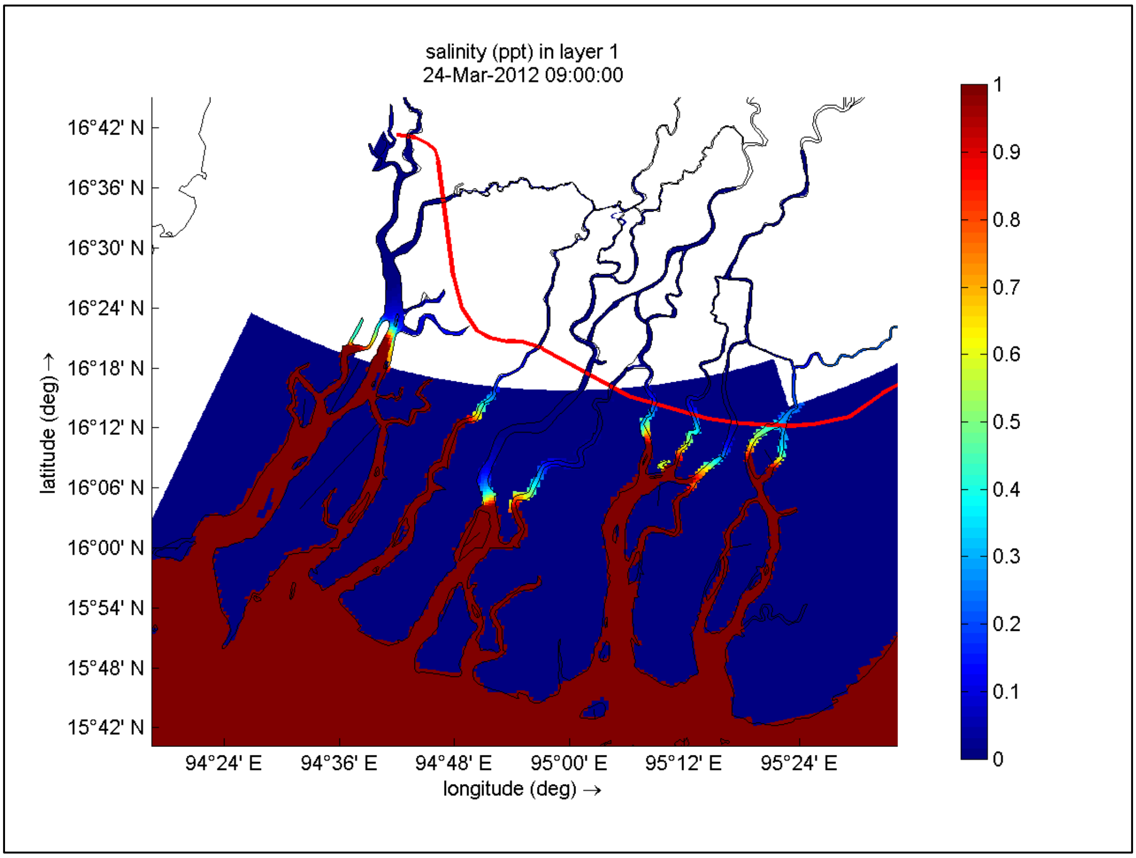

Figure 6.4: Salinity in western Ayeyarwady delta on 24 March 2012.

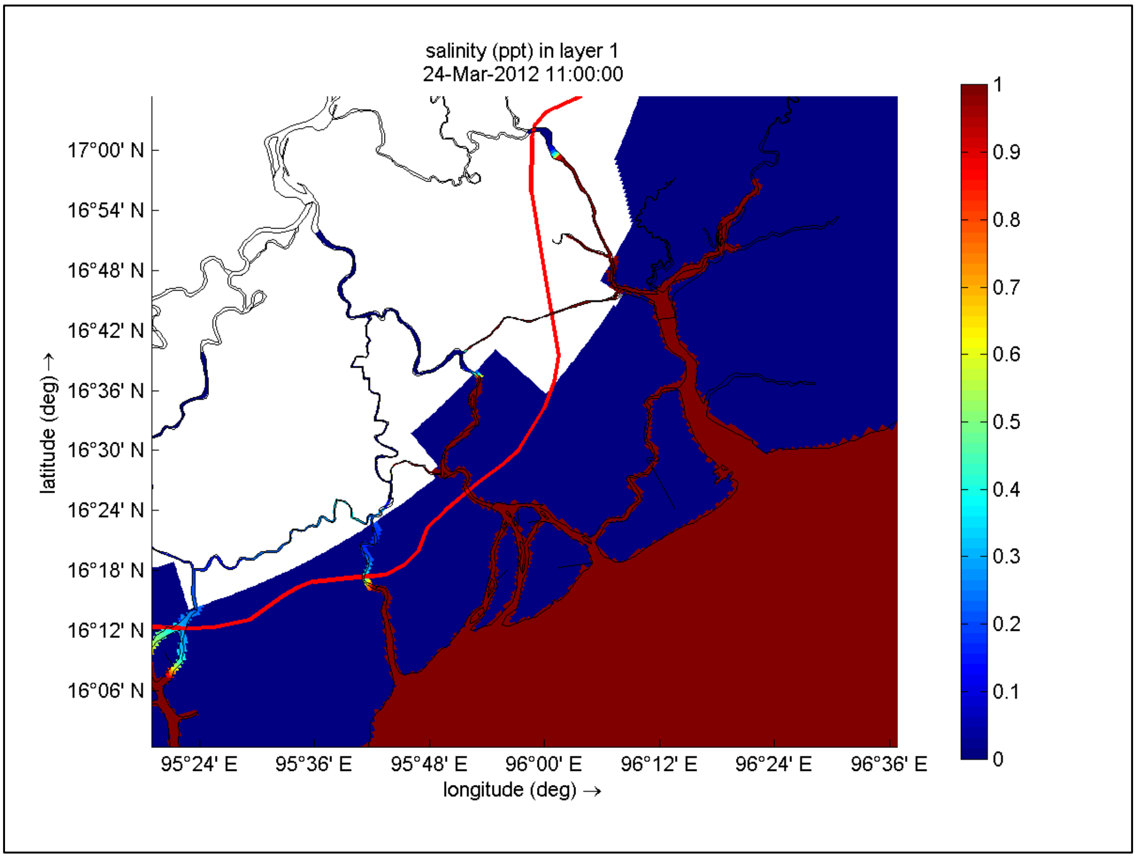

Figure 6.5: Salinity in eastern Ayeyarwady delta on 24 March 2012.

6.3 Concluding remarks about 3D salt intrusion model

As discussed in the previous sections, the results for the 3D salinity intrusion model look very promising. Especially the results for the eastern Ayeyarwady delta are in good agreement with the measurements performed by MoAI.

However, there are some observations about the model that will be discussed here:

- Long runtime, but still coarse grid

Runtime for the model is in the order of 3 to 4 days (when the model was run in Myanmar computational times went up to 6 days, due to restricted computational power). However, the computational grid is still quite coarse and for the area of interest, grid sizes are in the order of approx. 500 m. So, the computational time doesn't leave any room for increasing grid resolution, without increasing the computational power.

- Focus on smaller area

Focusing on a smaller area, for instance by setting up nested detailed models, allows you to increase grid resolution and also to specify data requirements. In this way one can efficiently search for data, to find out whether there actually is data available for a certain location, such as bathymetry or river discharge. If the data doesn't prove to be available for that location, focusing on a smaller area might allow you to collect data for this specific location. Additional data that might be useful when further improving the 3D salt intrusion model includes (but is not limited to):

  - Vertical profiles for salinity and/or velocity
  - Sediment properties
  - River discharge data

7 Conclusions and recommendations

The development of the Delft3D model of the Ayeyarwady delta has been carried out since the end of 2013. A first setup was made by Attema (2013) at Deltares in the fall of 2013. During 2014, this model was developed further, both at Deltares in Delft and in Yangon, Myanmar. (in cooperation with the engineers from DWIR)

This chapter presents an overview of the current state of the model, how it can be used in the future, and will present some suggestions for further improvements.

The current model state will be discussed for the 2D tidal model and the 3D salt intrusion model, which are actually the same model, but with or without averaging over the depth, respectively. To begin with, the model state for predicting water levels along the coast of Myanmar and in the Ayeyarwady delta is discussed.

7.1 Current model state 2D tidal model

The 2D tidal model produces reasonable to good estimates of the water level along the coast and in the Ayeyarwady delta. For results and the adjustments that have been made to the model during this research, see Chapter 5. The main adjustments during this research were adjustments made to the model bathymetry for the delta area, as additional bathymetric charts were made available. Besides that, comparing simulated water levels with measured water levels provided the insight that some areas of the delta were too shallow in the previous version of the model (see Chapter 5 for details).

Next to the changes in bathymetry, additional data for the upstream river discharges became available. This has been used to further tweak the upstream discharges for the model area, together with values found in literature.

About the possibility of further improving the 2D tidal model: with the data that is currently available for validation and calibration, the current results are the maximum result. We recommend to further improve the model by:

- acquiring additional bathymetric data

Adjusting the bathymetry has a profound impact on the model results, especially in the delta area. However, for most parts of the model the bathymetry is not exactly known. To improve the model bathymetry, multiple cross-sections for every river branch should be measured, as the bathymetry of the Ayeyarwady is thought to vary over the length of the river.

- additional tidal measurements

During this research, the data collected at the gauging stations of DMH was used to perform a qualitative analysis of the simulated water levels. If one would want to perform a quantitative analysis of simulated water levels, you would need more measurements per tidal period to further investigate tidal asymmetry and phase differences between simulated and measured water levels. It is advised to narrow down the area of interest, as the analysis for the 8 different river branches proved to be quite extensive. But even more important, collecting data with a higher frequency than the available data requires narrowing down the area of interest, as it does not seem to be realistic to collect a detailed dataset of measured water levels for the entire Ayeyarwady delta.

- check reference levels and validity of currently available data

As was indicated in Chapter 5, the datum of the gauging stations does not seem to be correct. To quantitatively compare measured and simulated water levels, the reference level for both water levels needs to be known. The same can be said for the supplied bathymetric charts. These are referenced to a local reference point, which is, in turn, referenced to MSL.

Finally the river discharges and computed velocities need to be validated more extensively..

In conclusion: the results of the 2D tidal model seem to be sufficiently accurate to utilize this model for 2D water level applications and for storm surge computations. They provide a more complete image of the tidal motion in the Ayeyarwady delta region than the (less frequent) measured water levels.

7.2 Current model state 3D salt intrusion model

In order to model salt intrusion correctly, a lot of different aspects are important: the upstream river discharges, the bathymetry, the river outline, the tidal motion, the type of sediment and 3D salt and velocity profiles. This already indicates that salt intrusion is a very complex phenomenon to model accurately, that requires a lot of data.

When compared to the preliminary runs performed by Attema(2013), model bathymetry has been adjusted, which was elaborated on in Section 5.3, discharges were adjusted(Section 5.3 as well) and numerical parameters have been tuned(Section 6.1). For more details on the model setup, one is referred to Section 6.1.

The current model approximates the measured 1-ppt isohaline quite well for most of the river branches, especially those in the eastern part of the Ayeyarwady delta (the region which is directly to the west of Yangon). This improvement of the 3D salt intrusion model is also caused by the improvements in the 2D tidal model. As was stated before, the tide is one of the main driving forces of salinity intrusion and a correct representation of the tide in the numerical model is of great importance when setting up a 3D model.

Despite the improvements that were made, many assumptions were needed when setting up the model, and the changes to, for instance, bathymetry are mainly based on interpolations of measured data, as data is scarce in large parts of the model. One needs to be aware of this when using the model or trying to interpret its results.

7.3 Recommendations

Besides the specific recommendations, there are some general recommendations following from this research. First and foremost, it is advised to focus on a smaller model area, for instance the region around the Yangon estuary. This has a couple of reasons:

- computational power required

Running the full 3D model requires a lot of computational power. If this computational power is not available, this leads to long computational times (in the order of days). Besides that, the large model area leads to large output files, which need to be stored and post-processed.

- grid resolution

Focusing on a smaller model area allows you to increase grid resolution, both in the horizontal and in the vertical. This enables you to input more detailed bathymetry, but will also represent the physics more accurately. (as on a coarse computational grid, a lot of the flow characteristics are averaged out)

- data acquisition

Acquiring data for one river branch is much easier and less costly than acquiring data for the entire delta. If one needs to make a detailed model, which is preferred for modelling salt intrusion or sediment-related processes, the availability of measured data is of crucial importance to validate and calibrate the model.

