Project Jamaica 2012

Sedimentation and Flood assessment for the expansion of the Kingston Harbour

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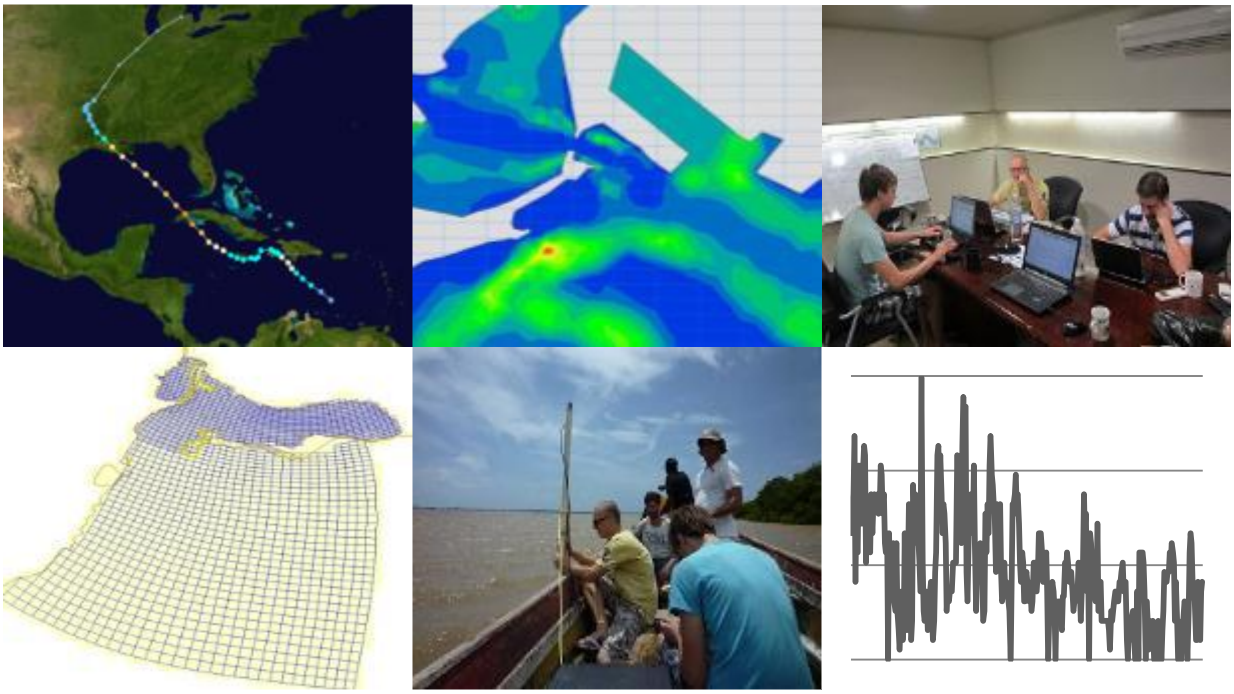

26-9-2012

Preface

In the last 9 weeks research has been done by four students of the Delft University of Technology. This project is part of the master Hydraulic Engineering in which a Multidisciplinary project can be done.

We would like to thank the International office at the Civil Engineering department from the TU Delft to make it possible to do such a project. Thanks to ir. H.J. Verhagen, our supervisor from the TU Delft, to put up the contact with Smith Warner and for being our mentor during the project period.

We did the research in cooperation with Smith Warner International Ltd. (SWIL). With some brainstorm sessions our research topic was determined in the first weeks. The research subject forced us to start at the beginning of the project cycle and come up with a problem description after the modeling. Therefore a short time was available to come up with a solution of the problem. Eventually this report gives a good insight into the conditions of the present Kingston Harbour area and the consequences of the harbour expansion, which is a good base for further study.

The modeling didn't go always as smooth and there was a lot of struggling with the software. Therefore we would like to thank Graham Jervis (SWIL) for the help with the MIKE program and Gerben de Boer (Deltares) for the help with the Delft3D program via e-mail.

We would also like to thank Jamel Banton for his input during meetings and for our startup in Jamaica the first few weeks. Thanks to David Smith and Philip Warner (via Skype) for their input during the meetings. We would like to thank the company for arranging the apartment were we stayed in. Finally Dyonne Harper will be thanked for her help of some administrative issues during the weeks and all the things she took care of without us even knowing.

Kingston, Jamaica, 26 september 2012

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Summary

The capacity of the Panama Canal is being increased. This work is planned to be finished in 2014. Therefore this shipping route will become busier and sailed by larger vessels. Especially Kingston, Jamaica is on the route towards the Panama Canal, so these ships will pass the Kingston Harbour as well. In order to strengthen its competitive position and increase annual throughput, the harbour needs to be expanded as well, in particular the container terminal of the harbour. This expansion entails land reclamation for a new terminal, expansion of the existing Kingston Container Terminal and dredging of the harbour area. Changes in the hydrodynamics of this area are expected. The expansion is divided into two phases. Both expansions are planned around the connection between Hunts Bay and the Kingston Harbour. Hunts Bay is the output location for the Rio Cobre and several storm surge canals.

At this moment the shipping channels slowly accrete. When the harbour is expanded, the local and global sediment transport is likely to change. During this project it is investigated whether these changes are significant and if they will have a negative influence on the Kingston Harbour area. Also the increase of flood risk for the area surrounding Hunts Bay is investigated. This investigation is done by modeling the hydrodynamics of the Kingston Harbour area with MIKE21 and Delft3D, where after both modeling programs are compared to each other. For the input data for the models, research has been done concerning the boundary conditions. This data is gathered from several projects done in the past about other areas in the harbour and fieldwork in Hunts Bay.

During the year, most of the wind comes from the east and south-east direction. There are also two mayor streams which debouch into Hunts Bay, namely the Sandy Gully and the Rio Cobre. Since there is only discharge known about the Rio Cobre (daily values from 1985 to 2010), only the Rio Cobre is taken into account. The maximum measured value was 563 m^3/s (during hurricane IVAN) and the average value is about 12 m^3/s. For the sediment input data some fieldwork is done in Hunts Bay to gather information about the type of soil. From this it is concluded that it is silt, which is confirmed after a lab research of the sediment. However these accurate soil properties couldn't be implemented into the models due to the lack of time. During the fieldwork also a bathymetric survey was done, which showed that Hunts Bay is sedimented compared to the previously used bathymetric data, gathered from admiralty charts in 2000.

Calibration of both models is done by comparing it with the measured water level and flow velocities underneath the Causeway Bridge. Since this is the only point where data was available for, the calibration kept global, and should be improved in the future.

Since there is not enough correlation found between the discharges and the wind to define a 1/x year event, it is chosen to model four extreme events that have passed Jamaica in the past, namely:

- Hurricane Ivan (2004): High peak discharge and high winds coming from the east
- Hurricane Gustav (2008): High peak discharge and exceptional winds from the north.
- Tropical storm Nicole (2010): High Peak discharge and moderate winds
- May Flood (2002): High discharge for a period of 13 days with low wind speeds

Due to a lack of data, the output value of the sediment quantities could not be used for itself, but only for a comparison between the present situation and the situation with the expansion included.

The modeling showed that most of the sediment transport into the shipping channel is caused by the high discharge of the Rio Cobre. Ivan showed the most extreme sedimentation and the biggest change due to the expansion. In the present situation the shipping channel is gradually silting, with two areas where the siltation is concentrated. With the first phase expansion these 'mountainous' areas will be much more concentrated. However it can be concluded that the changes in the sediment transport due to the first phase expansion are not significant and will not lead to more problems than there are without this expansion. For this problem a sediment trap is proposed. At first it was placed just eastward of the Causeway Bridge, but this didn't solve the problem and it would be in the way for the phase two expansion. Therefore a sand trap is designed in Hunts Bay, just westward of the Causeway Bridge. This location is really effective, since it stores the sediment from the rivers. This solution prevents the shipping channel to silt. Again, since the lack of reference data, on the size of the pit nothing can be said.

There is also looked at the flood risk of the surroundings of Hunts Bay after the construction of the phase 2 expansion. The connection between Hunts Bay and the harbour is designed as a curved tube. This proposed design is expected to cause severe resistance on the discharged water. This cause on its turn accumulation of the water into Hunts Bay and the flood risk will increase. Therefore this second phase of the expansion can cause unintended side effects. Before this plan will be made concrete, it is important to investigate thoroughly the consequences for the flood risk and, when necessary, come up with a solution for that.

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Appendices

1 Introduction

1.1 Reason of research

At this moment the Panama Canal is enlarged. After completion, the new Post-Panamax ships are able to pass this canal. Most ports in the Caribbean region are trying to benefit from the higher traffic intensity when the canal is completed. One of these harbours is the Kingston Harbour in Jamaica, located at a strategic location along the route in order to get to the Panama Canal. The harbour of Kingston will be prepared to be able to handle the Post-Panamax ships, so these ships will be able to enter the area of Jamaica after completion of the upgraded canal. For these bigger ships a deeper shipping channel area is required in the harbour. Since these ships can carry much more containers, the dry area of the harbour needs an expansion as well. The container terminal of the harbour of Kingston will get an increased capacity of approximately one million TEU (Twenty feet Equivalent Unit). The access channel should be deepened to a depth of 17 meters in order to allow these ships to enter the new and existing harbour area. The expansion plans can be found in Appendix D for phase 1 (subject to investigation on sedimentation and flood risk) and phase 2 in Appendix E (subject of investigation for flood risk).

Figure 1-1: Location of the Kingston Harbour

1.1.1 Local consequences

As said before, the reconstruction of this part of the harbour has a lot of consequences for the bathymetry (NB. The channels need to be dredged due to the increased depth needed). Together with the change in layout, the hydrodynamic system inside the harbour will change as well. There will be a different sediment transport rate, local water levels, local wave heights and a change in currents. These changes might cause a negative impact on the harbour area. In this report research is done about the change in hydrodynamics compared to the existing situation. This is done by using the modeling software *MIKE21* [1] and *Delft3D* [2]. The existing situation with the Kingston Harbour and Hunts Bay are shown in Figure 1-1. A detailed description of the expansion will be discussed further on, together with the possible problems occurring due to this expansion. Also, a comparison between the two modeling programs will be done on key features such as computation time, accuracy, and results.

1.1.2 Hunts Bay

The focus of this research will be on the influences on Hunts Bay due to the Kingston Harbour expansion. Hunts Bay is a shallow bay west of the Kingston Harbour. Until 1967, it had an open connection, of about two kilometers wide, with the harbour. But since then, the connection was mostly cut off from open water due to the construction of the highway. Now, it is only connected by a channel underneath the Causeway Bridge. Two rivers and three storm water drains debouch into Hunts Bay. That is why it is a very important part of the hydraulic system and needs to be investigated very carefully. During tropical storms, heavy rainfall causes large discharges, that all need to flow out of the system via the narrow passage underneath the bridge. This could lead to high water levels including the increasing chance of inundation.

Figure 1-2: Points of interest in Hunts Bay

The two rivers feeding Hunts Bay are the Rio Cobre and the Duhaney River. The source of the latter is for the largest part ground water, so its discharge is supposed to be constant. The Rio Cobre is mainly fed by rainwater and by its large catchment area, the major source of high discharge into Hunts Bay. Of the three storm water drains, Waterford Canal, Town Centre drain (for the Portmore area) and the Sandy Gully, the last one has by far the largest catchment area.

To keep the models within the possibilities of the available time for this project, it is presumed that the Rio Cobre and the Sandy Gully are the causes of water level rise and sediment transport in Hunts Bay. The situation which will be used by investigating the Hunts Bay, is sketched in Figure 1-2.

1.2 Problem definition

During this project, data will be gathered with respect to the input variables in the models. This finally results in a good overview of the available data and the areas of interest where research is needed. Together with assumptions made in the past, this data gathering will be a good base for further research. The output of the modeling can point out some locations where in the future, after the construction works, problems might occur. These problems will be mapped as well, and a few of these problems are taken within the scope of this project. Flood risks will also changes due to the phase 2 expansion, see Appendix E. Therefore, investigation will be done on these changes compared to the present situation, to do a first estimation of the quality of this design.

Thus in short, during this project an assessment will be made about the difference in sedimentation before and after the expansion. Also a flood risk study is done, due to the second phase expansion.

1.3 Outline

First the situation of the project area is sketched in chapter 2 by discussing the history and the developments of the Kingston Harbour area. This will be followed up by the boundary conditions of the project area in chapter 3. In chapter 4 a closer look will be taken at the set-up of the computer model and the calibration of this model. The results concerning the sedimentation will be discussed in chapter 5 followed up by the conclusion concerning the sedimentation. In chapter 6 a possible solution to reduce the sedimentation in the shipping channel will be presented. The flood risk due to the phase 2 expansion will be investigated in chapter 7 and the final chapter, chapter 8 contains recommendations to improve future research and the design of the expansion.

2 Problem objective

2.1 History

It is to be prevented that the wheel will be reinvented. Therefore some literature research is done about projects and researches that have been done in this area of interest. These references will give a base for the information required, and information already available, for this project and are shortly summarized in this chapter. The outcomes of the reference reports are represented in Appendix A.

2.1.1 Developments

In the last decades the harbour had a few changes in lay-out. These are, for example, the construction of the Petroljam refinery, the 7th harbour and the displacement of the Jamworld fisherman's beach. With these changes not a lot of fine research has been done, mainly because these were minor developments with respect to the lay-out and the hydrodynamic system. The expansion of the container terminal on the other hand, can have a significant influence on the hydrodynamic system in Kingston Harbour. The research and location of these developments are more explained below.

2.1.2 Research till present

In the past already some research is done about a few parts of the Kingston Harbour. These reports are used for the initial literature research, so a good insight in the environment and research done, is known. Some conclusions and data will be used in the scope of this project and some assumptions will be kept in mind. The locations of the research projects are shown in Figure 2-1.

Figure 2-1: Projects in the harbour area

As it can be seen, there is some research done around Hunts Bay and east of the Causeway Bridge. Some data gathered in this research, like the bathymetry, wind and wave conditions are used as a base for this study. This information will be used as input data in the models. The values used for these conditions are explained in the next paragraph.

2.2 Statistics on location

Before the Kingston Harbour area can be modeled, input parameters have to be valued in order to get an output which is as reliable as possible. In the past the area is also modeled, which resulted in information which could be used in this model, after converting it to a format which could be read by the modeling programs. The used values are explained in this section.