Smaller models can be nested in the large 2D tidal model, to provide the correct water levels and velocities. (as has been said before, the results from the 2D tidal model are sufficient) These smaller models can be used to accurately model specific river branches and to investigate, for instance, the morphodynamics of a particular river branch.

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Appendix A Bathymetric Charts

To improve the model bathymetry, bathymetric charts have been supplied by both DWIR and MPA. An overview of the bathymetric charts is provided here.

Bathymetric Charts supplied by DWIR					
Year	Township	Channel	River	Inside model area	File type
12-13	Nyaung Tone (Nyaungdon)	Bo Myat Tun (BMT) + Ayeyarwady bridge	Ayeyarwady	no	CAD
12-13	Myanaung	Kannaung Channel	Ayeyarwady	no	PDF
12-13	Ingapu	Nyaunggyo channel	Pathein	no	PDF
12-13	Ma u bin (Maubin)	Ma u Bin Bridge channel	Toe	yes	CAD
12-13	Ingapu	U shitkone + Ye Le Kyun Channel	Pathein	no	CAD
12-13	Danuphyu (Danubyu)	Danuphyu channel	Ayeyarwady	no	CAD
12-13	Da de ye (Dedaye)	Dadeye bridge channel	Toe	yes	CAD
12-13	Kyaik lat	Gon nyin dan bridge channel	Kyone tar	yes	CAD
12-13	Ma u bin (Maubin)	Pan ta But Channel	Toe	yes	CAD
12-13	Hinthata (Hinthada-Henzada)	Myo Gwin (Railway)bridge channel	Pathein	no	CAD
12-13	Hinthata (Hinthada-Henzada)	Nga wun Bridge (Myo Gwin) Channel	Pathein	no	CAD
12-13	Nyaung Tone (Nyaungdon)	Pan haling Channel	Ayeyarwady	no	CAD
12-13	Ma u bin (Maubin)	Out Htone Channel	Ayeyarwady	no	CAD
12-13	Kan gyi daung	Thet Kay Chaung Channel	Da Ka	no	CAD
12-13	Maw la Myine Kyun	Ya Zu daing bridge No. (1) Channel	Ya Zu Daing	yes	CAD
13-14	Bogalay	Gon nyin dan river channel	gon nyin dan	yes	CAD
13-14	La but ta (Labutta)	Thin gan gyi (Ywe river) channel	Ywe	yes	CAD
13-14	Pya pon (Pyapon)	Pyapon channel	Pyapon	yes	CAD
13-14	Nyaung Tone (Nyaungdon)	Sa ma lauk channel	Panhlaing	no	CAD

13-14	La but ta (Labutta)	Sa Gyin Chaung channel	Sa Gyin Creek	yes	CAD
13-14	Nyaung Tone (Nyaungdon)	Bo Myat Tun (BMT) + Ayeyarwady bridge	Ayeyarwady	no	CAD
13-14	Kan gyi daung	Da Ka river channel	Da Ka	no	CAD
13-14	Kan gyi daung	Da Ka river channel (2)	Da Ka	no	CAD
13-14	La but ta (Labutta)	La but ta (kanna) channel	Ywe	yes	CAD

Table A.1: Bathymetric charts provided by DWIR

Bathymetric Charts supplied by MPA					
Year	Township	Channel	River	Inside model area	File type
N/A	Thilawa port area	D'Silva shoal channel	Yangon	yes	PDF
N/A	Thilawa port area	Naval dockyard to mitt jetty	Yangon	yes	PDF
N/A	War ba lauk thauk	Myat Sein Kyun channel	Yangon	yes	PDF
13-14	Botahtaung	Monkey point and Dunneedaw reach	Yangon	yes	PDF
13-14	Thaunggon	Yangon river western channel	Yangon	yes	PDF
13-14	Thanlyin	Between Monkey point to Thanlyin bridge	Bago	yes	PDF
13-14	Thilawa port area	Chokey shoal channel	Yangon	yes	PDF

Table A.2: Bathymetric charts supplied by MPA

Appendix B Simulated water levels & Measured water levels

In this Appendix, an overview is given of simulated water levels compared with measured water levels for particular gauging stations in the Ayeyarwady delta region. (the gauging stations are listed in Table 4.1 and their location can be seen from Figure 4.1)

The figures plotted in this section display the simulated water levels (as has been generated by Delft3D) in blue and the measured water levels in red. As the water levels are only measured three times daily, these are displayed as dots. The simulated water levels are displayed as continuous lines.

Simulated vs. measured water levels for 2D tidal model run ***1*** (corresponds with Section 5.2)

In Section 5.2, the results for simulation run 1 are discussed, when compared with the measured water levels. The results for each gauging station included in the analysis are presented here alphabetically. The period for which the values are plotted is March 2012. Water levels are relative to Mean Sea Level (MSL).