2.2.1 Bathymetry

The bathymetry of the Kingston Harbour and Hunts Bay are provided via research done in the past. This is digitally delivered by Smith Warner in *.xyz*-format, which is the format to be implemented into *MIKE21*, and after a small conversion, into *Delft3D* as well. The visualization of the bathymetry can be seen in Figure 2-2.

During the fieldwork inspection to the sediment properties, also a bathymetry survey is done. This information gives the most recent bathymetric data, which can be added to the database.

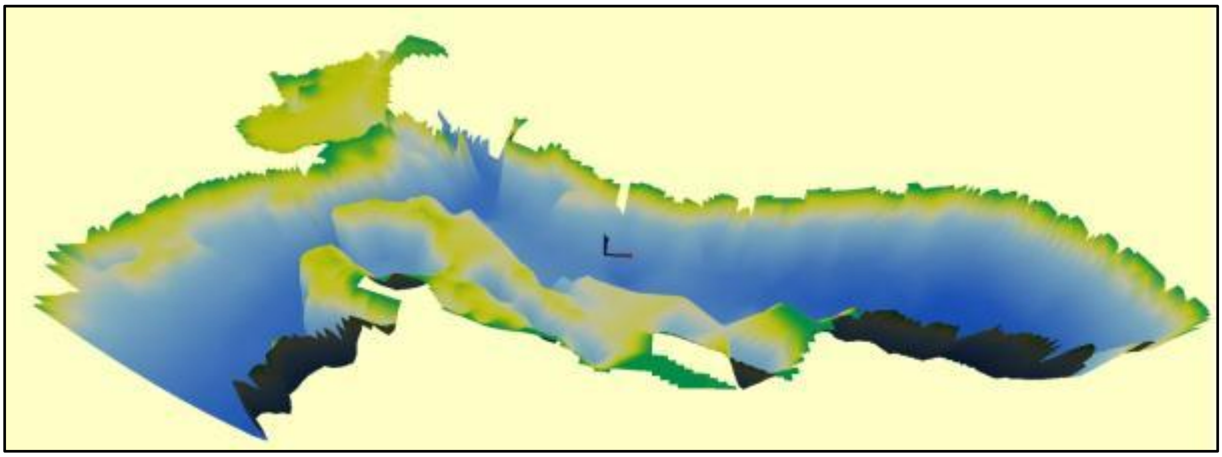


Figure 2-2: Bathymetry of Kingston Harbour and Hunts Bay in Delft3D

2.2.2 Wave conditions

The waves generated offshore of the Kingston Harbour are expected to be dissipated in such a way there is no influence of those waves in the harbour area. The locally generated waves on the other hand, can have a big impact and will therefore be included in the model. For these waves no data is available and should therefore be extrapolated from the given wind data (see next paragraph).

2.2.3 Wind conditions

Information about the wind conditions is gathered from previous investigations as well. Kingston is located at 18^{o}N latitude, which gives it a tropical monsoon climate. The majority of the winds are moderate trade winds coming from the East. This is confirmed during the fieldwork. There was almost no wind at all until 10 a.m. From then, a significant wind starts blowing from Easterly directions until around 3 p.m. After this time the wind drops down.

The gathered wind data [3] was already converted into a wind rose, which can be seen in Figure 2-3. From those records it is concluded that the wind comes most of the time from the east and east- south-east direction.

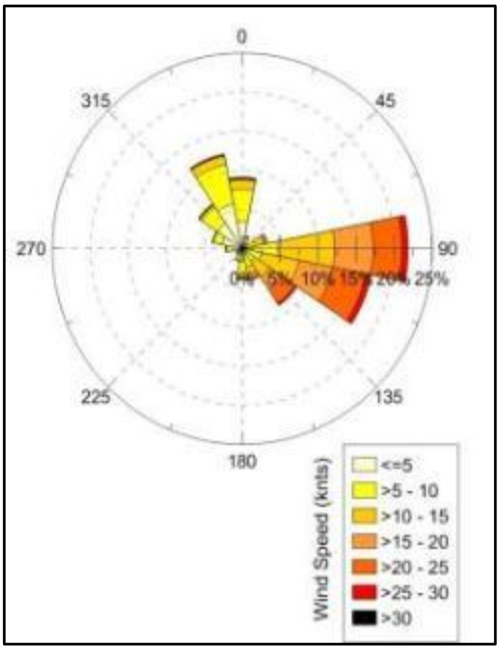


Figure 2-3: Directional distribution of wind speed

2.2.4 Sediment

In contrast with the statistics above, for the sediment no research has been done yet. At the moment of writing, nothing is known about the sediment size, whether it is (non-)cohesive, the density and such properties. This project yields research towards the change of sediment transport with the possible siltation of either the access channel and/or the berthing areas. In order to get the model as reliable as possible, it is therefore important to find out the properties of the sediment on the bed of Hunts Bay.

Within this project therefore some fieldwork has been done, to get samples of the sediment of the bottom of Hunts Bay. Since the time for the project is limited, this fieldwork will be done in a rudimentary manner. Therefore it will be recommended that more thorough research will be done in the future about the sediment properties. Fieldwork has resulted in two types of information. The first is a recent bathymetry file of Hunts Bay and the connection to the shipping lane in Kingston Harbour. Secondly, on strategic locations in Hunts Bay, samples of the bottom have been taken. Samples are taken from the Sandy Gully, in the deeper discharge channels of Hunts Bay and at the mouth of the Rio Cobre. These samples are being investigated by a lab, but in an initial conclusion can be said that most of the sediment consists of silt, combined with sand in the channels towards the Causeway Bridge. In the Sandy Gully, a thick layer of bad smelling mud was found.

Figure 2-4: Fieldwork at Hunts Bay

The sediment samples gathered from the bottom of Hunts Bay are saved in a zip lock bag, as can be seen in Figure 2-5. The lab research is performed by Jets Laboratories Limited. This report [4] can be found in Appendix C. For every sample the sieve curve is drawn. This gives a good insight into the sediment properties. From this curve the percentage sand, silt and clay of the sediment are determined. The outcomes are presented in Table 2-1. This shows that in general the assumption of the silt bottom was a good one. Also the input data of the sediment in the models, gives indeed a realistic view of the real sediment properties. Yet, it is recommended to adjust the input data with the information gathered from the lab research to make the model more reliable.

Table 2-1: Soil properties of the sediment samples

Sample #	% Gravel	% Sand	% Silt	% Clay
1	0.0	9.6	76.9	13.5
2	0.0	49.3	41.0	9.8
3	0.0	3.1	78.8	18.0
4	0.0	2.6	71.3	26.1
5	0.0	30.0	51.1	18.9

Figure 2-5: Example of sediment sample

2.2.5 Longshore current

The main source of sediment, which settles into Hunts Bay and in the Harbour basin, is sediment transported via the Rio Cobre and Sandy Gully. However, this is not the only source. A strong a longshore current runs down the south coast of Jamaica. This can be seen using Google Earth images looking at the same location over a period of ten years. This comparison is shown in Figure 2-7. The points in Figure 2-6 indicate the most recent image, made in 2011, whereas the yellow markers indicate the coastline in 2002. The left pictures are the pictures at the same location dating from 2002. Point 1 and 2 are clear examples of coastline changes east of the harbour entrance. Point 3 is an example of coastline changes west of the harbour.

Figure 2-6: Locations of the examples illustrating this acknowledgment

Accretion spread out over the entire Southeast coast is clearly visible. A very important side note to this visual observation is the assumption that the different pictures taken by the satellites over the year are roughly at the same part of the tidal cycle.

It can be concluded that the Kingston Harbour basin is sediment importing, deriving from the signs of accretion all along the coastline and also along the coast towards the Hunts Bay entrance. The alongshore current is westward directed, due to the East/Southeastern winds driving the waves towards the coast. So the majority of sediment imported by the Kingston Harbour is sediment that doesn't continue towards the west in the larger off shore current. Some accretion is seen at the western coastline of the harbour entrance, but a lot less significant.

Although these facts are known and the processes are clearly visible, no accurate information about the transport rates, directions, sediment properties etc. is known to date. To include this information in the model, research needs to be done which takes much more time (years) than there is to execute the research for Hunts Bay. Therefore, the alongshore current is not taken into account in the models of Hunts Bay.

Figure 2-7: **Top.** East of Kingston Harbour. **Middle.** Port Royal peninsula. **Bottom.** West of Hunts Bay's entrance. Left from 2002, right from 2010 (Google Earth, 2012)

2.3 Future development

Since the harbour expansion is still in a preliminary state of design, the models have to be based on the latest version of this design. This design can be found in Appendix D. It can be concluded that this design is not a very good design from a terminal layout point of view. It can be concluded that this design is not a very good design from a terminal layout point of view. A lot of space cannot be used where berthing as well as storage isn't possible. Also, the bend in the route of flow leaving Hunts Bay due to the form of both terminals, is something to look into. The Port Authority mentions that this design is the combined design of both a Chinese engineering company, working on the large land reclamation in the Southwest and a French engineering company working on the expansion of the existing terminal. These companies made their design independent of the other. Improvements on the design are therefore most likely to occur. However, this is beyond the scope of this report. Due to the time restrictions on this research, this is the design that will be used in the models.

The Port Authority announced in the final investigation stage a possible phase 2 expansion following the latest design as found in Appendix E. Sedimentation research would reach far beyond the available time for the investigation, but problems are expected on flood risks. Therefore, a small investigation on the possible flood risks of this phase 2 expansion is done in chapter 7.

3 Boundary conditions

One of the most important aspects when modeling, are the boundary conditions. These conditions should be defined in such a way, that it corresponds with reality as accurate as possible. The system, of which the Kingston Harbour is part of, is a complicated system with different inputs. The waves and currents enter the system from the offshore direction, the day-to-day wind and extreme wind conditions such as storms and hurricanes and the discharge from the Rio Cobre and the Sandy Gully, both with different catchment areas and different run off times. Since this study is focused on the Kingston Harbour and Hunts Bay, the off-shore boundary is placed far enough off-shore that the boundary discrepancies with the real boundaries disappear in the model. The models have been extended far enough into the sea that near Port Royal the model shows reliable results. In the model these boundaries are placed at ± 10 km from the entrance. The boundary conditions and its input in both models are represented in Table 3-1. This chapter is dedicated to explain the different boundary conditions.

Another very important aspect of the boundary conditions is the occurrence of multiple conditions at the same time, an event as for example a hurricane including heavy rainfall. This possibility of combinations will be further explained in Chapter 4.

Table 3-1: Boundary conditions and input

Boundary Condition	Input MIKE 21	Input Delft 3D
Offshore wave conditions	No waves on overall grid	No waves on overall grid
Wind	Hurricane file	Hurricane file
Discharge	Input daily average	Input daily average
Tide	Actual tide using a tidal generator.	Actual tide using Delft Dashboard

3.1.1 Wind

For the wind, data of Norman Manley Airport is used [3]. The airport has provided records of the wind conditions dating back to 1980 until present.

The hurricanes will be simulated with HURWave[1], using in house data to recreate the path and wind speeds and directions of 5 days of event. It combines the NOAA database of hurricane tracks with advanced wind-distribution algorithms and statistics.

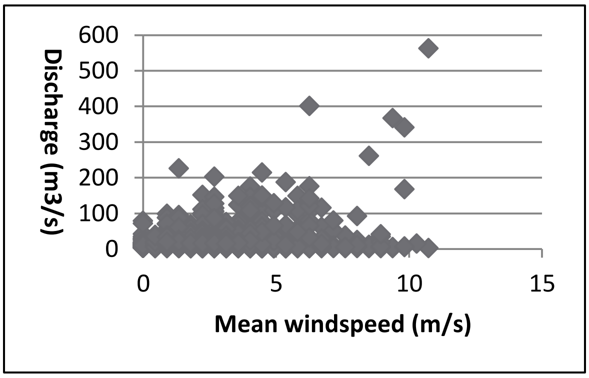


Figure 3-1: Scatterplot of the wind speed vs. discharge

No relation has been found between high winds and high discharges. A scatterplot is made for all the known data, which is shown in Figure 3-1.

The distribution of the discharges, from 1986 to 2010, can be found in Figure 3-2. Here some very high peaks are visible which, as is said, is related to the occurrence of storms. These data is gathered from the Water Resource Authority [5].

[1] HURWave is software for modeling hurricanes, created by J. Banton M.Sc., MBA. (SWIL).

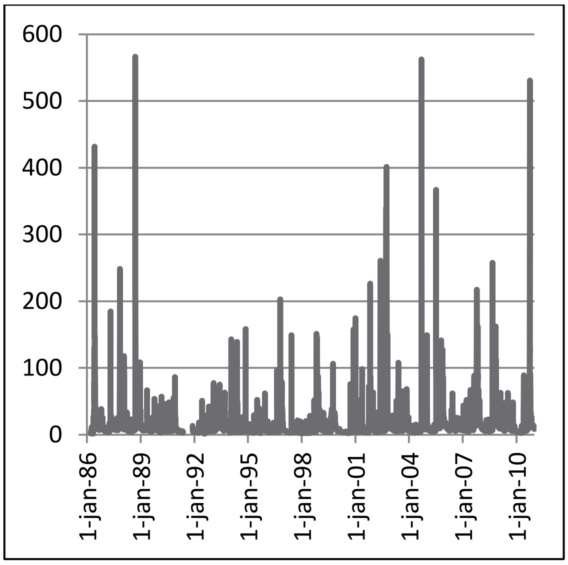


Figure 3-2: Discharge plot of the Rio Cobre [WRA, 2010]

After a small research about the correlation between the discharge and extreme events, it is found that there is indeed a link between these two. In Table 3-2 the high discharges are connected with the events which occurred at the moment of high discharge. This correlation, together with the data available about these events, is used in the modeling. More about this topic can be found in the chapter about modeling.