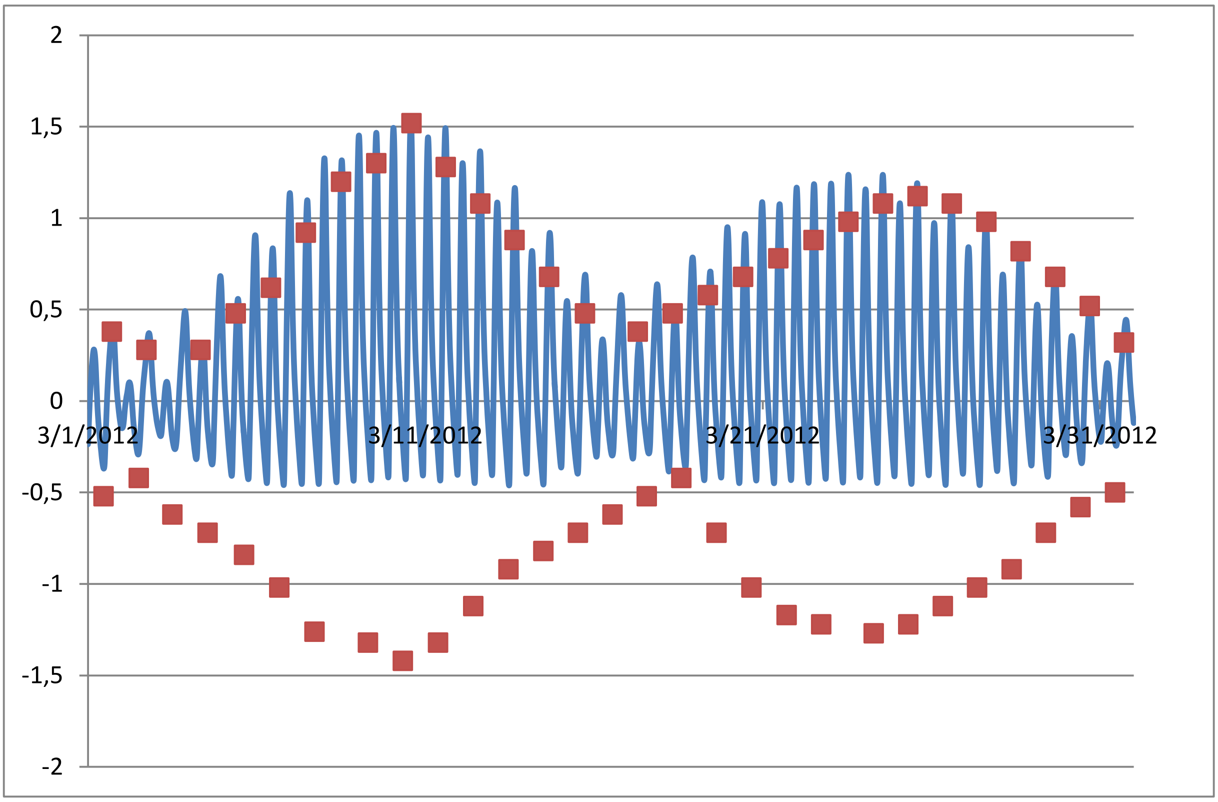

Figure B.1: Simulated vs measured water levels at Amar gauging station – Run 1

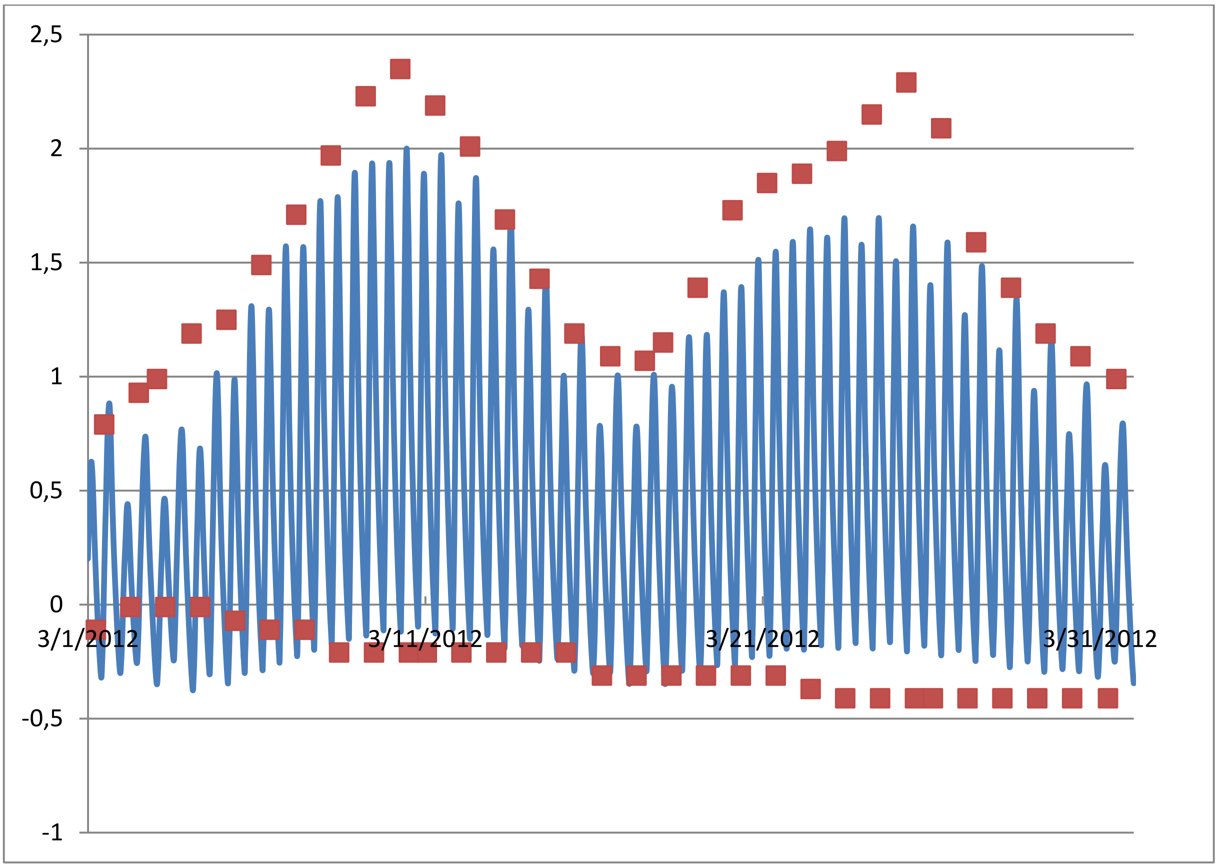

Figure B.2: Simulated vs measured water levels at Dedaye gauging station – Run 1

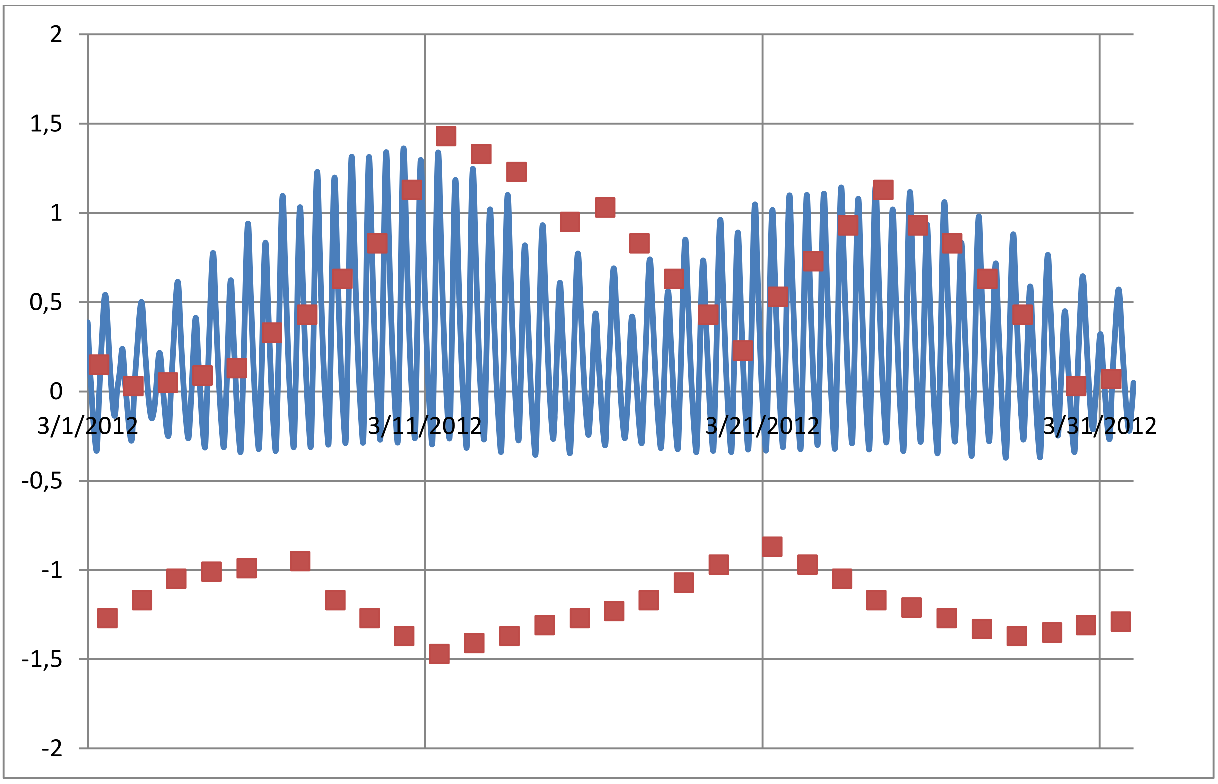

Figure B.3: Simulated vs measured water levels at Hlaingbon gauging station – Run 1

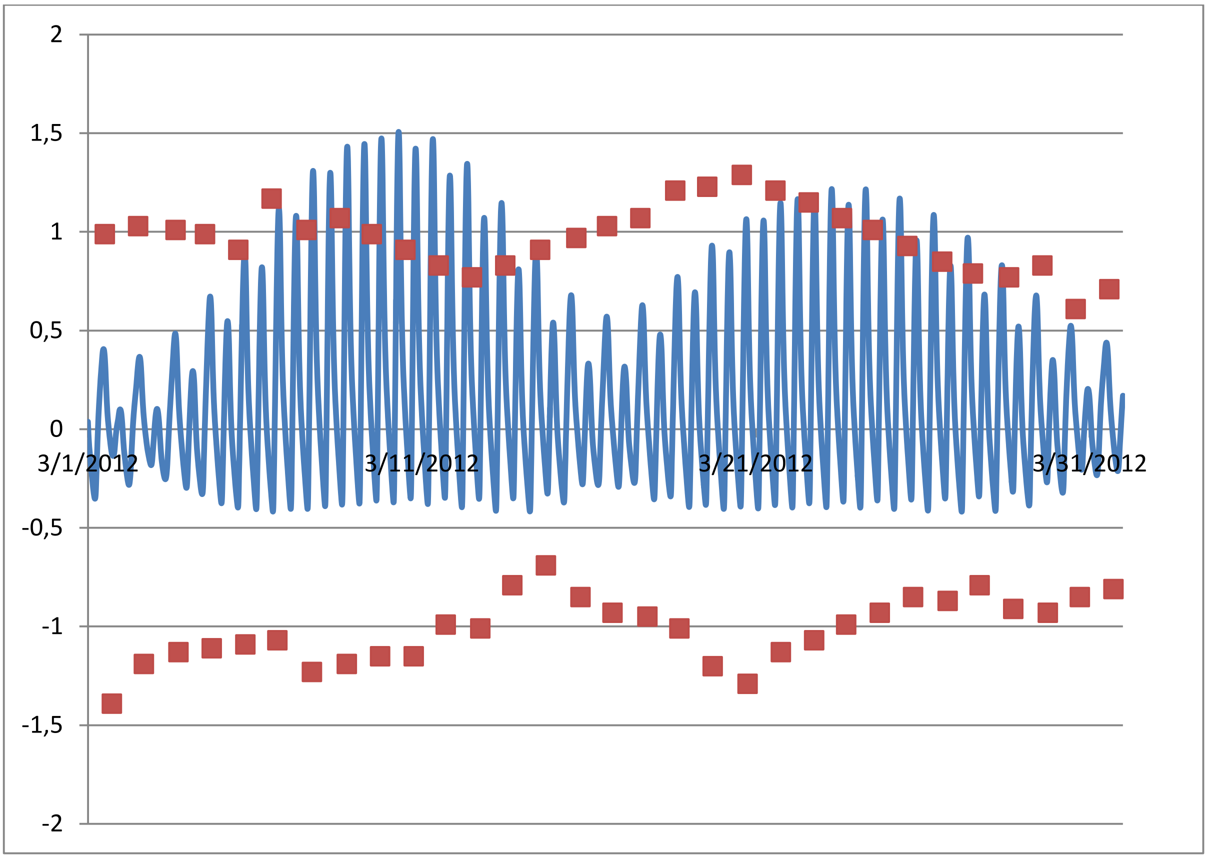

Figure B.4: Simulated vs measured water levels at Kadonkani gauging station – Run 1

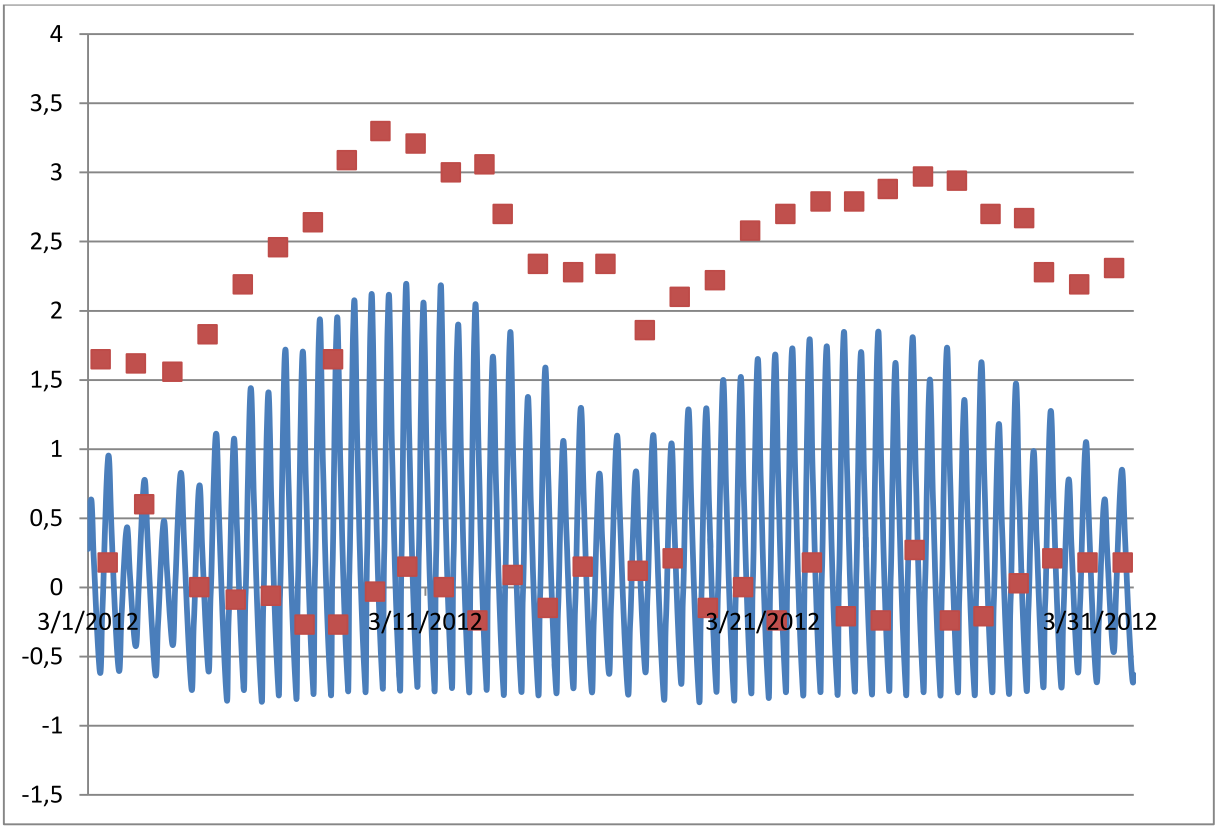

Figure B.5: Simulated vs measured water levels at Kungyankon gauging station – Run 1

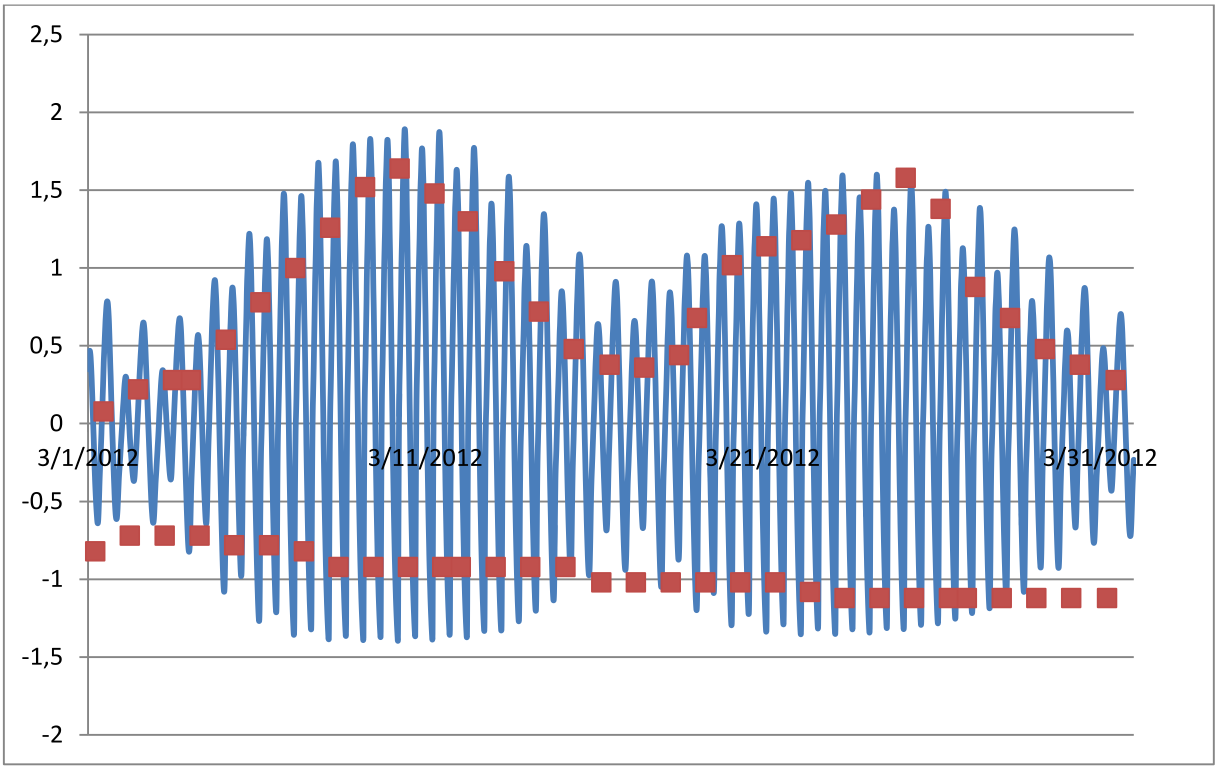

Figure B.6: Simulated vs measured water levels at Kyondar gauging station – Run 1

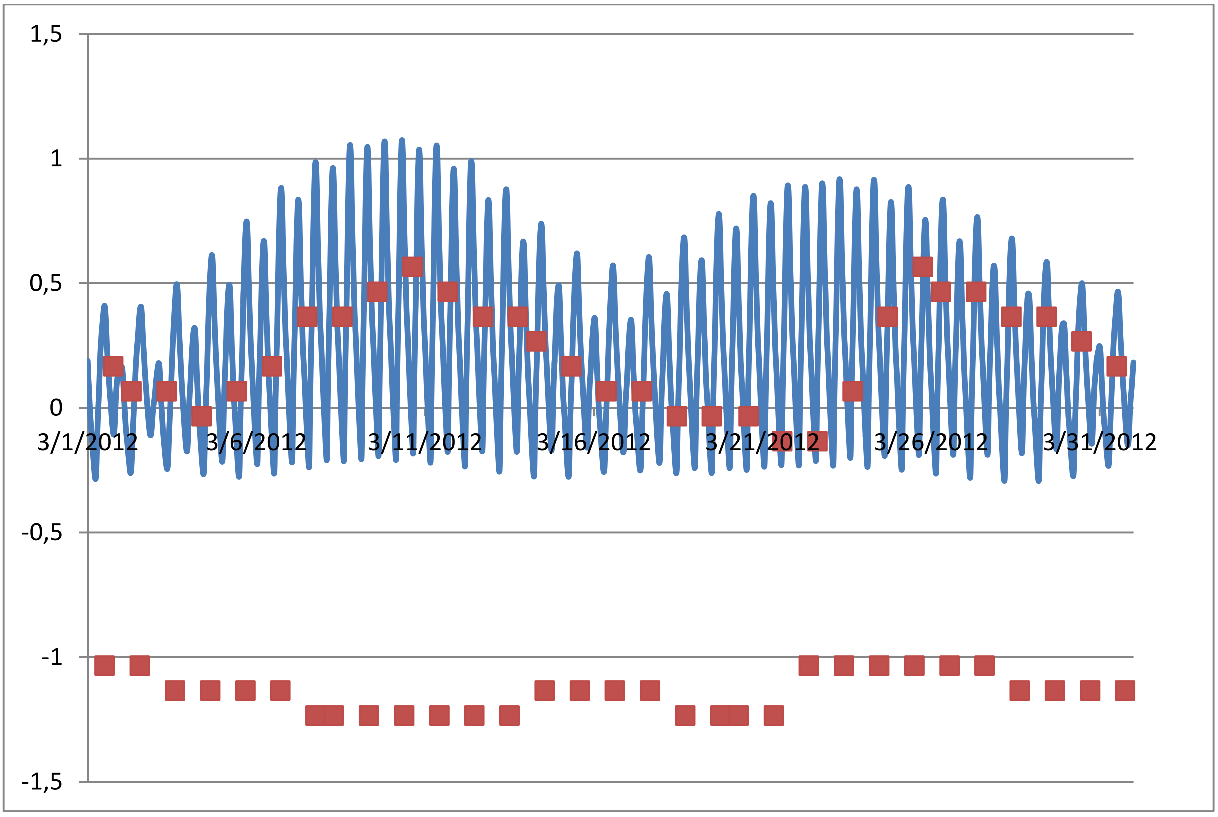

Figure B.7: Simulated vs measured water levels at Laputta gauging station – Run 1

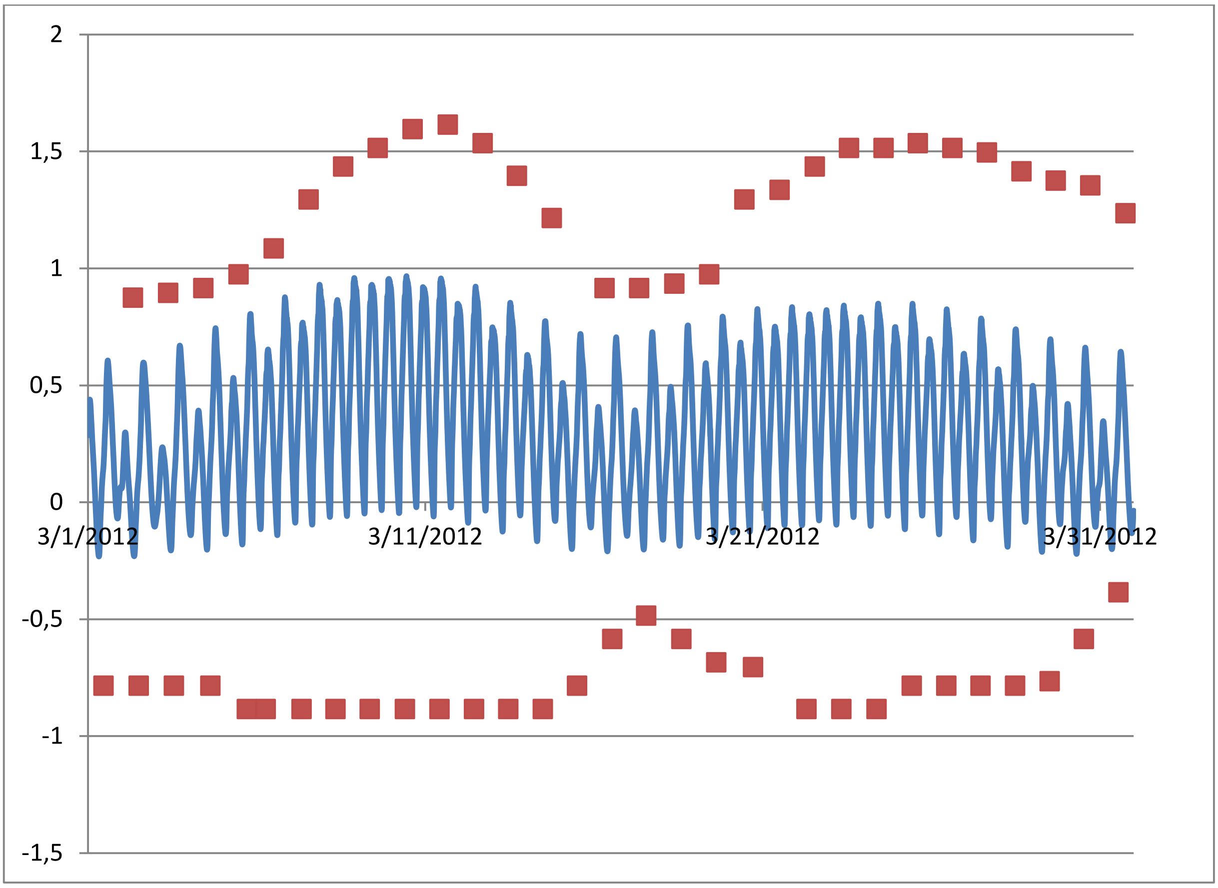

Figure B.8: Simulated vs measured water levels at Pyopye gauging station - Run 1

Simulated vs. measured water levels for 2D tidal model run 2 (corresponds with Section 5.3)

In Section 5.3, the results for simulation run 2 were discussed, when compared with the measured water levels. The results for each gauging station included in the analysis are presented here alphabetically. However, now there are two periods for which the values are plotted. These are, once again, March 2012, but next to that also a five-day period in the month of March 2012, to actually see whether the measured and simulated water levels match when they are observed in detail. Water levels are relative to Mean Sea Level (MSL) with a shift in the measured water levels as has been indicated in Table B.1.

Name	River	Shift of measured water levels
Amar	Bogalay	+ 0.3m
Dedaye	Toe	-0.3m
Hlaingbon	Ayeyarwady	+0.5m
Kadonkani	Bogalay	+0.2m
Kungyankon	Kadonkani	-1.0m
Kyondar	Toe	+0.3m
Laputta	Ywe	+0.7m
Pyopye	Pyarmalot	-0.2m

Table B.1: Shift of measured water levels per gauging station

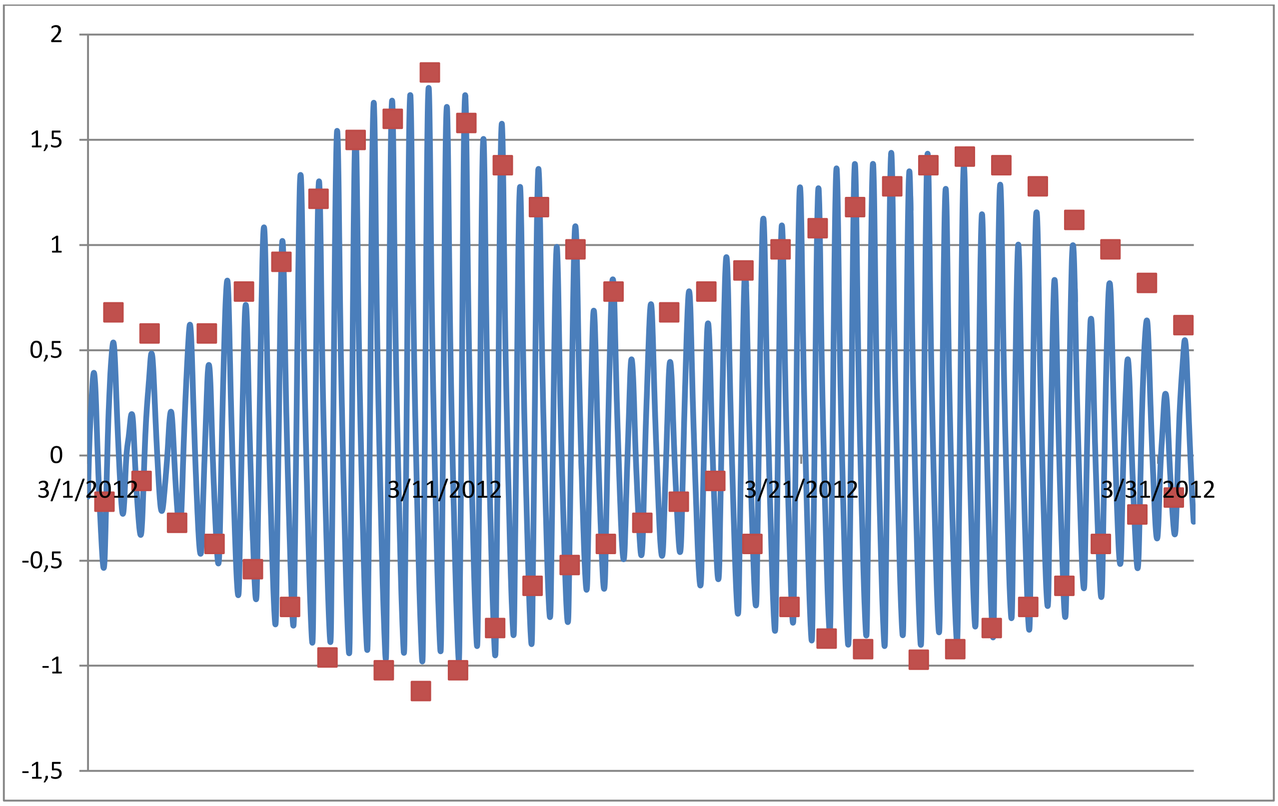

Figure B.9: Simulated vs measured water levels at Amar gauging station, full month – Run 2

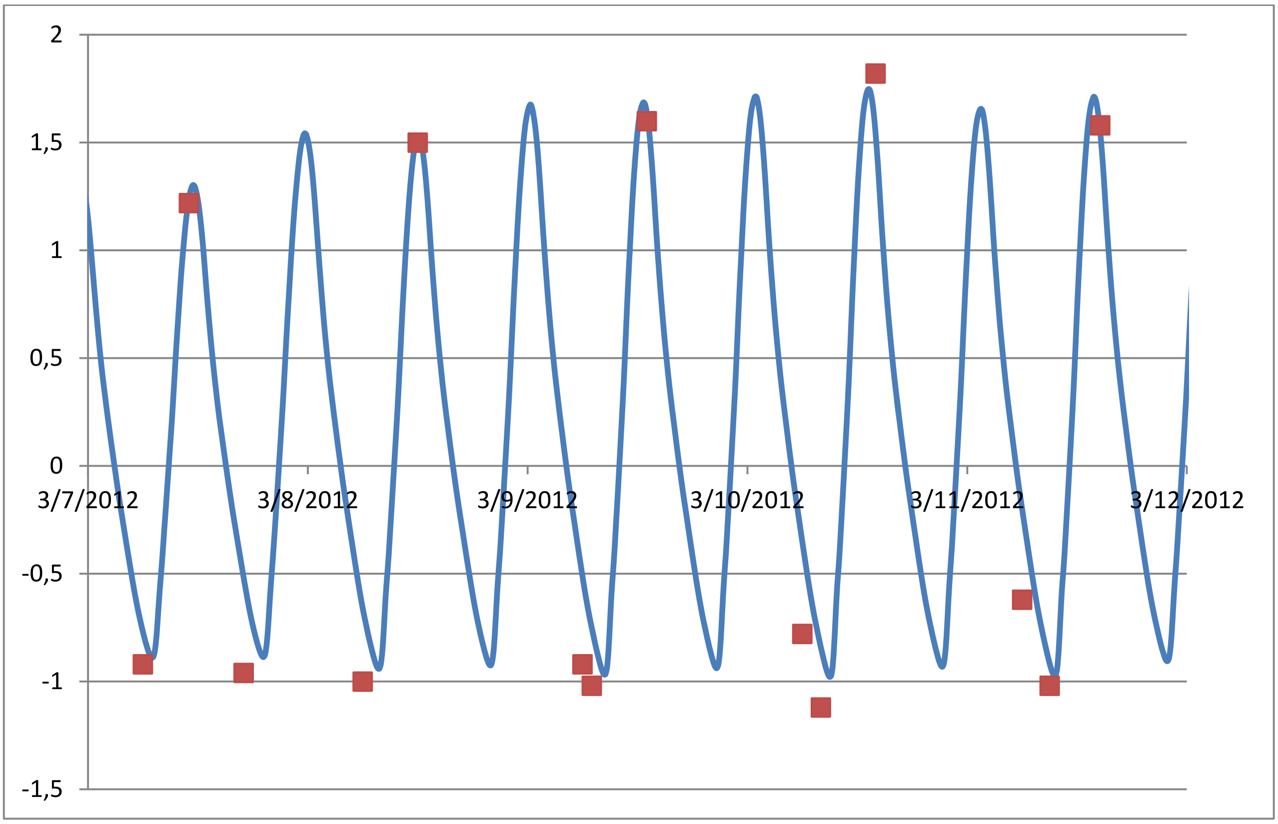

Figure B.10: Simulated vs measured water levels at Amar gauging station, 7 March till 12 March – Run 2