Table 3-2: Dates of the most extreme events in recent history

Date	Discharge [m^3/s]	Event	Intensity	distance to Jamaica	
13-sep-88	566	Gilbert	Cat 3	direct	0
11-sep-04	562,6	Ivan	Cat 4	direct	0
29-sep-10	530,82	Nicole	TS	direct	>300 km
5-jun-86	431,52	Andrew	TS	Indirect	>300 km
30-sep-02	401,12	Lili	TS	direct	50 km
6-jun-86	373,93	Andrew	TS	Indirect	>300 km
8-jul-05	366,77	Dennis	Cat 4	direct	50 km
18-sep-02	340,59	Isodore	TS	direct	50 km
30-sep-10	273,72	Nicole	TS	direct	>300 km
23-mei-02	260,81	May floodings	rain	direct	0

3.1.2 Discharge Sandy Gully

For the Sandy Gully, only data of extreme events of once in every 10, 25, 50 years is known from the research done for the Highway 2000 project [6]. The discharge quantities can be found in Table 3-3.

However, this data is too vague to give a good estimate of flow (NB. it can almost double the flow). Another limitation is the complete lack of information on sediment transport from Sandy Gully. Therefore, qualitatively, information of Sandy Gully cannot be implemented in the model. It will be taken into account during conclusions and acknowledgments.

3.1.3 Discharge Rio Cobre

The most important factor that induces fluctuations in the discharge is rainfall. Discharge quantities for extreme events and day-to-day situations are available, provided by the WRA [7]. This is information over a period of 1986 to 2010. The discharge induced flow is the main driving force of sediment displacement and therefore very important boundary conditions. During heavy rainfalls, the large discharges cause set up in Hunts Bay, since the flow surface of the Causeway Bridge is not sufficient to handle the same amount of water at the same time. These discharge quantities can be found in Table 3-3.

Table 3-3: Peak flow rates for extreme events

Return period [yr.]	Rio Cobre [m^3/s]	Sandy Gully [m^3/s]
10	550	590
25	860	780
50	1180	930
100	1580	1050

3.1.4 Tide

The tide is a constant occurring event, but nevertheless an important boundary condition. Tidal flows increase and decrease the residual flow underneath the Causeway Bridge. To simulate the extreme events as accurate as possible, the tides present at that moment of time are implemented in the model. This tidal information was found in the MIKE21 database and Delft dashboard for respectively the MIKE model and Delft 3D model [8]. The resulting maximum amplitudes for spring and neap tide are in the order of magnitude of a few decimeters.

3.1.5 Offshore wave conditions

Outside of the Kingston Harbour, the offshore wave conditions are not set as boundary conditions for the model. In the south and in the east, the distance to the Hunts Bay area is too large to be of any influence on the sediment transport. Therefore, on the boundary conditions offshore, the waves are set to zero. The waves which will have influence on and in the system are locally generated by the wind.

3.1.6 Correlations

Unfortunately, an unlimited amount of variables are of influence on the processes that cause sedimentation and flooding and would take illusory computations times. Connections and correlations have to be found between the boundary conditions, namely: offshore waves, tide, wind and discharge. This is important to exclude certain situations that are not of interest of the scope of this project, without deteriorating the model quality. Connecting different input variables will limit the computation time. The combinations found to be of interest are summarized into four different scenarios, or extreme events. Details can be found in the next chapter.

4 Modeling of sedimentation

To see if the models represent reality with acceptable accuracy, calibration runs[2] are done (see Appendix I for the calibration criteria and process). If these runs prove the models to meet this accuracy, they can be used. Differences between the existing situation and the situation with harbour expansion on a day-to-day basis are a slow evolving process. It would take weeks to run a model investigating significant changes. Should there be a notable change in sedimentation ratio or transport, this process will be significantly larger during extreme events.

4.1 Event scenario's

To keep the models as accurate as possible, four different extreme events are distinguished. These events have occurred in the recent past and are well documented, which enables accurate simulation. All of these events are combinations of the most important boundary conditions.

1. *Hurricane and high discharge due to heavy rain storms*
   These are the most extreme events in the last 30 years of documented data. The highest discharge recorded and the highest winds, resulting in lots of sediment transport. In this category, two different scenarios are tested, with different wind directions as striking difference.
   - Hurricane Ivan (2004). The largest discharge recorded including severe winds coming from the East. For these recent hurricanes, the path, directions en wind speeds are accurately measured and implied in the model[3]. The flow direction is towards the East. This is the most extreme event, with interesting detail: flow and wind set up are opposed.
   - Hurricane Gustav (2008) is another hurricane but with exceptional winds coming from the North. In this case, wind and flow are working more or less together.
2. *Tropical Storm and high discharge*
   Tropical Storm Nicole (2010) was a tropical storm causing severe rain and thunderstorms. Moderate winds together with very high discharge thus are another common extreme event.
3. *Only high discharge due to heavy rainfall*
   In May 2002, it rained nonstop for almost two weeks, causing massive flooding over the entire island of Jamaica. This model runs multiple days of very high discharge to see the results of such an event.

These four scenarios will be simulated for the old, existing situation and new situation to see what differences will be noted. Should this bring severe problems into notion, a run with "normal" conditions will be executed. The input data for these events can be found in Appendix F.

[2] Calibration means testing the model on proven data to determine the model's accuracy
[3] Data about the storm is processed via HURWave to simulate the entire hurricane in the model

4.2 Modeling tools

MIKE21 is the first program used for the modeling. It was founded by the Danish Hydraulic Institute (DHI) in order to model the complicated flow patterns in the Baltic Sea. At this location, a bridge between Sweden and Denmark was going to be built. Today it is one of the most used programs for modeling hydraulic problems. A detailed explanation of the modeling process in MIKE21 can be found in Appendix G. Delft3D is also used for the modeling, but since this program is not used for analyzing the results, its work can only be found in Appendix H. The information below refers only to the MIKE modeling.

4.2.1 Assumptions

4.2.1.1 Waves

Spectral storm waves are used. These waves traveling in from the boundaries have little influence further inside Hunts Bay but do result in waves in the area around the harbour. They need to be modeled well if this is of concern.

The tidal wave has been extracted from the MIKE toolbox, which contains the time series of global tides. With this data, the tidal boundary condition can be rendered. This is very important, since it has a large influence on the flows inside Hunts Bay. This influence travels deeper into the domain of interest. Even though the tidal boundary condition is given in a correct water level, it is also been known that an increase or decrease of this tidal range can result in more accurate flow velocities. This is done with the calibration process that compares the yielded flow rates with actual measured flow velocities in the field on a specific location.

4.2.1.2 Wind

The wind is chosen to be non-varying. Since this gives the strongest result of the wind. If the wind varies the waves will not grow anymore in a certain direction. This gives a clear view on what has strong influence and what has not. The wind can be inserted with a direction and a velocity and stays the same over the domain and time.

4.2.1.3 River discharges

The river discharges have extremes, namely the, low, day to day discharges and episodic events with extreme run-off. The day to day discharges induce a steady flow in Hunts Bay and eventually flow into Kingston Harbour. But with episodic events the discharges results in a lot more than just flows. These two scenarios need to be addressed separately to see their specific result but also in combination.

4.2.2 Grid

For the grid it is important to know where accurate information is necessary. This mainly focuses on the harbour area and Hunts Bay. And even more specific on the area around the Causeway Bridge. At that point the advective components are large. So they need to be modeled accurately as well. The increased accuracy is attained by decreasing the grid surface area. With a smaller grid cell also a smaller time step is used (in order to get the Courant number[4] not too high). But it is not desirable to decrease the size everywhere, since it will increase computational time dramatically. Therefore some prudent decisions have to be made. For that the Causeway bridge area is modeled with a smaller grid

[4] The courant number is a parameters which describes the numerical stability

size over a stretch where the flow velocities can be expected to be larger. At the point where the flow will have lost most of its energy, the grid size will increase again to a medium size with which the model can calculate the more precise currents in the harbour and Hunts Bay. This needs to be done with a medium grid size, since it is not so deep, and the bottom has some detailed aspects that are of influence on the flow and waves. Outside the Kingston Harbour area the grid size is left to a maximum to minimize computation time. This can be done because of the large depth. This part is only necessary to let the outside boundary condition travel towards the domain of interest. In this distance from the offshore boundary towards the Kingston Harbour, it is assumed that the conditions have adapted to the local environment and resemble the real situation.

4.2.3 Calibration

With the calibration there is one point that has been thoroughly measured. In the past measurements are done about the flow velocities under the Causeway Bridge. These measurements will be used to calibrate the model. It will be difficult to approach this setting, since a lot of influences, besides the tide, play a role in the flow velocities. The river discharges in Hunts Bay for example. But also atmospheric changes will induce flow at this location. The problem of these extra aspects is that they are not coupled to the data of the measurement. This fact should be taken into account when calibrating. Deviations can and should be explained qualitatively with this knowledge in mind. This will be done in the chapter on calibration later on. The calibration process is thoroughly discusses in Appendix I.

5 Results of sedimentation

The earlier discussed events on both the existing situation and the situation with the phase 1 expansion have been simulated. In this chapter the results will be explained and the differences emphasized.

The discussion of the results will be accompanied by an illustration of the bottom height changes at the end of each model run, when the extreme event is over. Also, the amount of sediment in tons, measured underneath the Causeway Bridge, giving an indication of the amount of erosion inside Hunts Bay (the sediment supplied by the Rio Cobre stays the same for both situations). Note that this number is not realistic on the actual processes, but purely for comparison in the model, since these values have not been calibrated with real data.

This chapter only contains the conclusion between the original situation and the expansion. An elaborate discussion of the processes can be found in Appendix K.

5.1 Ivan

Properties: a big hurricane and lots of rainfall would pass the Kingston area.

Sediment passed in existing situation: 134 000 ton

Sediment passed with expansion: 128 000 ton

The most remarkable difference is that the deposition in the shipping lane is more concentrated and intense (twice as much as in the existing situation) but more concentrated at a smaller part of the channel. Hunts Bay experiences almost no erosion except in the gullies, which it did without expansion. Near Ford Augusta, erosion reduces with around 40 %. Further towards the southwest, the shoreline towards Hellshire Beach undergoes a lot of erosion (up to 1.0 meter of bottom layer was eroded away in the model) With the expansion, at the little peninsula just North of Hellshire Beach the peak erosion is 30% higher compared to the old situation. However, this is just a small stretch of shoreline. The majority of shoreline experiences no significant differences. The flow has slightly less impact on the Port Royal shoreline, around 10 % more accretion at the northwest shore.

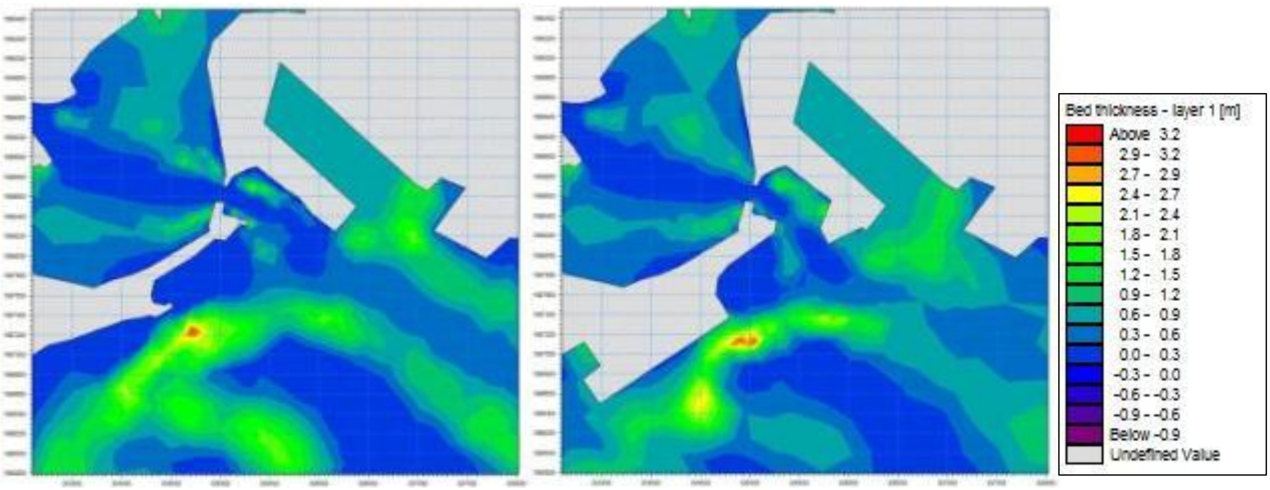


Figure 5-1: The result of hurricane Ivan

5.2 Gustav

Properties: a big hurricane, but now coming from another direction.

Sediment passed in existing situation: 32 000 ton

Sediment passed with expansion: 31 000 ton

The most important difference between the old and new situation are accretion right before and after the Causeway Bridge, less erosion under the bridge itself, erosion along the West bank and sediment deposit further off shore for the new situation. Near Ford Augusta, some accretion is visible in the lee of the terminal, instead of erosion. As well as during Ivan, significant erosion is visible around Hellshire Beach, but differences between the old and new situation are negligible. The same holds for Port Royal, what also was concluded during Ivan, its shore line undergoes a fraction more accretion and less spread out erosion in the south of the peninsula

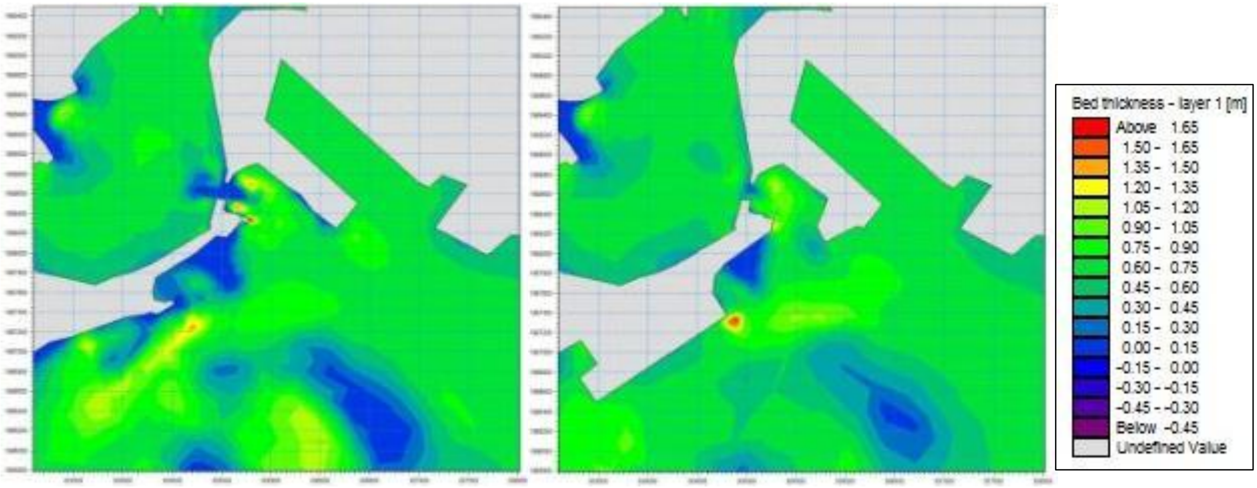


Figure 5-2: The results of hurricane Gustav

5.3 Nicole

Properties: Moderate winds, but very heavy rainfall.

Sediment passed in existing situation: 99 000 ton

Sediment passed with expansion: 85 000 ton

No significant accretion of the shipping lane, the only deposition is a shoal just outside the exit of Hunts Bay. Conclusion of this comparison is that only the location of the sediment deposit changes a little. The magnitude of accretion is slightly less in the new situation.

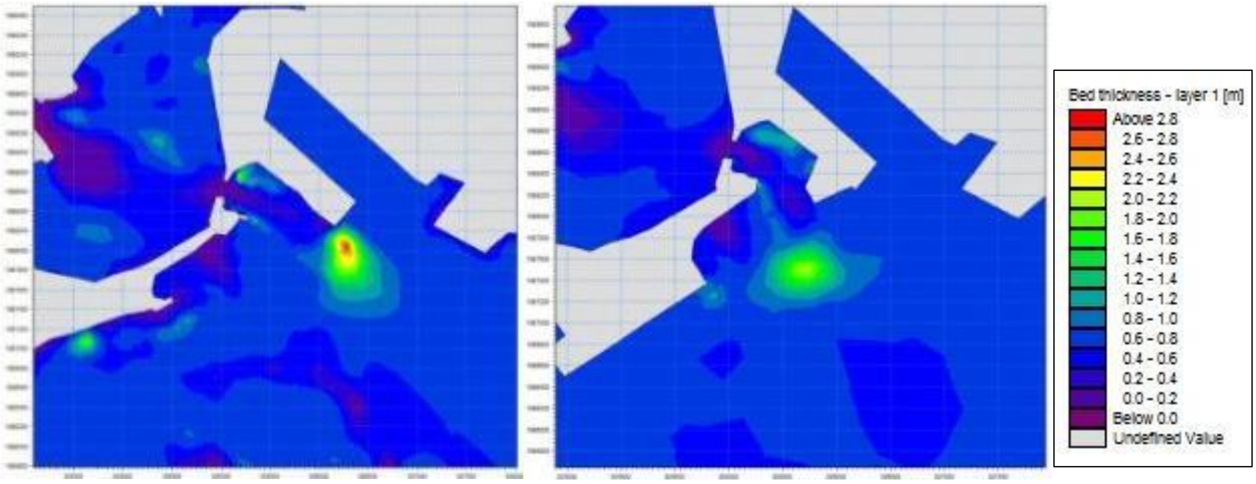


Figure 5-3: Results of storm Nicole

5.4 May Flooding

Properties: high discharges for a long period, moderate wind speeds

Sediment passed in existing situation: 24 000 ton

Sediment passed with expansion: 25 000 ton

After the expansion is build, no true significant change of morphology will be visible, when comparing it with the Flood event. The visible changes are the erosion spots near the quays of the expansion, which should be taken into account when constructing the quay walls. Also a small area of sediment is concentrated in the shipping channel, but it can be seen that this accretion doesn't influence the accessibility of the area. At the end though, no significant change will occur during the flooding event.

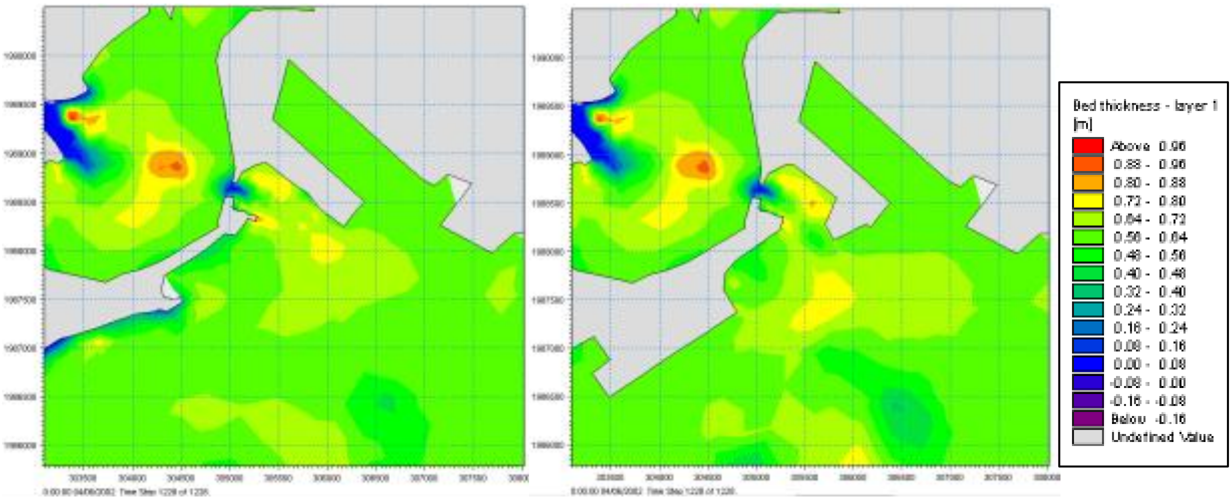


Figure 5-4: Results after Floodings

5.5 Conclusion

After analyzing the differences between these four events, no substantial difference is found in sedimentation. The expansion causes a little bit of slowdown of the flow coming out of Hunts Bay, which is seen in a little less sediment leaving Hunts bay. Input of the Rio Cobre stays the same, meaning less erosion in Hunts Bay itself.

The magnitude of erosion / accretion of the shorelines stay the same. Overall, one can say that there is even a little more accretion along the Kingston Harbour shorelines, especially along the Ford Augusta and Port Royal area.

The only thing that can cause problems in the new situation is the more compact sedimentation in the shipping lane. Therefore it can be possible, that the new situation will require more maintenance dredging.

6 Solution to limit sedimentation in the harbour basin

6.1 Introduction

The general image that followed from the current design and the expansion designs showed accretion in the shipping lane. This is mainly from Hunts Bay. Possible solutions are change in design of the harbour to let sediment settle before it reaches the access channel. Also withdrawing the sediment load from suspension before it reaches the access channel by a sediment trap will be a solution.

The first plan is outside the scope of this report. A change in lay out would have too many consequences that are impossible to review in this short time notice. It is advised though that it should be investigated. Especially the phase 2 expansion on the French part will cause challenges that need to be addressed.

The latter plan to decrease the sediment load to a minimum before the flow enters the access channel is more feasible in many ways. The execution though can be done in two different ways, inside Hunts Bay and between the Causeway Bridge and the access channel.

6.2 Modeling Results

The visualization of the results can be found in Appendix J. It should be clear that the sediment trap outside Hunts Bay has many downsides. Especially when compared to the sediment trap inside Hunts Bay. The sediment trap inside Hunts Bay is able to decrease sedimentation in the channel.

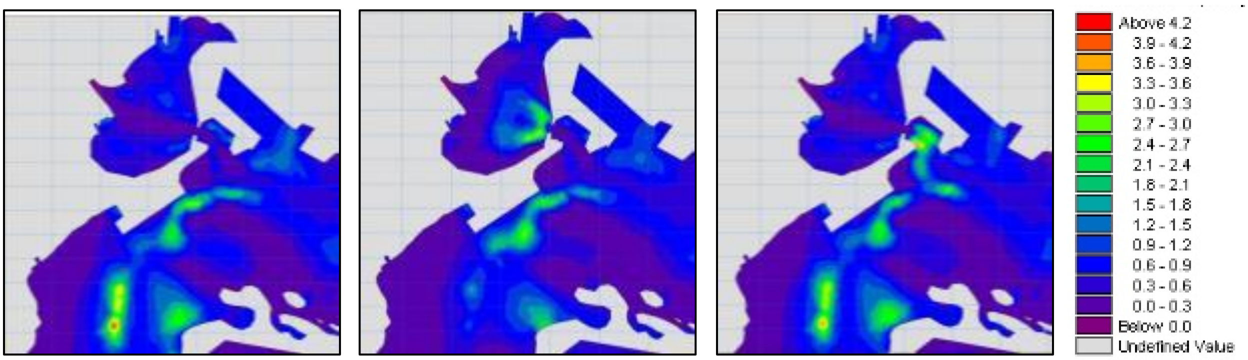


Figure 6-1: **Left** Present situation. **Middle** Sediment trap inside Hunts Bay. **Right** Sediment trap outside Hunts Bay

6.3 Conclusion

The conclusion that can be drawn here is that a sediment trap inside Hunts Bay is in all perspectives the best solution. Albeit that access to Hunts Bay is limited. But when feasible, this solution offers low cost non-stop maintenance of the access channel without actually dredging in the access channel. Another benefit is that the dredging that needs to be done in Hunts Bay can be done by local dredgers, which boasts local economies.

7 Possible expansion phase 2: flood risks

The Port Authority also announced a possible second expansion (see Appendix E) of the Kingston Container Terminal, added to the French Expansion. In this plan the width of the outflow of Hunts Bay will be canalized for about 1.5 kilometers. It is expected that the flood risk will increase due to this second phase expansion and therefore needs to be investigated. This will be done by using the same model as is used for the first phase expansion but now with the second phase expansion implemented. Due to a restricted amount of time left, only one extreme event is modeled, namely Ivan (2004). The depth of 'the canal' is planned to be dredged to 12 meters depth. Also a simulation is done with a depth of 5 meters to check if a possible sedimentation of the canal will lead to an increase of flood risk.

7.1 Ivan

Properties: a big hurricane and lots of rainfall would pass the Kingston area.

Sediment passed in existing situation: 134 000 ton

Sediment passed with phase 2 expansion: 115 860 ton

The water level recording is taken where the highest water level is during hurricane Ivan (see Figure 7-1). The water level does not increase very significantly due to the second phase expansion (with the design channel of 12 meters) compared to phase one expansion. It is in the order of 1-2 centimeters. When the depth is decreased to 5 meters the water level increases 4-5 centimeters compared to the first expansion. So when the canal starts to accrete, it will lead to a higher flood risk.

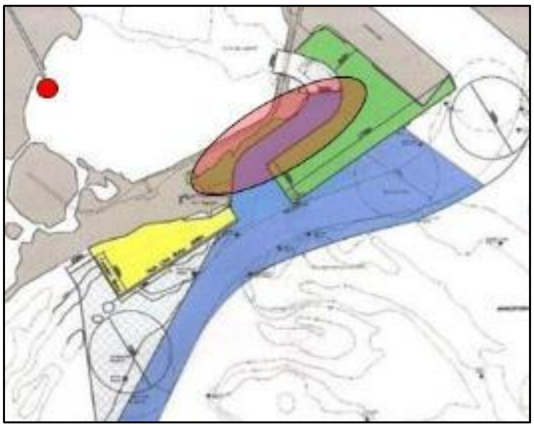
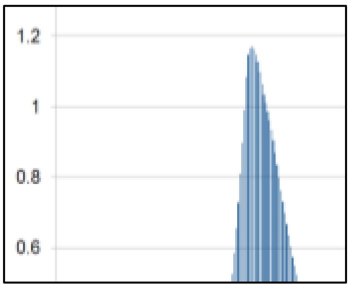
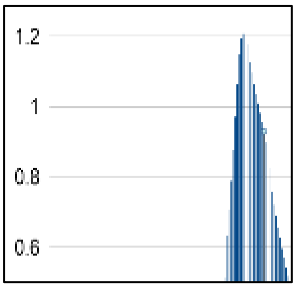


Figure 7-1: Location of the water level measurement in Hunts Bay (red dot)





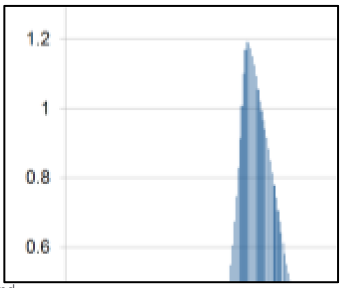


Figure 7-2: max. water level without expansion (left); max water level with 2nd phase expansion and a cannel depth of 5 meters (middle); max water level with 2nd phase expansion and a canal depth of 12 meters (right)

7.2 Conclusion

The differences between the water levels become larger when the discharge increases. Although the water level difference is not very significant, it must be noted that the Sandy Gully is not taken into account in this model. When this will be done it is likely that the water level differences between the phase 1 expansion and the phase 2 expansion will increase. Also Ivan has a discharge which has a once in 10 year return period. For a design period of once in 50 years return period, the discharge and therefore the increase in water level will be higher. It is therefore recommended to further investigate the flood risk of the areas surrounding Hunts Bay due to the 2nd phase expansion.

8 Recommendations

This research is done in a time of two months, which means that a lot of assumptions have been made. Therefore this study has to be used as a baseline investigation. In this chapter recommendations are done for possible further research. When more information and data is gathered about these topics, the project in general will be more reliable.

8.1 Research

- A more elaborate (lab) research on the sediment in Hunts Bay was available after the computations were completed. To increase the accuracy of the models, this information should be implemented in new model runs. Shortly mentioned in the report, the alongshore current is also a source for sedimentation in the harbour. Since this is beyond the scope of this research, the assumption is made that this is not a source for sedimentation in the harbour. However, in more advanced stage of modeling the consequences of the expansion, the alongshore current has to be taken into account.
- An alternative bypass for discharge out of Hunts Bay during flooding events is recommended to investigate.

8.2 Boundary Conditions

- More accurate data on discharges from all sources debouching into Hunts Bay will result to a more detailed model.
- The influence of the Sandy Gully is not taken into account in the models due to a complete lack of useful information. A flow measuring device in the mouth of Sandy Gully would lead to very relevant and new information on this boundary condition of Hunts Bay.
- A model should be composed that describes day to day conditions over the lifetime of the Harbour.