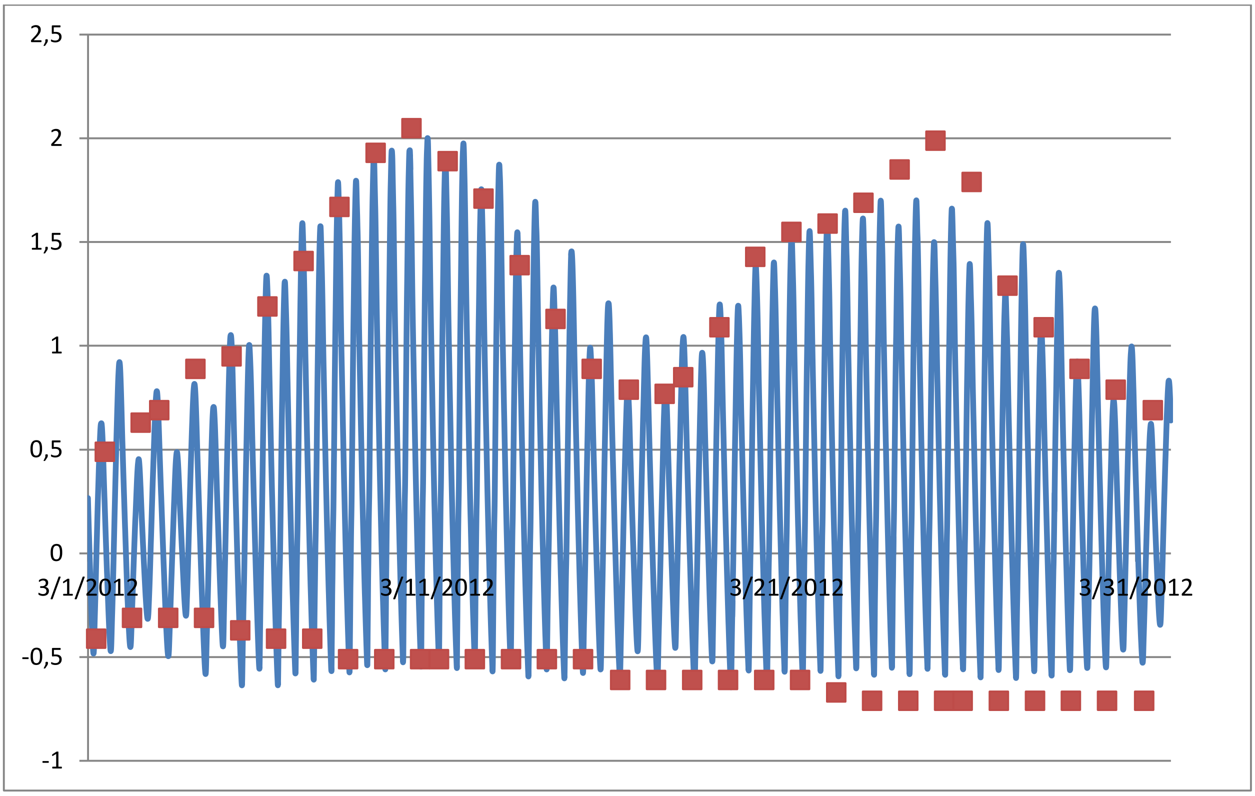

Figure B.11: Simulated vs measured water levels at Dedaye gauging station, full month – Run 2

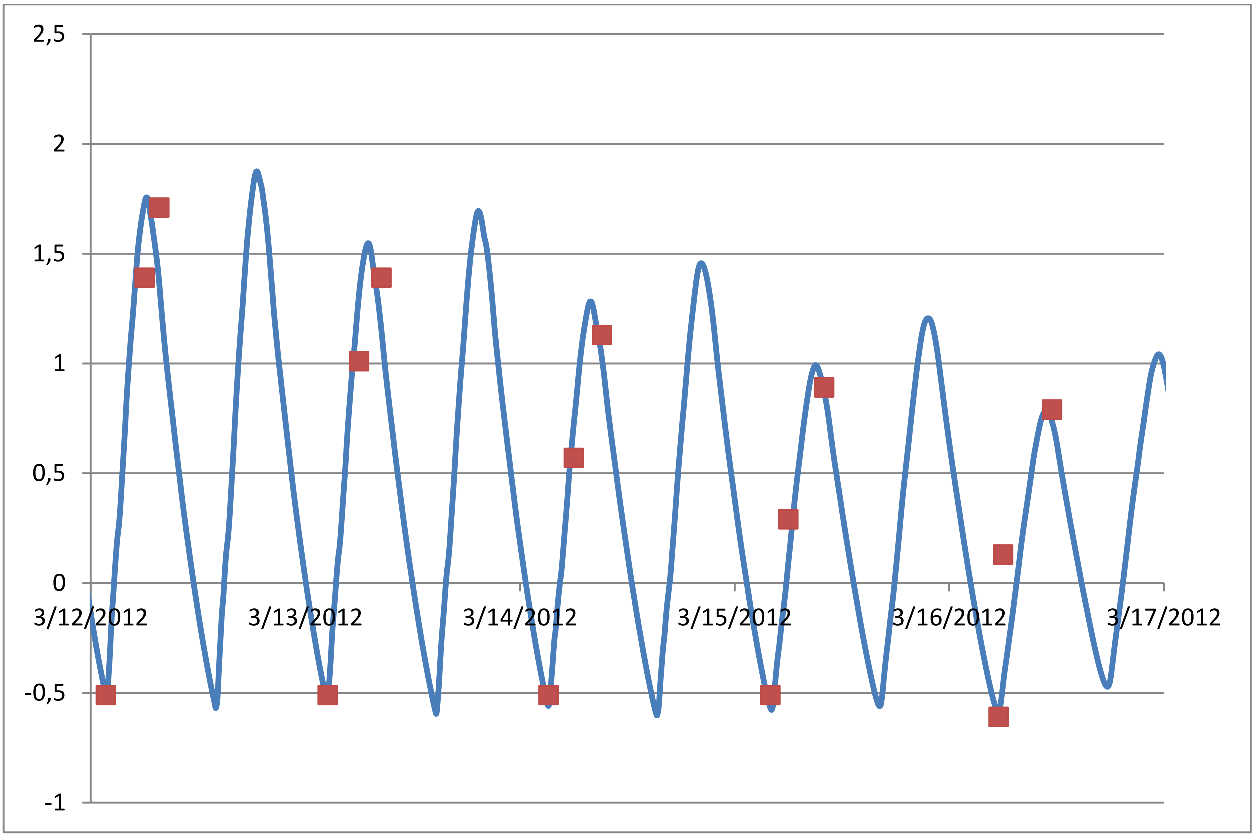

Figure B.12: Simulated vs measured water levels at Dedaye gauging station, 12 march till 17 march – Run 2

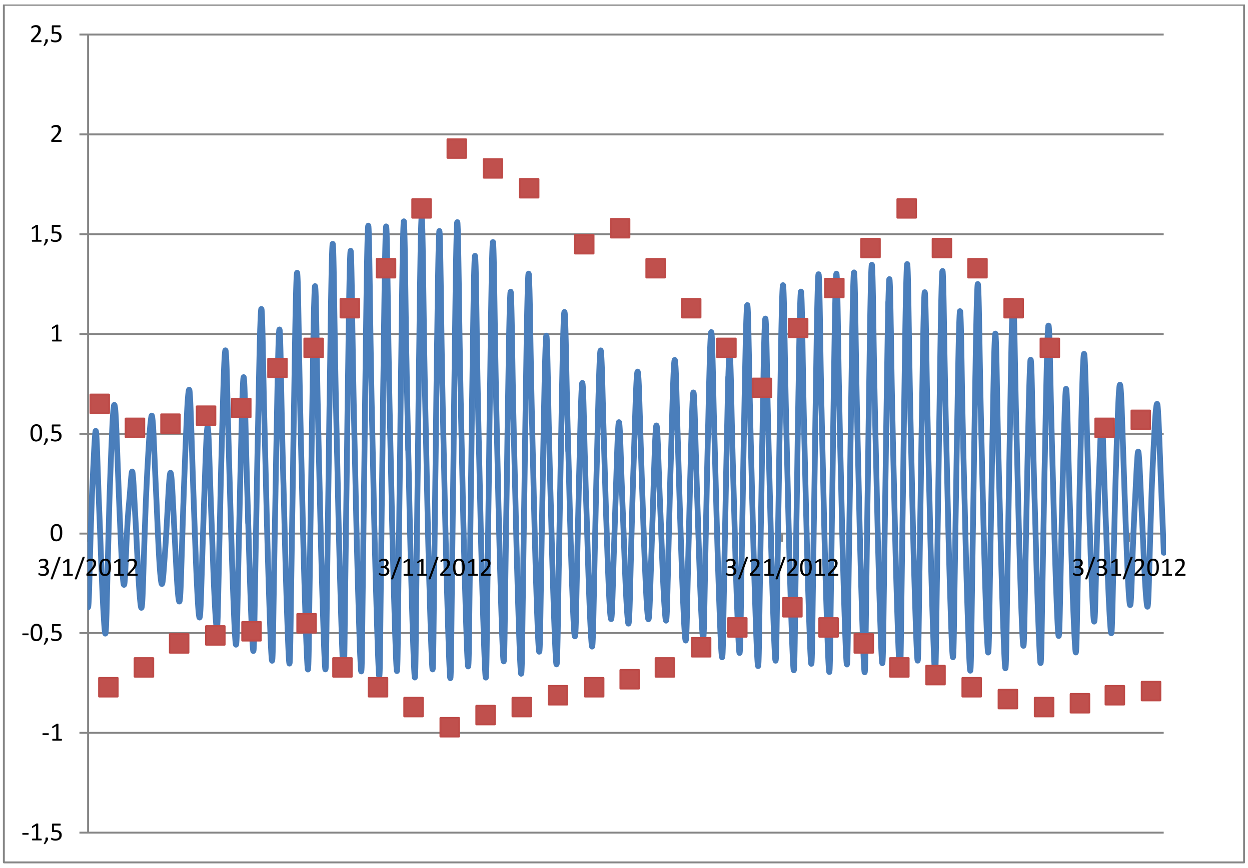

Figure B.13: Simulated vs measured water levels at Hlaingbon gauging station, full month – Run 2