8.3 Input data

- The Charnock parameter is a number which tells something about the growth of the waves. This parameter is used in MIKE21 and it is given an arbitrary value. It was adjusted to fit the values coming from the calculations done with the Brettschneider-formula for the significant wave height and the calculation of the wind setup. The problem by doing this was that the processes which were directly of influence for the sediment transport were not reliable anymore. Therefore the Charnock parameter was set to the standard value. For a more reliable model in general, this parameter should be investigated more thoroughly. Adjusting this to achieve theoretical wave heights as from Brettschneider would not be justifiable since there is no way to examine this on location to verify the Charnock parameter.

8.4 Modeling

- In this project, the focus is on extreme events, since modeling day-to-day conditions of sedimentations would take too much time. The effects of these calm conditions are expected to be a fraction of the effects during an extreme event. Nevertheless, to estimate an accurate long term sediment process, this has to be run in a model as well.
- Choosing extreme events that would represent every possible aspect of extreme weather conditions, hurricane Dean was also taken into account for research. Hurricane Dean was a severe hurricane, without heavy rainfalls. Therefore, no significant higher dischargers were

recorded during this time. This event would investigate the stirring up and possible transportation by wind alone more accurately. Unfortunately, no more time was available during this project to model this situation. This should be done in future studies.

- Phase 1 expansion was the subject of investigation for sedimentation. Data is available of the changes of flood risk, which in short don't change significantly. Because of the limited time, priority of this report was investigating the sedimentation patterns and no more time was available to carefully evaluate the flood risks. This is interesting to work out in detail, especially with the Sandy Gully included in the model.
- Phase 2 expansion is only investigated for possible flood risks. The same argument is valid as the recommendation above; no time was available to investigate sedimentation properly. Based on a quick study of the results, the conclusion of phase 2 is that sedimentation of the channel between Hunts Bay and the Kingston Harbour needs to be thoroughly investigated.

8.5 Final design

- At the moment of writing the report, no final design of the expansion is ready yet. The research in this report is based on the latest proposal that contains 2 phases. The first phase is mainly about the Chinese expansion at Fort Augusta. The second phase is the French part that connects to the existing harbour directly. The French part is in a much earlier state of design.

9 References

1. DHI, *MIKE ZERO*, 2009: Hørsholm, Denmark.
2. Deltares, *Delft3D*, 2011: Delft, Netherlands.
3. Norman Manley International Airport, *Windspeed data*, Smith Warner International Ltd., Editor 1980-1991, 1996-2005: Kingston.
4. Jets Laboratories Limited, *Kingston Harbour Expansion, purchase order No. 2012-06*, 2012, Jets Laboratories Limited.: Kingston.
5. Water Resources Authority, *Discharge Rio Cobre @ Bog Walk*, Water Resources Authority, Editor 1986-2010.
6. Smith Warner International Ltd. and Dessau Soprin International, *Highway 2000 Project. Preliminary design phase. Hunts Bay - Portmore Causewey*, 2000: Kingston.
7. Water Resource Authority.
8. Deltares, *Delft Dashboard.*, 2012: Delft, Netherlands.
9. Smith Warner International Ltd., *Preliminary Design of a fisher's beach to Facilitate the relocation of fishermen to JamWorld, Hunts Bay, Jamaica*, 2007: Kingston.
10. Smith Warner International Ltd., *Hurricane wave & storm surge assessment at the Petrojam Refinery*, 2008: Kingston.
11. Smith Warner International Ltd., *Coastal Engineering Aspects for Seventh Harbour, Jamaica*, 2007: Kingston.
12. Smith Warner International Ltd., *Fort Augustus container terminal: Hydrodynamic, Sedimentation and Wave modelling*, 2004: Kingston.

Appendix A Literature research

A.1 Introduction

The research project will be within the Kingston harbour area. Plans have been made to expand this harbour to increase its capacity. Also, the harbour and channel will be deepened, to be able to handle larger ships. The expansion will have a large impact on the harbour and surrounding area, therefore these impacts will have to be researched.

Already a lot of research has been done; this report will give an overview of what has been done and what still needs to be investigated. To get insight of the situation at hand, the project database of Smith Warner International Ltd. (SWIL) has been used. The following reports from the SWIL project database have been studied:

- IDB storm surge mapping (2007)
- Jamaica PCJ storm surge Modelling (2008)
- Jamaica Fort Augusta Container Terminal (2007)
- Jamworld Fishers Beach-NROCC (2007)
- Sea control Fort Augusta Container Terminal (2004)
- Jamaica 7th harbour (2007)

A.2 Performed research till present

The expansion will be in the form of land reclamation southeast of the existing container terminal. Also the depth of the access channel will be increased. This will have an impact on the hydrodynamics in the harbour and the surrounding areas, the bathymetry, currents and the wave conditions will change.

The following subjects have already been investigated:

- *Bathymetric surveys have been done.*
- *Superficial soil research has been done. [9]*
- *The wave conditions and storm surge levels in the Kingston harbour and Hunts Bay for daily and tropical storm conditions. [10]*
- *The influence of a combined discharge of the Sandy Gully and the Rio Cobre, both with a 10 year return period. In these studies the hydrodynamics are investigated with and without the expansion of the Kingston harbour. The grain size that was used in the modelling is estimated. Four different locations have been used for the sedimentation patterns, within Hunts Bay, under the Causeway Bridge, between the causeway and the shipping channel and the channel itself. [11]*
- *Risk and vulnerability assessments have been done for the Portmore area.[10]*

A.3 Possible future research

Although there has been done extensive research in and around the Kingston harbour area, there is still improvement possible to gather more knowledge about the area.

Possible future research subjects are:

- *The composition and source of the sediment that will settle inside the future turning basin.*
- *Investigate the water quality inside Hunts Bay and how it will be influenced by the harbour expansion.*
- *Possibilities to decrease the retention time of the water in Hunts Bay to increase the water quality and when possible decrease the settlement of undesired or polluting particles.*
- *Modelling the possible contaminated sediment import under the Causeway bridge during a tropical storm/hurricane since there has only been used a rough model for this area.*
- *Find the weak spots in the sea defence surrounding Hunts Bay.*
- *Modelling the effects of a tsunami for the Kingston harbour area.*

Appendix B Fieldwork Hunts Bay

B.1 Introduction

In order to get the model as accurate as possible, the sediment properties should be entered in the model. Unfortunately, no research has been found about the type of sediment and its properties in Hunts Bay. To prevent that assumptions are made (the opinions about the sediment type differ very widely), it is best to gather data by actually taking some samples.

Therefore some fieldwork is done in Hunts Bay. Due to the lack of time and money, no extensive laboratory analyses and layer building in time can be executed. Within the possibilities an easy, cheap and fast way is found to pick up the sediment from the bottom of the bay. Two devices have been developed. One which uses a grab at the bottom, to take a bottom sample and the other is inserting a tube in the bottom, to take a core sample. The latter is also used to get an idea of layer building based on the resistance on the bottom and shaft.

Both models require a lot of parameters to represent sediment transport as accurate as possible. In the basic sediment testing that is possible to do in this limited timespan, the most important values to be determined are:

- Type of sediment (cohesive or not)
- Grain diameter
- Specific weight
- Sand/mud ratio

Other values have to be assumed via theoretical knowledge i.e. viscosity and critical shear stress.

Another advantage of doing this sediment research is updating the bathymetry data, by doing a depth survey as well. The most recent data is taken out of nautical maps of the British Admiralty dating around 2000. Over this period of 12 years, a lot may have happened with the bed.

The next paragraph is dedicated to the weather conditions and interesting observations. Watching the actual processes and conditions in real life gives a better understanding of the problems going on and improves judgment of the usefulness of the model output.

B.2 Conditions and visual observations

The fieldwork was done on Wednesday the 29th of August, from 7:00AM to about 2:30PM. The aftermath of tropical storm *Isaac* (which went over Jamaica the weekend before), was clearly visible since a lot debris was carried by the Rio Cobre into Hunts Bay. This was all blown back towards the West bank, due to the significant winds coming from the East. Results of heavier discharges in the past were large branches and remains of entire rooted trees, stuck in the shallow river mouth of the Rio Cobre. The water was still brown from the suspended sediment. These are clear indicators of the sediment processes going on in Hunts Bay.

The fieldwork started early in the morning. At that moment it was sunny and little to no wind. The bathymetry survey was done prior to the sediment samples, in order to utilize the calm weather as much as possible resulting in the most accurate data. Around 10 AM, the wind picked up and after a small rain shower around noon, the wind speed became higher, up to 7.9 m/s[5] (Beaufort scale 5), which persisted the whole afternoon.

This resulted in significant waves, once the wind had fetched enough to develop the waves. In the neighborhood of the Causeway Bridge, the outside influence of the offshore waves was noticeable. Much longer and higher waves entered Hunts Bay. Due to the shallowness and lee of the Causeway dam, those waves reduced shortly after entering.

Figure B-1: Debris in the river mouth

B.3 Bathymetry survey

First, the bathymetry survey is done. For this an echo sounder linked to a GPS tracker is used. This echo sounder makes every second a record of the current depth which is plotted on the map with the GPS input. To get data from the entire bay, with a zigzagging pattern the whole area is covered, shown in Figure B-2. The actual shipped path can be seen as the black line in the figure. Due to some shallow parts and the speed of the boat, not all the pulses have been recorded, so some data in between is missing. Interpolation of the useful data gives an accurate bathymetry file though.

In Figure B-3 the changes in bathymetry can be found. This is measured with the original bed level as reference. Positive values indicate erosion, while a negative value means a bottom rise, compared to the old data. The differences are due to sedimentation or by possible errors in the old or new measurements. Remarkable difference is the overall decrease of depth. The gullies, visible on the old maps are completely siltated. So there is definitely a sedimentation problem.

Figure B-2: Map of bathymetry survey

[5] Data obtained via www.weatherspark.com

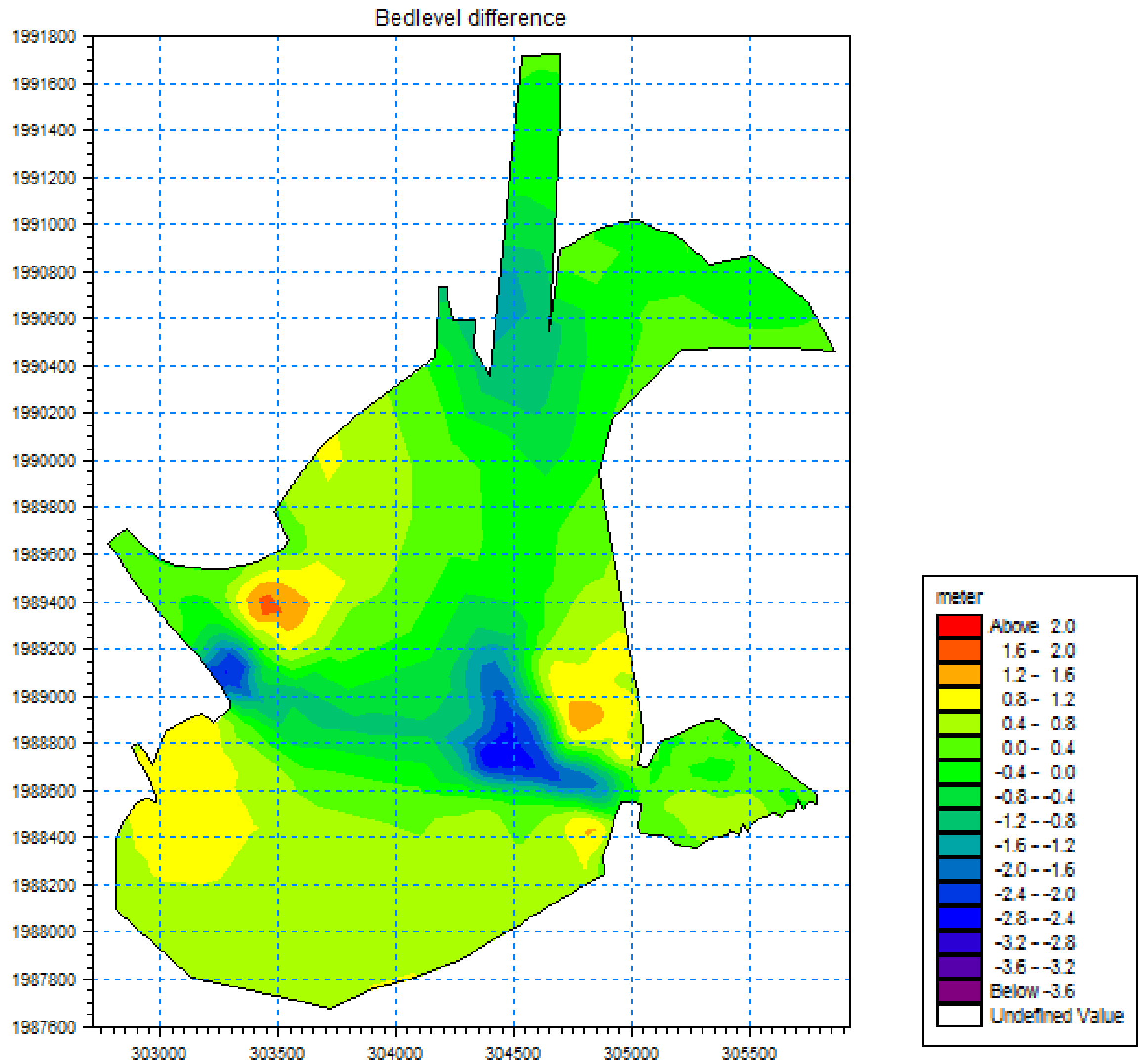


Figure B-3: Bathymetry changes of Hunts Bay

After the bathymetry data was gathered, at five locations samples are taken from the bottom, see Figure B-4. The sampling is done with a grab sampler, which was available at the office of SWIL. It is lowered to the bottom via a rope. However, this device was a prototype and tests "in the dry" did not show a very consistent working device. Even though, it is the simplest method of taking a bottom sample, not limited by depth.

The lack of time and budget is a limiting factor on the extension of information that we'll be able to get from the field work. The grab sampler only gives information of the top layer. It cannot for instance clarify the layering in time of the bottom. It will only be able to tell something about the top layer of the bottom. Another disadvantage is the amount of distortion by the grab picking it up of the bottom. Therefore the density cannot be determined.

Figure B-4: Location of sediment samples

Figure B-5: The grab sampler

For the back-up, not to be reliable of only a prototype, also a long steel pipe is taken with the survey. With this pipe, core samples can be taken, which do give information on the layers. Disadvantage of this method is the restricted depth it can be used. The biggest advantage was that it gave some information of the thickness of the top layer and what lay underneath. In the case of Hunts Bay, the majority of the bay wasn't deeper than 1.5 m, giving qualitatively results on the layers. The top layer is a soft layer of silt/mud without significant increasing density when penetrating the bottom further. At around 0.6m under this layer a much firmer base layer was found. This layer was very difficult to penetrate manually. This layer is assumed to be a mix between sand and silt. This information is used for the input of the bottom in the model. Based on these findings, a two layer set up is used.

Lab research will tell much more about the bottom, but at the moment the input was necessary for the models, only input estimated visually was available. The depth, location and first impression of the samples can be found in Table B-1.

The locations are chosen in such way it gives most information on flow and sediment. We did not take any samples far away from the flow area, since this would not be relevant information necessary for the model.

Table B-1: Information about the samples

Sample #	Location	Depth [m]	Impression
1	Mouth of sandy gully	3.40	Very fine, rotting and stinking material.
2	Channel sandy gully	1.40	Fine silt top layer around 0.6m thick. Dense sand layer underneath
3	West of causeway bridge	3.60	Silt
4	East of causeway bridge	4.70	Silt
5	Mouth of Rio Cobre	1.20	Fine silt top layer around 0.6m thick. Dense sand layer underneath

Concluding this fieldwork, it is important to state that this is only a first and preliminary research. The most important goal during this inspection was to discover what type of sediment lies in Hunts Bay. The properties are still assumed, but now the sediment type is determined and the right theoretical values can selected. Below this section the outcomes of the sediments are showed.

Appendix C Sediment lab research

The lab research, which was done by *Jets Laboratories Limited,* came back to the office on 17th of September. The results below are obtained from Hydrometer Analysis test carried out on the samples submitted on the 31th of August, 2012.

For every sample the sieve curve is designed. This gives a good insight into the sediment properties. From this curve the percentage sand, silt and clay of the sediment are determined. This shows that in general the assumption of the silt bottom was a good one.

JETS LABORATORIES LIMITED

14a Hope Road, P.O. Box 402, Kingston 10, Jamaica West Indies
Telephone Nos. (876) 926-2201/2, 926-7756; Fax No. (876) 929-2515

September 13, 2012 **Job No.: 12053**

Smith Warner International
Unit 13, 2 Seymour Avenue
Kingston 6

Attention: Mr. Roberto Lyn

Dear Sirs:

Subject: Kingston Harbour Expansion
Purchase Order No. 2012-06

Please find attached our Laboratory Report No. S/639/00547 of results obtained from Hydrometer Analysis Test carried out on samples submitted to us on August 31, 2012.

We trust that the attached is satisfactory to you; however, should there be any queries, please address them to the undersigned.

Yours very truly,
JETS LABORATORIES LIMITED

Kayanna H. Bromfield (Miss)
Laboratory/Q.A. Administrator

Gordon E. Hutchinson
Director

/cak

Attachments

JETS LABORATORIES LIMITED

14 a Hope Road, P.O. Box 402, Kingston 10, Jamaica West Indies
Telephone Nos. (876) 926-2201/2, 926-7756; Fax No. (876) 929-2515

LABORATORY TEST REPORT

OUR REF:	CLIENT AUTHORISATION:	REPORT NUMBER	REPORT DATE:
12053	P.O.# 2012-06	S/639/00547	September 13, 2011

CLIENT: Smith Warner International	REPORTED TO: Roberto Lyn
ADDRESS: Unit 13, Seymour Park, 2 Seymour Avenue Kingston 10	SAMPLING DATA: 5 Soil Samples in Suspension
PROJECT: Kingston Harbour Expansion	SOURCE: Kingston Harbour

CLIENT REP:	SAMPLES TAKEN BY: CLIENT	JETS	GEOTECH	DATE SAMPLE RECEIVED:	TEST SPECIFICATION:
Roberto Lyn	X			August 31, 2012	ASTM D422

SAMPLE IDENTIFICATION		KINGSTON HARBOUR EXPANSION		
U.S SIEVE SIZES		PERCENTAGE PASSING		
GRAINSIZE ANALYSIS		SAMPLE #1	SAMPLE #2	SAMPLE #3
Imperial	Metric (mm)	00310	00311	00312
1/2"	12.5			
3/8"	9.5			
#4	4.75			
#10	2			
#20	0.85			
#40	0.425	100.0	100.0	100.0
#100	0.145	94.5	78.1	98.8
#200	0.075	90.4	50.7	96.9

JETS Laboratories LTD. APPROVED BY Ka. Hinsley 13/9/12 Quality Assurance Office

DATE TESTED:	TECHNICIAN:	CERTIFIED BY:
September 7- 13, 2011	Clifford Grant	

Page 1 of 3

JETS LABORATORIES LIMITED

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Telephone Nos. (876) 926-2201/2, 926-7756; Fax No. (876) 929-2515

LABORATORY TEST REPORT

OUR REF:	CLIENT AUTHORISATION:	REPORT NUMBER	REPORT DATE:
12053	P.O.# 2012-06	S/639/00547	September 13, 2011

CLIENT: Smith Warner International

REPORTED TO: Roberto Lyn

ADDRESS: Unit 13, Seymour Park, 2 Seymour Avenue, Kingston 10

SAMPLING DATA: 5 Soil Samples in Suspension

PROJECT: Kingston Harbour Expansion

SOURCE: Kingston Harbour

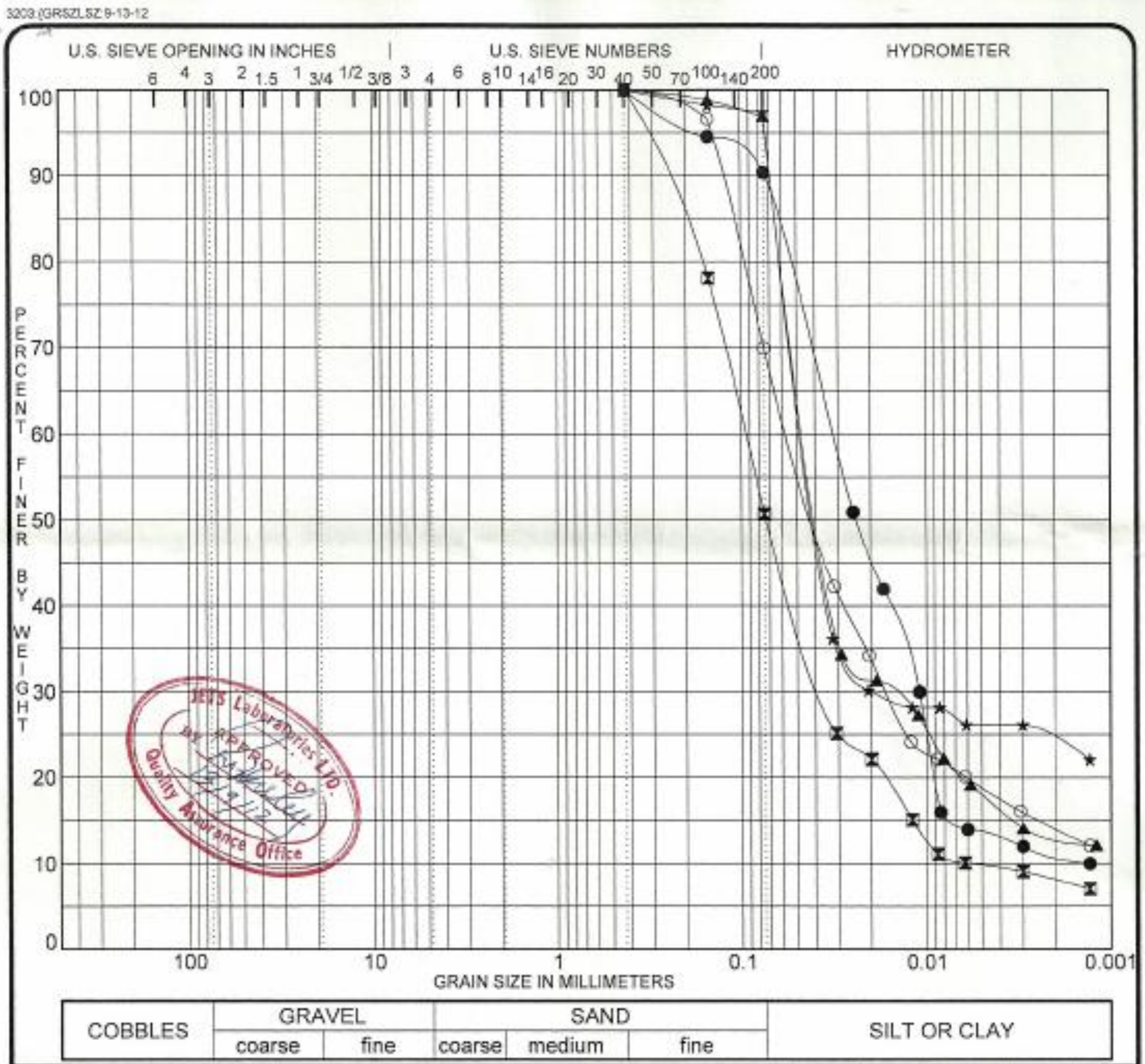
CLIENT REP:	SAMPLES TAKEN BY: CLIENT	JETS	GEOTECH	DATE SAMPLE RECEIVED:	TEST SPECIFICATION:
Roberto Lyn	x			August 31, 2012	ASTM D422

SAMPLE IDENTIFICATION		KINGSTON HARBOUR EXPANSION		
U.S SIEVE SIZES		PERCENTAGE PASSING		
GRAINSIZE ANALYSIS		SAMPLE #4	SAMPLE #5	
Imperial	Metric (mm)	00313	00314	
1/2"	12.5			
3/8"	9.5			
#4	4.75			
#10	2			
#20	0.85			
#40	0.425	100.0	100.0	
#100	0.145	98.1	96.6	
#200	0.075	97.3	70.0	

JETS Laboratories LTD. APPROVED BY [signature] 13/9/12 Quality Assurance Office

DATE TESTED:	TECHNICIAN:	CERTIFIED BY:
September 7- 13, 2011	Clifford Grant	[signature]

Page 2 of 3



	Specimen Identification		Classification	MC%	LL	PL	PI	Cc	Cu
●	00310	0.0						2.85	24.5
⧗	00311	0.0						2.36	15.9
▲	00312	0.0							
★	00313	0.0							
○	00314	0.0							

	Specimen Identification		D50	D60	D30	D10	%Gravel	%Sand	%Silt	%Clay
●	00310	0.0	0.02	0.03	0.011	0.0013	0.0	9.6	76.9	13.5
⧗	00311	0.0	0.07	0.09	0.036	0.0060	0.0	49.3	41.0	9.8
▲	00312	0.0	0.04	0.04	0.016		0.0	3.1	78.8	18.0
★	00313	0.0	0.04	0.04	0.020		0.0	2.6	71.3	26.1
○	00314	0.0	0.04	0.05	0.016		0.0	30.0	51.1	18.9

PROJECT **Kingston Harbour Expansion -**

JOB NO. **12053**

DATE **9-13-12**

GRADATION CURVES

JETS Laboratories Ltd.

Appendix D Lay-out Port Expansion "phase 1"

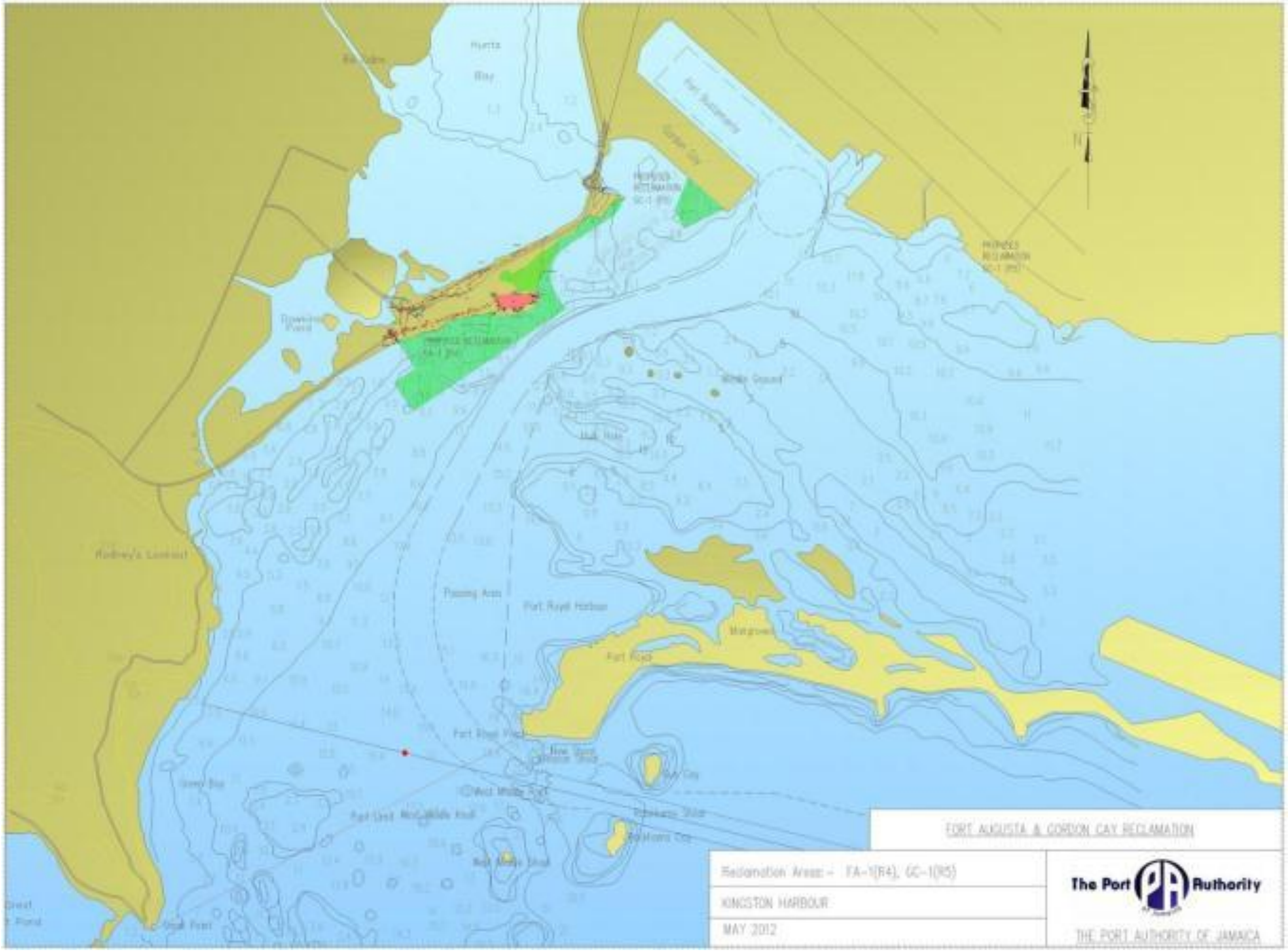


Figure D-1: Port expansion proposal from the Port Authority used in the models

Appendix E Lay-out Port Expansion “phase 2”