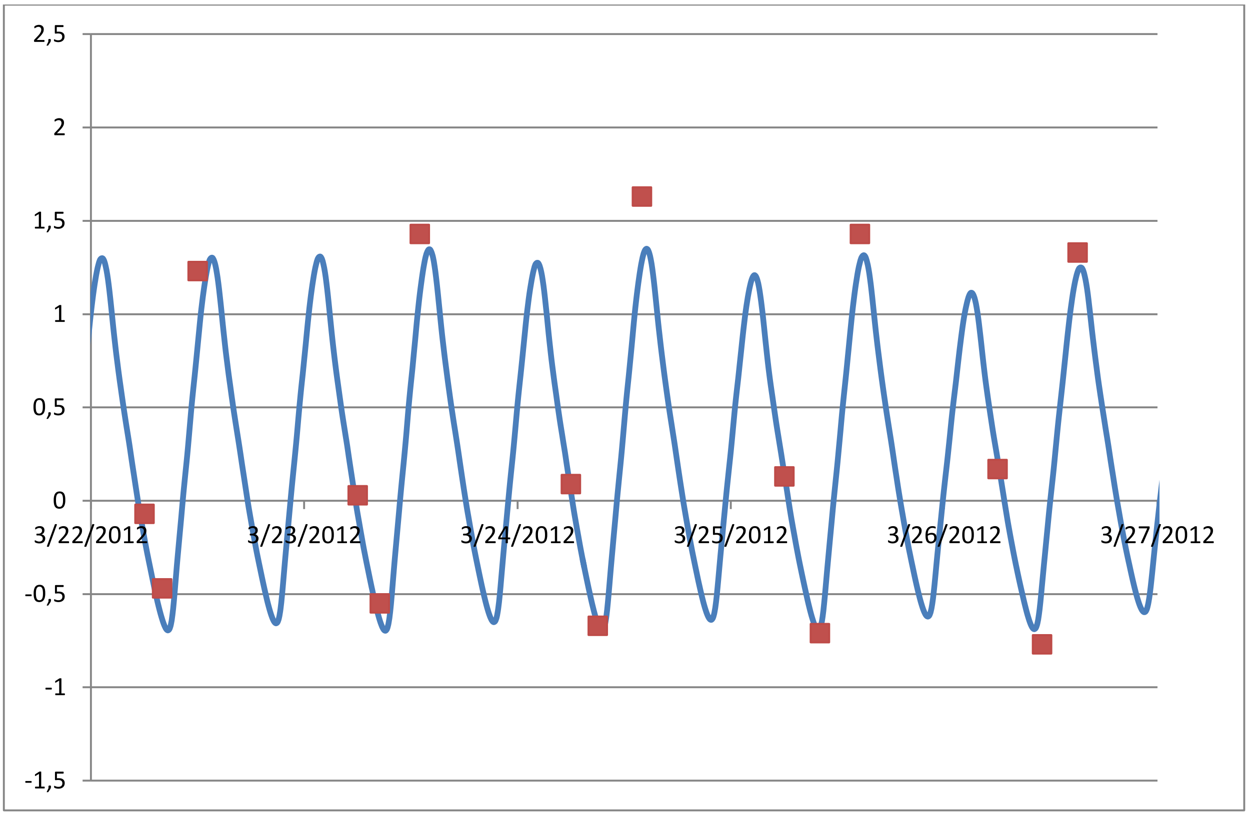

Figure B.14: Simulated vs measured water levels at Hlaingbon gauging station, 22 March till 27 March – Run 2

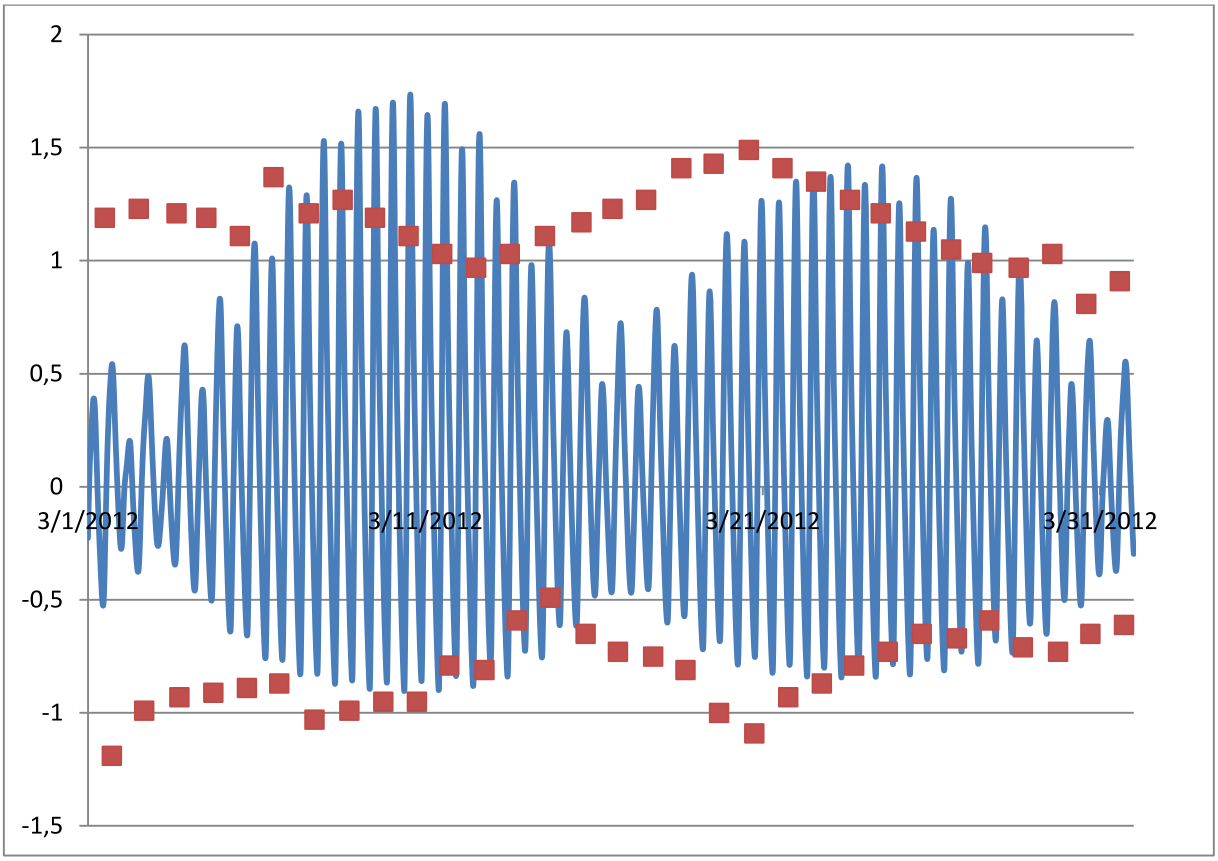

Figure B.15: Simulated vs measured water levels at Kadonkani gauging station, full month – Run 2

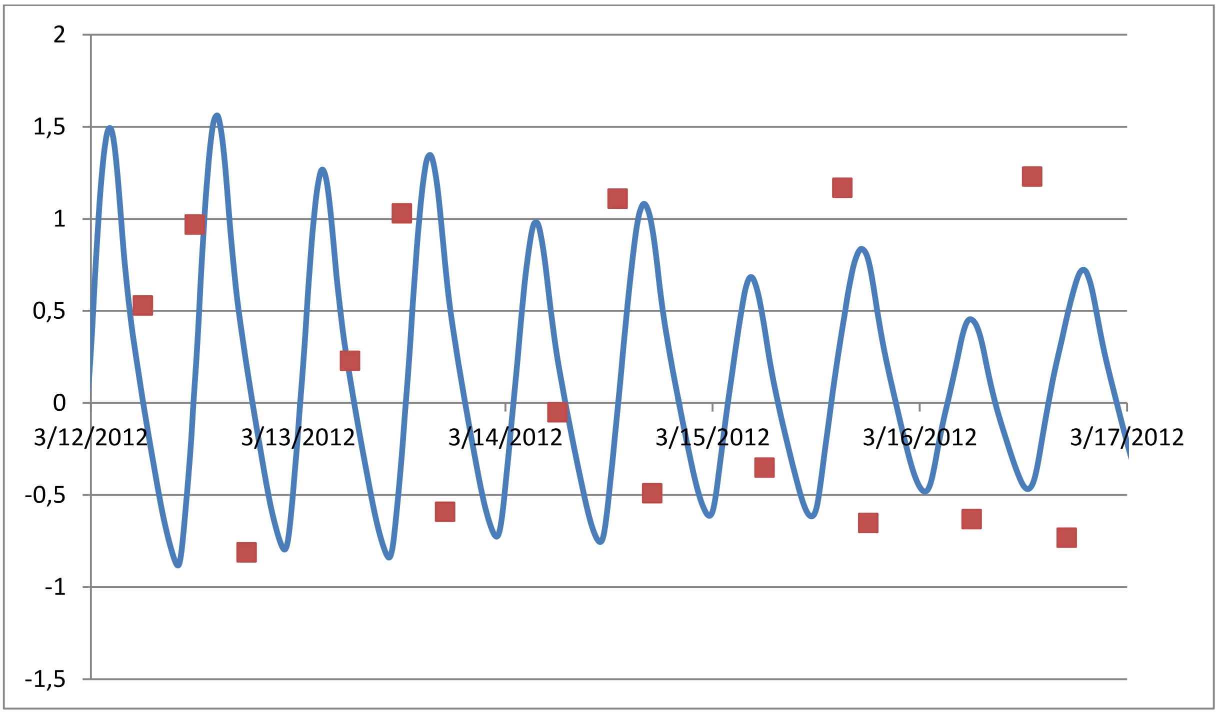

Figure B.16: Simulated vs measured water levels at Kadonkani gauging station, 12 March till 17 March – Run 2

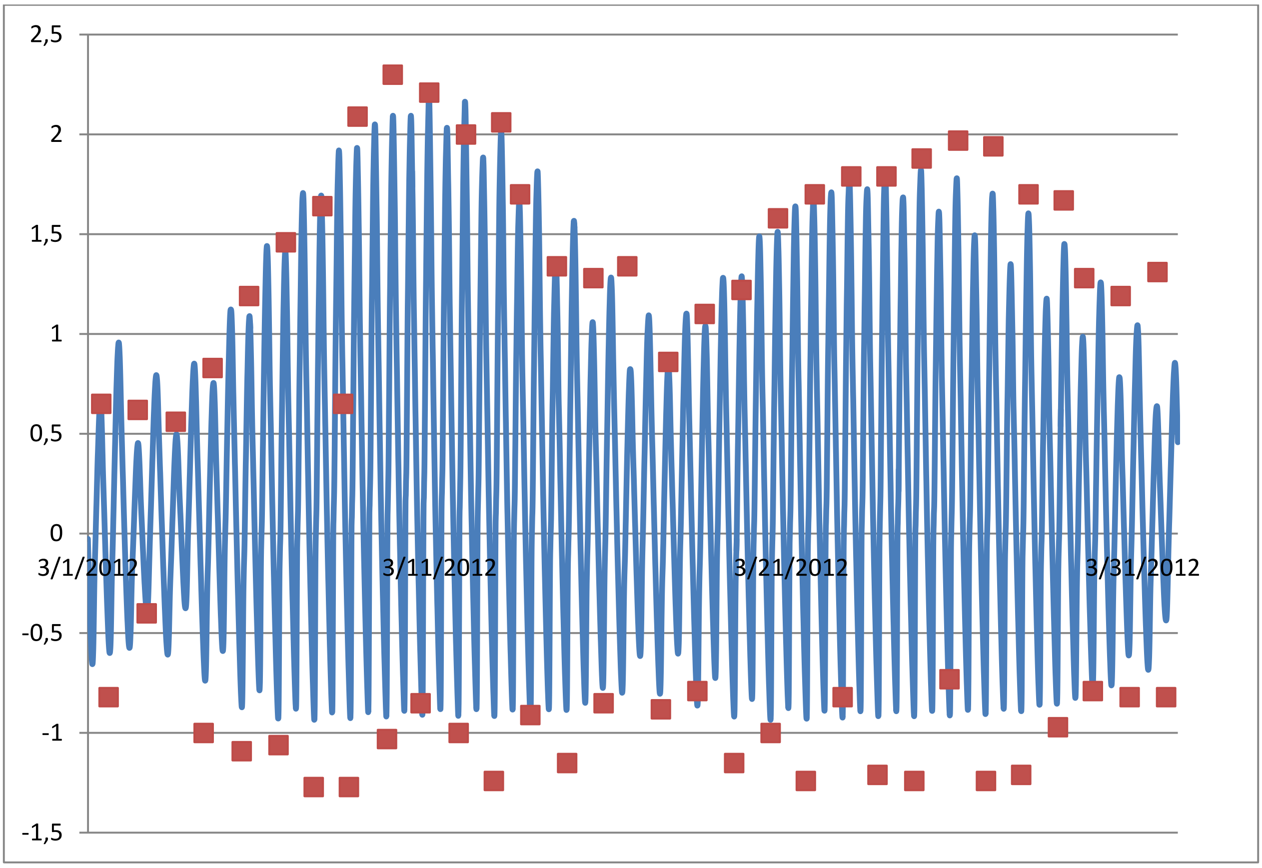

Figure B.17: Simulated vs measured water levels at Kungyankon gauging station, full month – Run 2