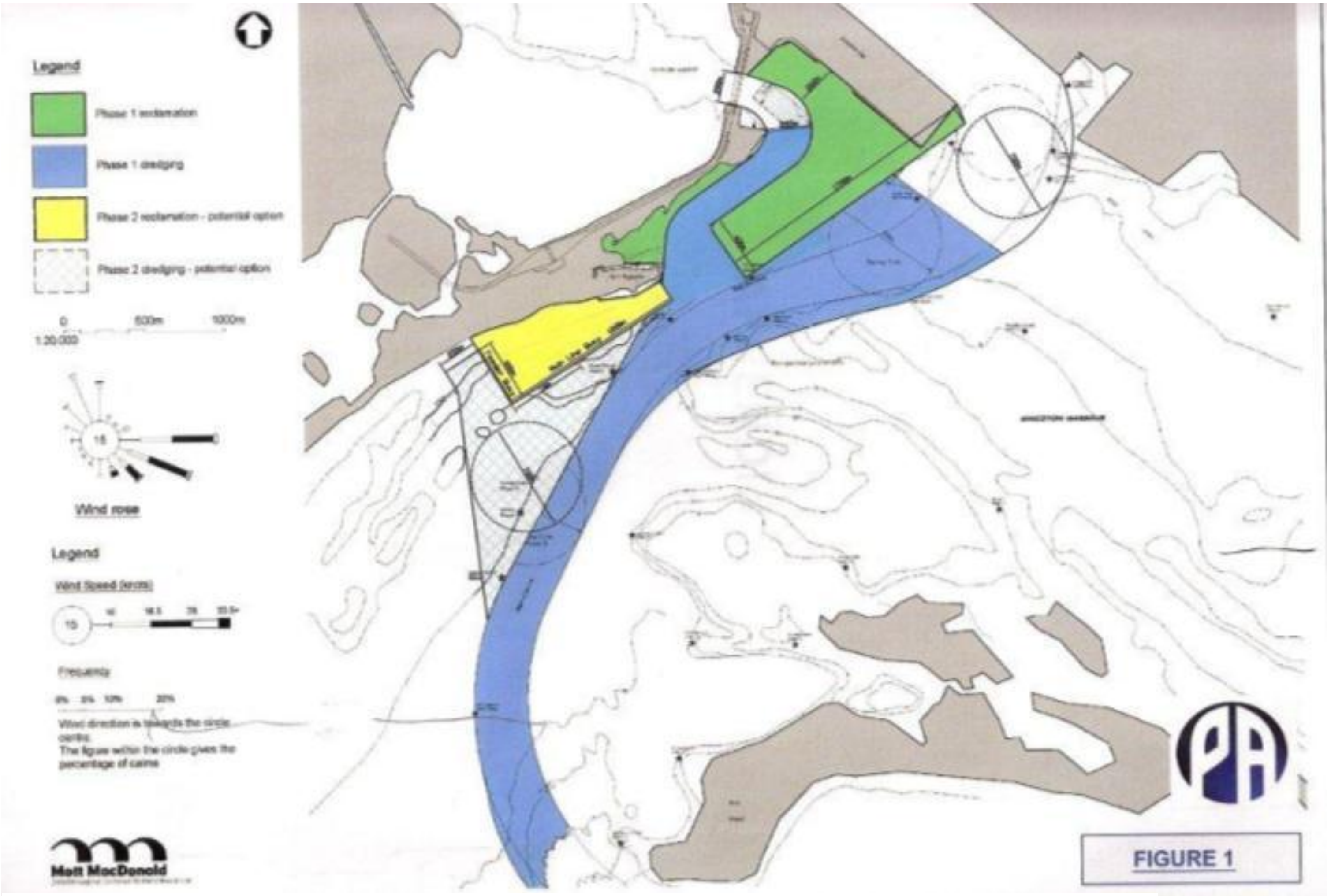


Figure E-1: Expansion "phase 2"

Appendix F Input values of the extreme events

For the research four historical events were chosen to use as input for the computer models. These four events have distinctive differences and will show the consequences of almost all thinkable scenarios. Only day to day conditions are omitted in this research as implied by these events. The four scenarios can be divided in two groups. One is the hurricane simulations and two flood simulations. For the hurricane simulations there are Ivan and Gustav. They struck Jamaica practically head on. It's a no-brainer to realize that these have caused severe damage to the island. Ivan is still very fresh in memory here and there for an interesting piece in our research. The other two, Nicole and the floods of 2002 have less wind influence. Nicole was far away from Jamaica and didn't cause significant damage, because of destructive winds. The major thing about Nicole was the extreme rainfall. In five days there was even a record of almost one meter of precipitation. Mud slides caused severe damages and even thirteen people perished. For the floods in 2002 there wasn't even a storm present. There it rained for almost two straight weeks. As can be seen later on de sediment discharge is a factor four higher than with Ivan for example. This is something to realize when thinking of sediment transport caused indirectly by the weather.

For all four scenarios the input values that were required were the river discharge and the wind. The discharge was easily acquired, although this is only Rio Cobre and not Sandy gully. In this appendix all the information is gathered. For the hurricanes the path with the categories along it, are given together with the discharge time series. For Nicole and the 2002 floods the wind is given as a time series as well. The difference in method is that for the hurricanes the hind casting is not reliable and for less extreme winds it is. So for the hurricanes the wind data originates from NOAA and for Nicole and the 2002 flooding from the Norman Manley airport measurements.

F.1 Scenario 1: Hurricane Ivan (10 Sep 2004 – 15 Sep 2004)

Table F-1: Input discharge for Ivan

	Discharge [m³/s]
1 day prior to	60,8
Day of event	562,6
Day after	167,9
2nd day after	133,0
3rd day after	116,3
4th day after	73,0

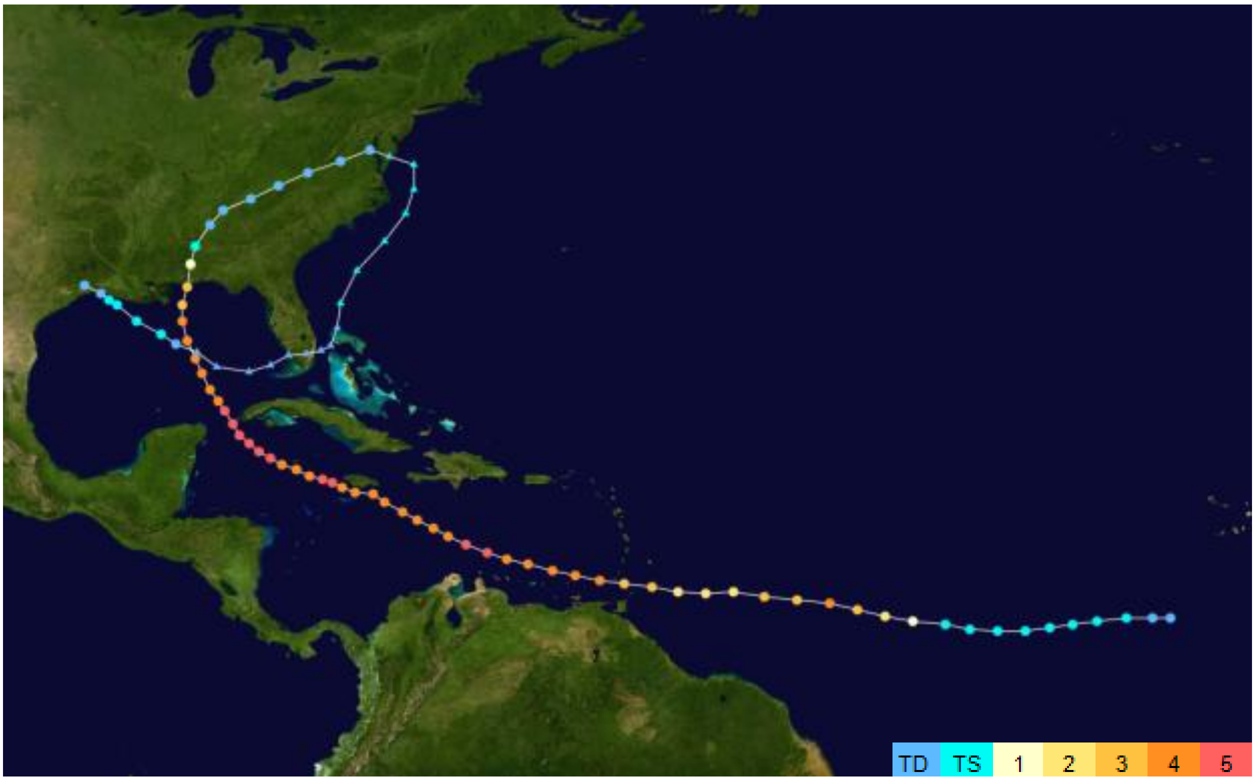


Figure F-1: Track Ivan

F.2 Scenario 2: Hurricane Gustav (28 Aug 2008 - 2 Sep 2008)

Table F-2: Input discharge for Gustav

	Discharge [m^3/s]
1 day prior to	10,5
Day of event	257,2
-p-;Day after	166,6
2^{nd} day after	128,2
3^{rd} day after	84,2
4^{th} day after	52,5

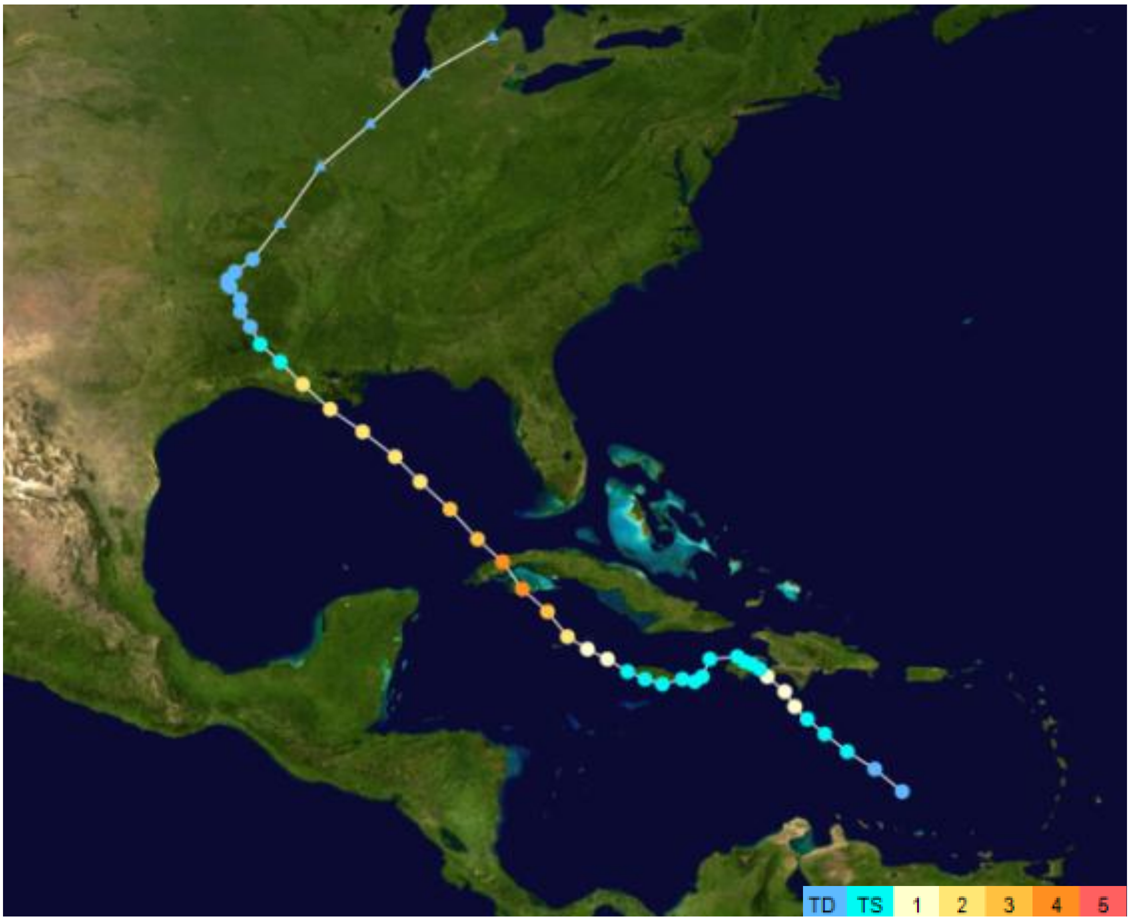


Figure F-2: Track Gustav

F.3 Scenario 3: Tropical Storm Nicole (28 Sep 2010 – 3 Oct 2010)

Table F-3: Input discharge for Nicole

	Discharge [m^3/s]	Wind speed [m/s]
1 day prior to	54,8	2.39
Day of event	530,8	7.48
Day after	273,7	3.33
2nd day after	137,8	2.28
3rd day after	123,3	4.68
4th day after	130,2	1.96