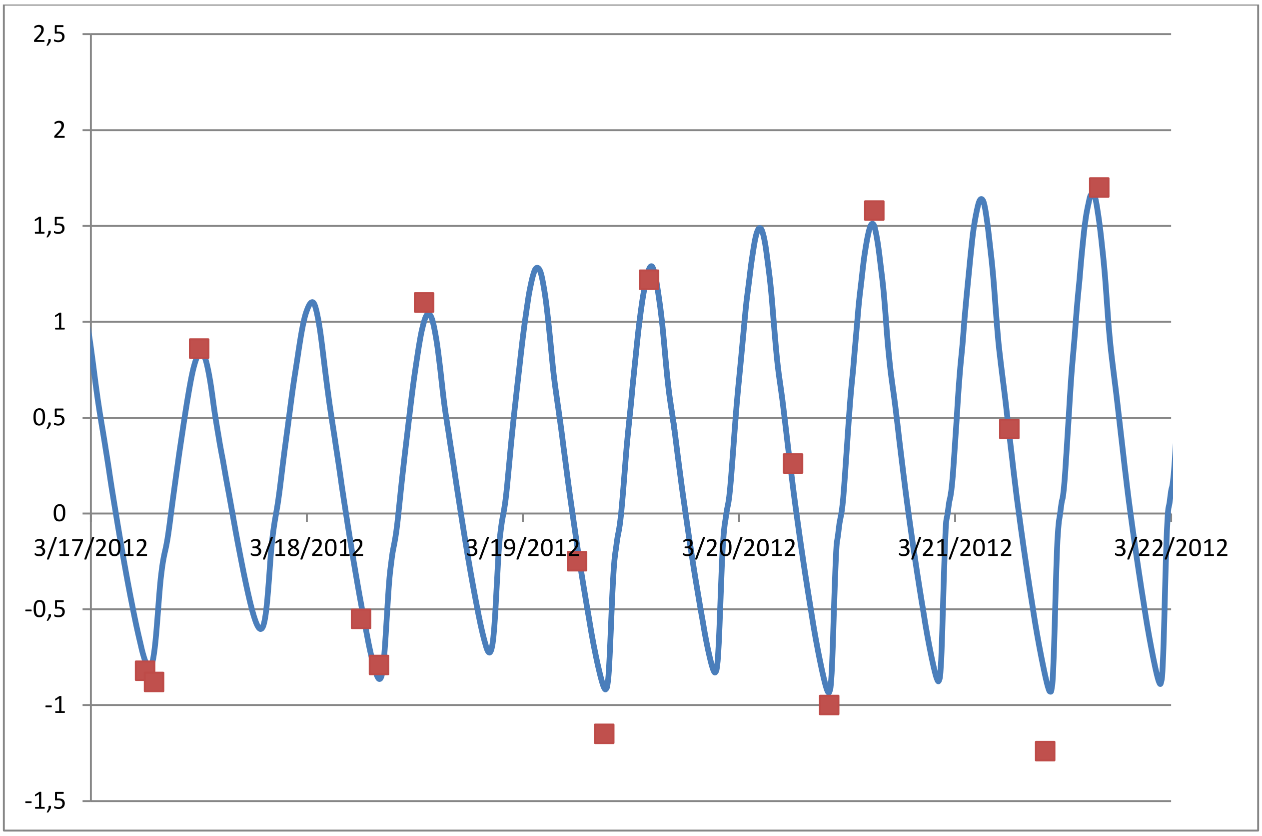

Figure B.18: Simulated vs measured water levels at Kungyankon gauging station, 17 March till 22 March – Run 2

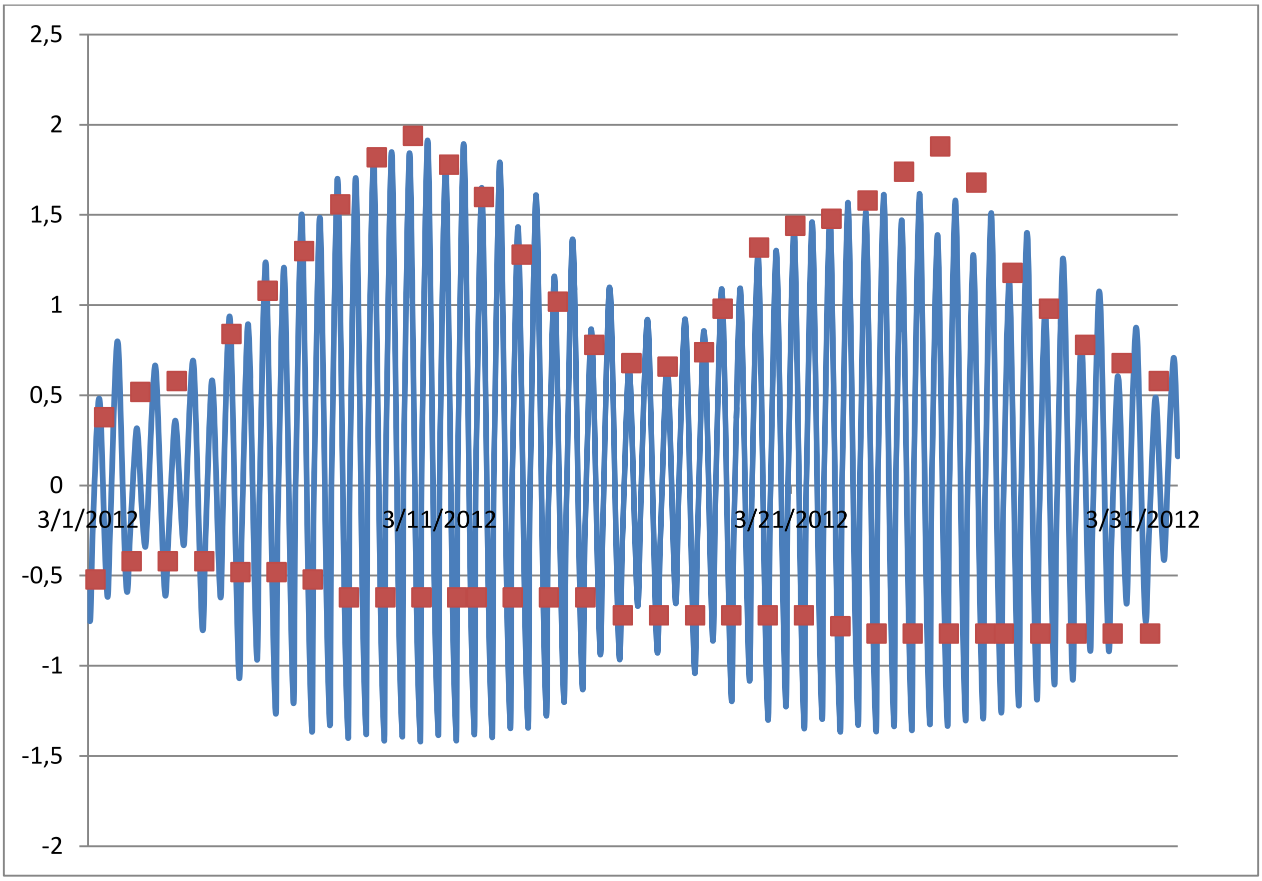

Figure B.19: Simulated vs measured water levels at Kyondar gauging station, full month – Run 2

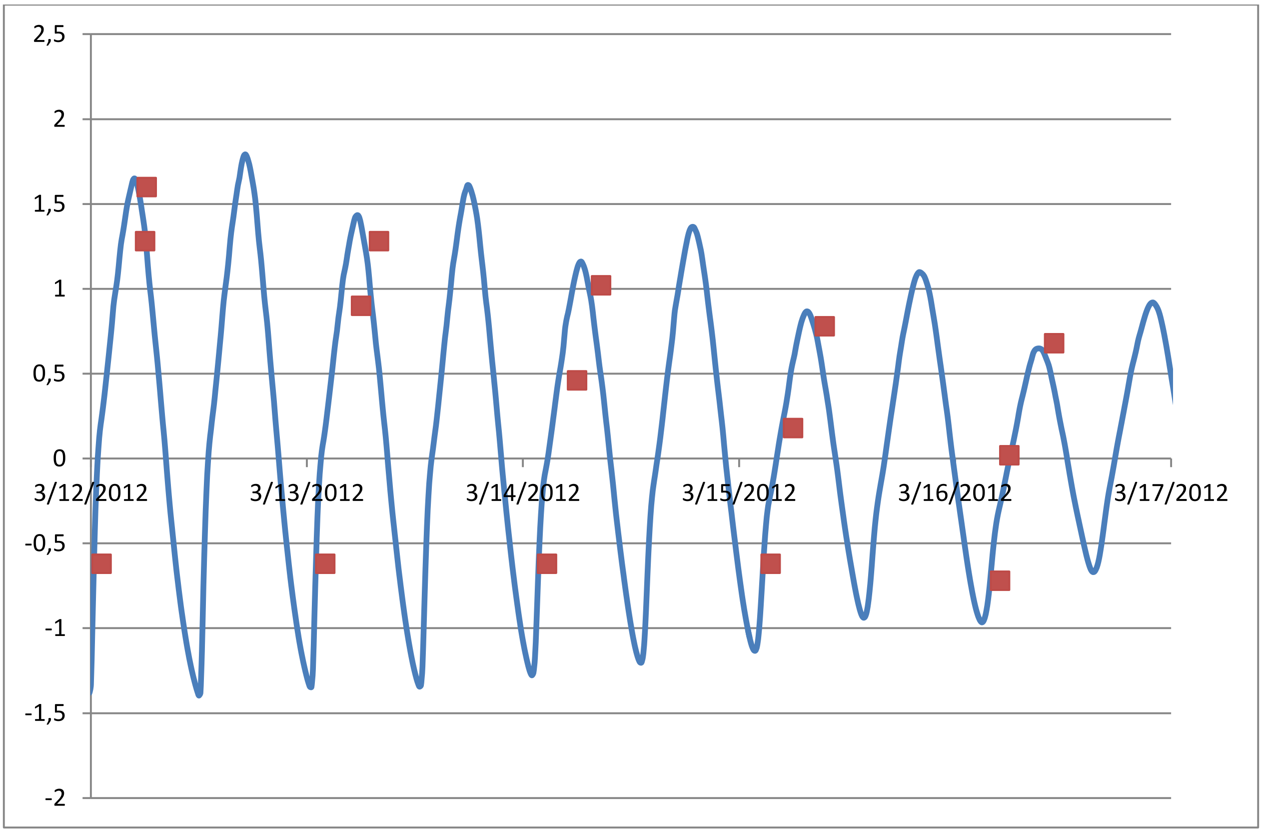

Figure B.20: Simulated vs measured water levels at Kyondar gauging station, 12 March till 17 March – Run 2

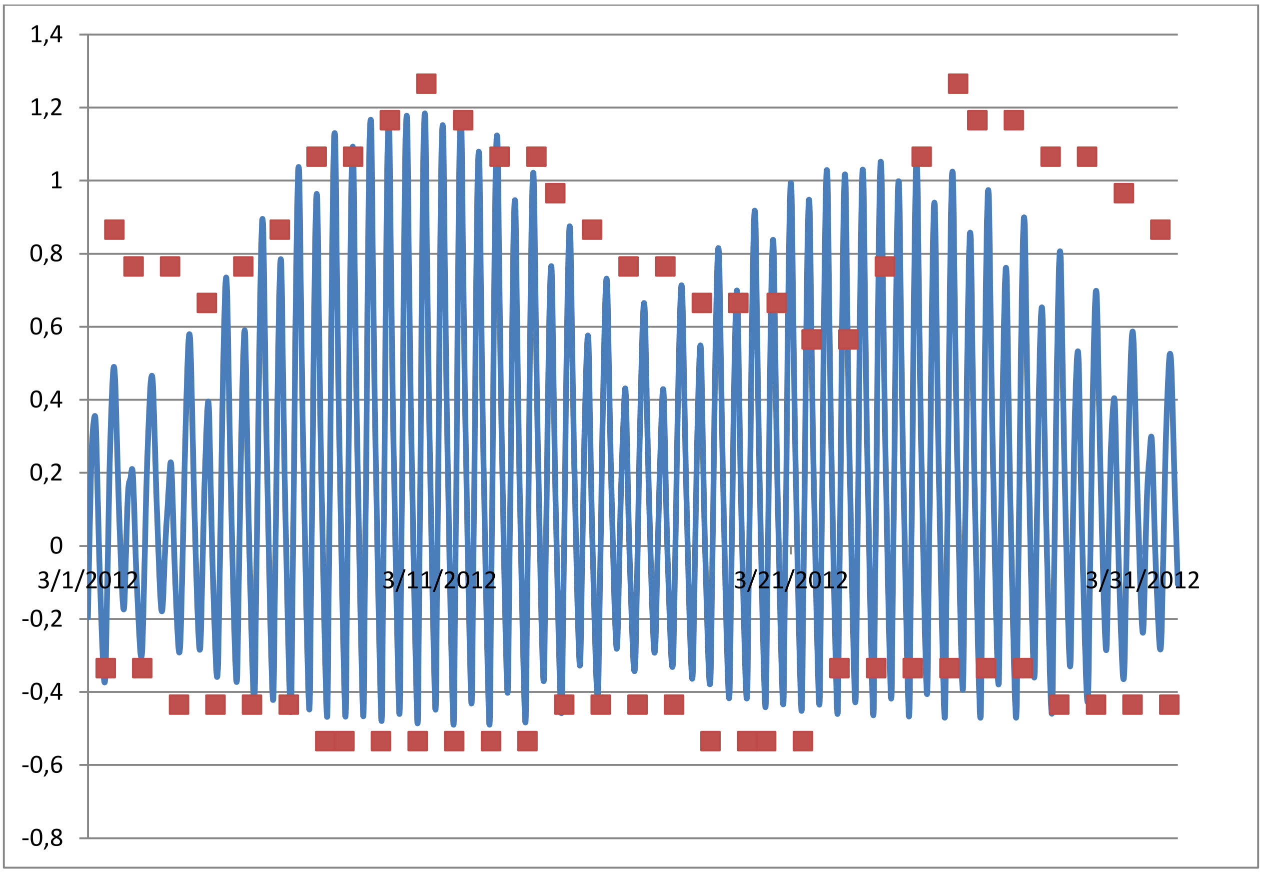

Figure B.21: Simulated vs measured water levels at Laputta gauging station, full month – Run 2

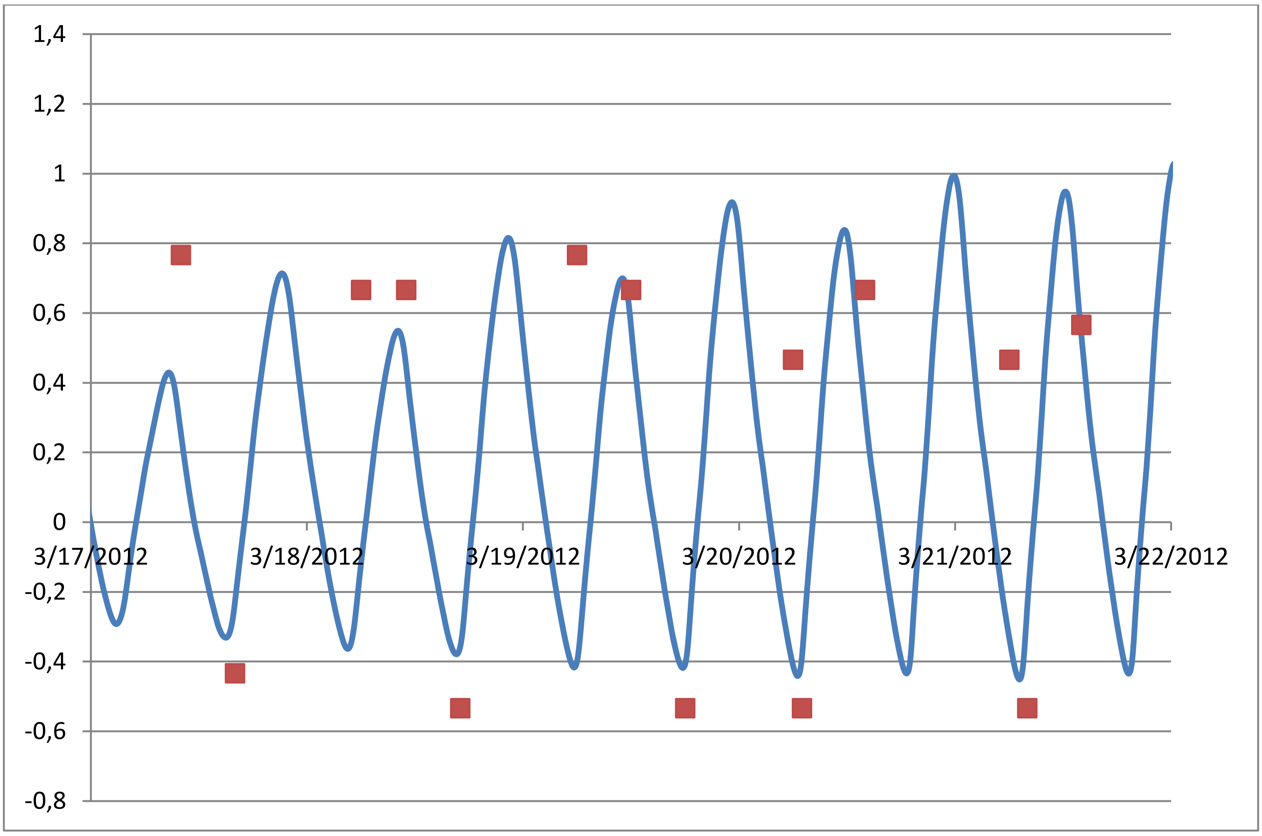

Figure B.22: Simulated vs measured water levels at Laputta gauging station, 17 March till 23 March – Run 2

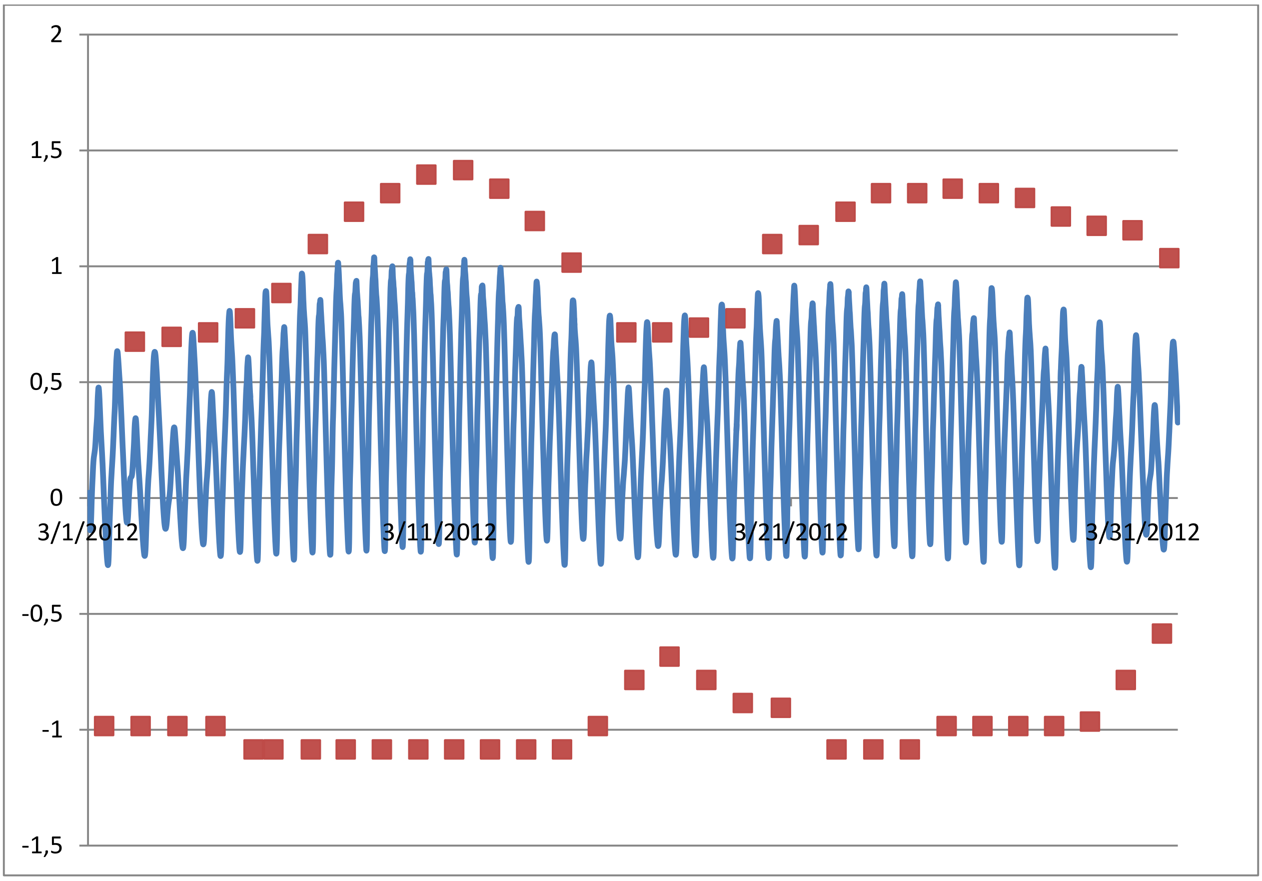

Figure B.23: Simulated vs measured water levels at Pyopye gauging station, full month – Run 2

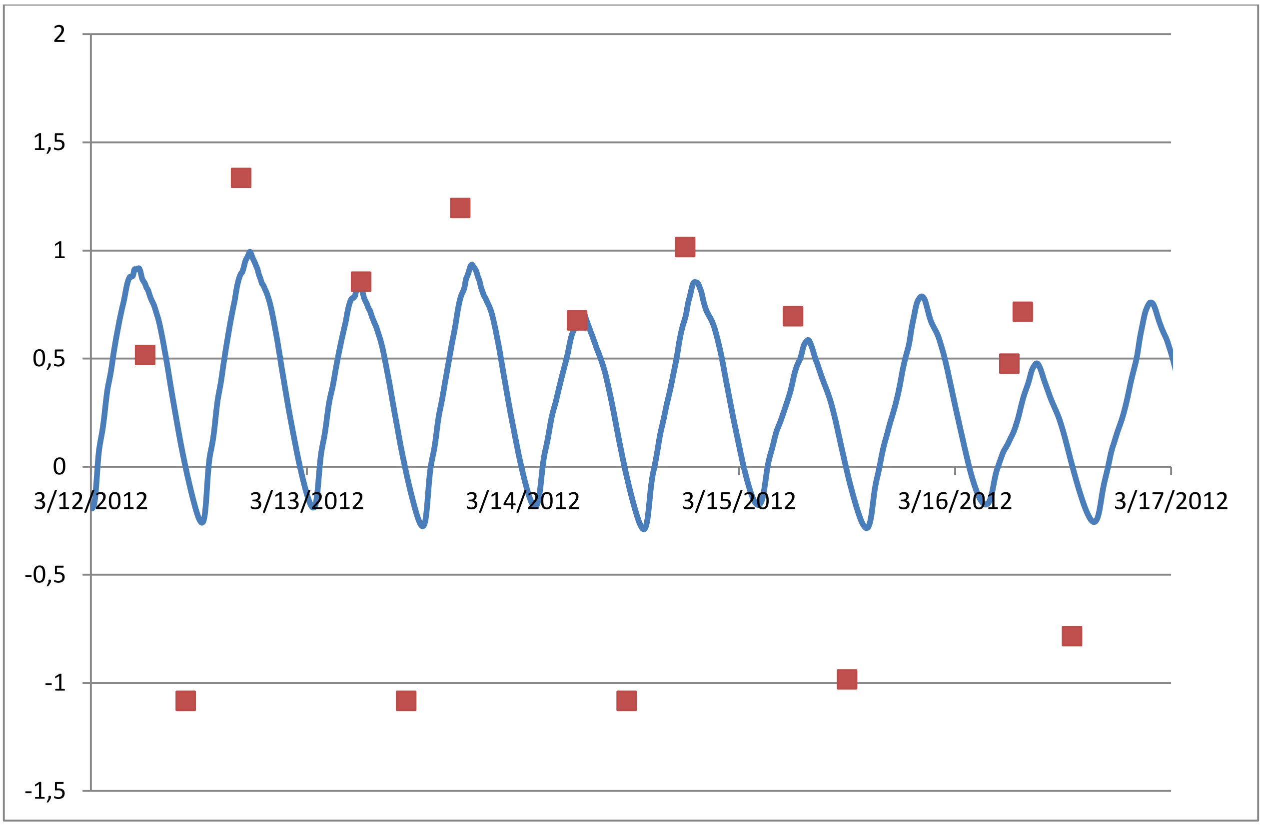

Figure B.24: Simulated vs measured water levels at Pyopye gauging station, 12 March till 17 March – Run 2