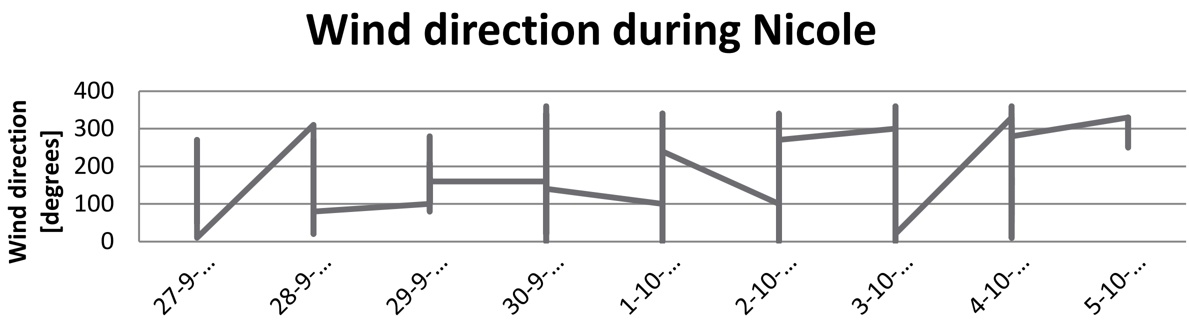


Figure F-3: Time series of wind direction during Nicole

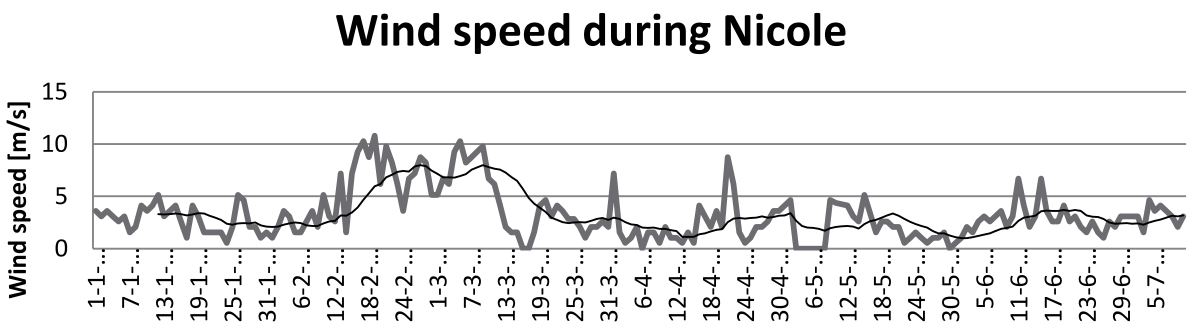


Figure F-4: Time series of wind speed during Nicole. Black line is the moving average

F.4 Scenario 4: May floods (23 May 2002 – 27 May 2002)

Table F-4: Input discharge for Flood

	Discharge [m^3/s]	Wind speed [m/s]
1 day prior to	260.81	6.73
Day of event	103.01	4.33
Day after	142.91	5.77
2nd day after	175.83	6.54
3rd day after	186.95	6.56
4th day after	102.16	5.61
5th day after	76.61	4.57
6th day after	77.32	3.20
7th day after	146.06	4.20
8th day after	111.5	2.90
9th day after	64.64	2.81
10th day after	54.42	2.43
11th day after	40.04	2.66
12th day after	31.92	2.88

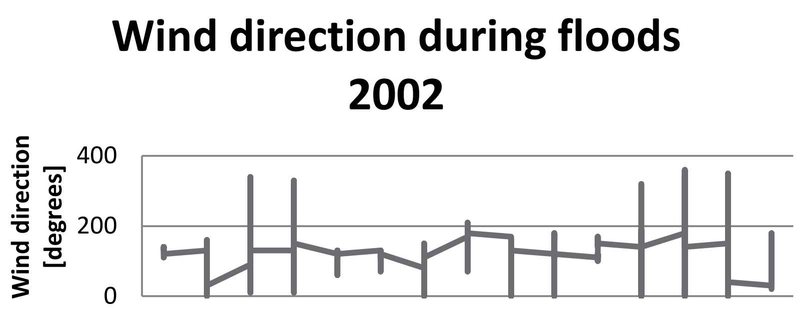


Figure F-5: Wind input direction for Flood

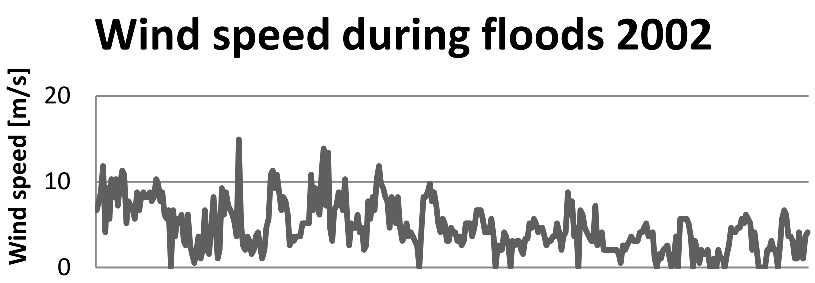


Figure F-6: Wind input speed for Flood

Appendix G Modeling in MIKE21

As with every model this one is based on supposedly wise choices, like detailing, mesh-size, bathymetry and calibration. Hence this needs to be addressed. All components are mentioned in order of chronology.

G.1 The area

The area needed to be determined first. How far will the coastline be detailed and how far into the deep ocean. The first is assessed by thinking that the smaller the details the more accurate the area is modelled. A good thing one would say, but the downside is that it causes small grid cells at the coastline, because the follow every detail. The advantage of the triangular mesh of MIKE is that it diverges into larger grid cells when further away from the small cells. Nevertheless it results in more grid cells. So if avoidable there is hardly any detailing in the coastline. This is done outside the Kingston Harbour basin for example. Inside the artefacts to be found on the coast can be of influence. And there for the coastline there is drawn based on sensible engineering judgement keeping the rough corners to a minimum and smoothing out edges.

G.2 The boundary conditions

In the deep water part of the model the boundary conditions need to be applied. There are two elements there. The tide and the deep water wind waves. The tide can be rendered with a package that is included in the software by DHI. This is done by applying two tide time series on the east side and the west side. There is a phase difference between them as is with all tidal amplitudes along a coast. This causes a tidal wave to propagate along the coastline through the domain. This is realistic and also advised by DHI software. The other elements are the deep water wind waves. They cause a serious problem for determining them. Since conditions in the domain are determined by choosing past occurred events, the offshore conditions need to be determined by information from those events, but that is not possible for all scenarios. The model was tested for the sensitivity of offshore waves compared to the locally generated waves. It was found that even though the offshore waves did penetrate into the Kingston Harbour basin the effect was negligible on the sediment transport around the Causeway bridge area in the harbour. To avoid making mistakes with the generation of correct offshore waves, this was the argument for not using offshore waves at all. For sediment transport at the Kingston Harbour mouth near Port Royal this argument would be invalid.

Besides the deep water boundary conditions there is also the Rio Cobre. In fact there is also the Sandy Gully. The problem is that there is no data available on Sandy Gully during either of the events chosen. What is known is that Sandy Gully behaves differently from Rio Cobre. Therefore the behaviour cannot be copied. A choice had to be made if the difference was too large or not to apply a similar discharge in the Sandy Gully or no discharge at all. The latter was chosen. Using wrong data or no data at all was a difficult decision.

For the Rio Cobre thorough measurements were available with a many yearlong time series with daily averages. Since the simulations to be done would cover several days the daily discharges will suffice.

Something to smooth the model start-up is increasing the bottom friction at the boundary. This is done for the tidal boundaries. What can also give a problem is the tidal elevation at the beach. If the boundary goes all the way up to the beach and travels lateral to it the elevation can be way off what happens in reality. The problem with that is that it keeps going on since the boundary elevation is a permanent element. It is there for that the land boundary at the beach takes a turn into the sea up until a suitable depth is acquired.

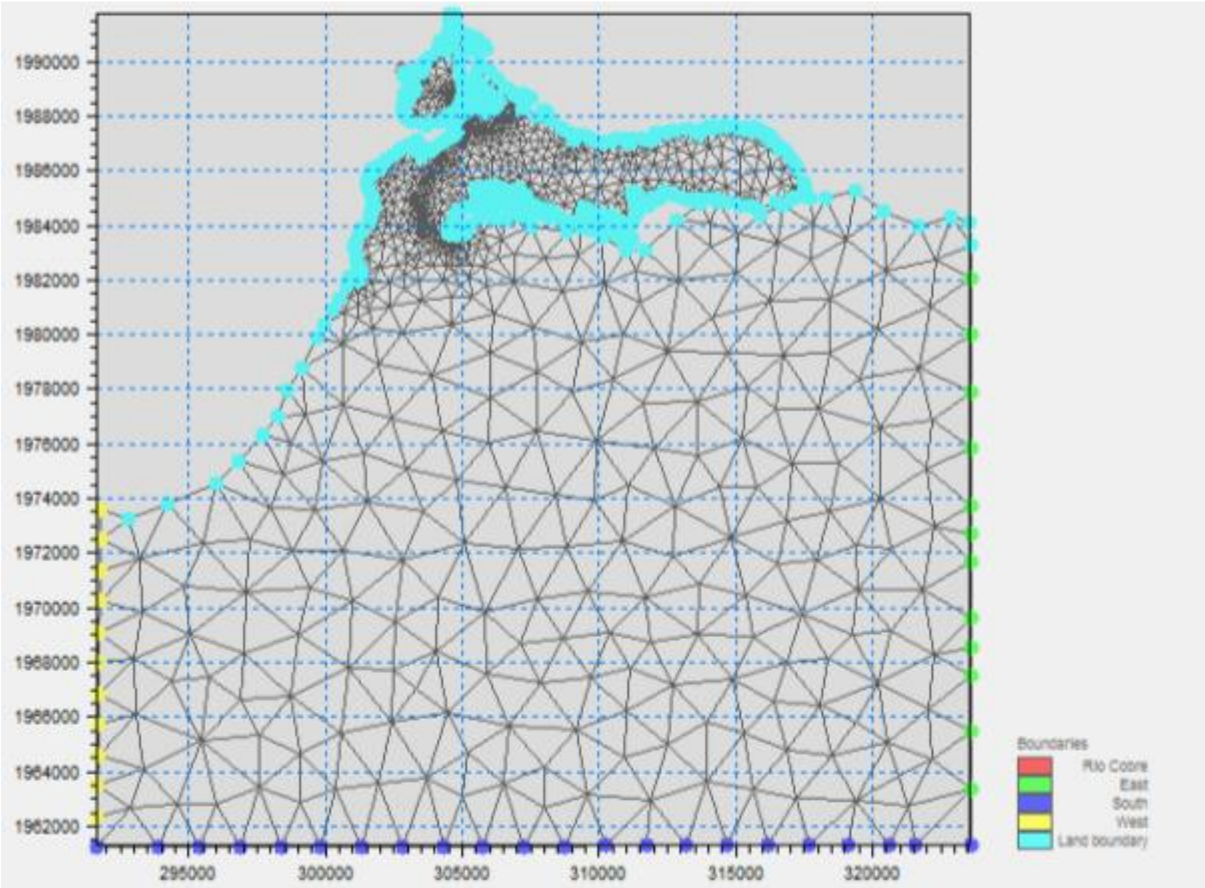


Figure G-1: Domain specification X-Y notation is in easting and northings

G.3 Grid

As mentioned in the chapter about the area definition the grid is among things, depending on the detailing of the area. Initially the detailing was at a high level. When stability problems started to occur due to small spatial scales compared to time scales (CFL condition) the detailing was reduced to a minimum at problem areas and in general where detail was not of the essence, hence reducing unnecessary computational time. It must be stressed that the maximum grid-cell size has been reached to still represent a detailed bathymetry. Especially the access channel gave limitations to the grid-cell size increase.

There is on the other hand of course the issue of required detailing at the area of interest. That is the area of the Causeway Bridge. The mesh-size was strongly reduced at that point. It never resulted in violations of the CFL conditions, which is convenient since the time step would have to be reduced in that case for just a small area. Problems mainly occurred in shallow beach areas outside the Kingston Harbour basin.

A big advantage of MIKE is that the grid is easily adjustable. The input by the person building the model, is based on parameters as maximum surface of one cell and the minimum angel of the triangles. Or when quadrangulars are used the length, width and direction is used. Problem areas can be adjusted manually after letting MIKE generate the grid based on these parameters or when the grid is not satisfying, changing the parameters instead.

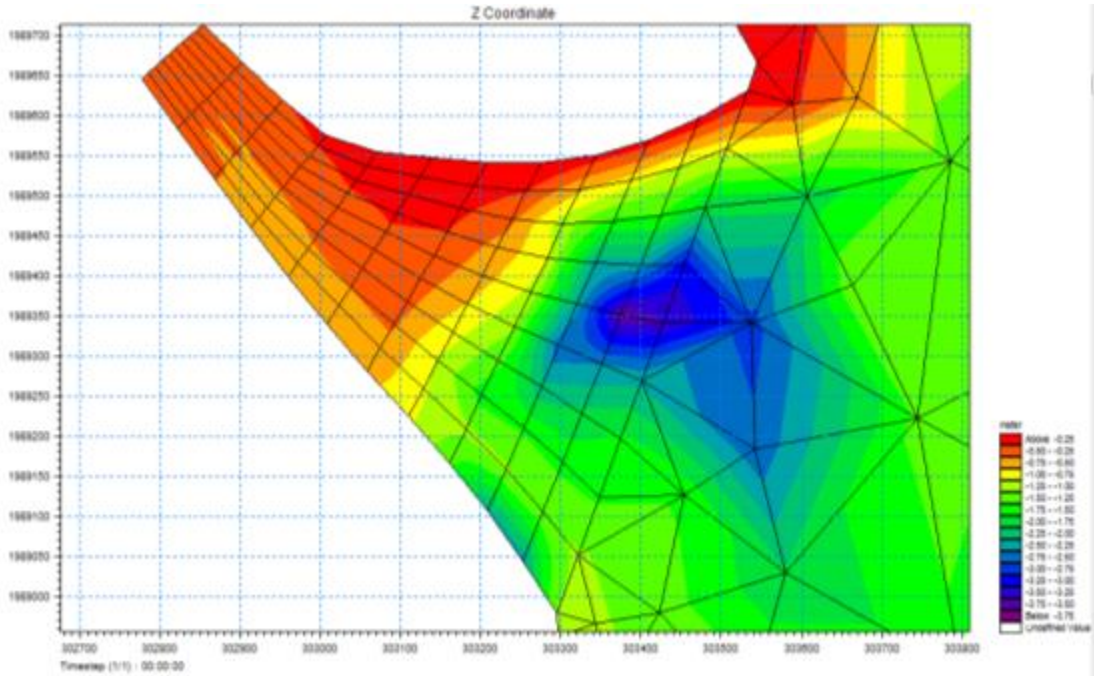


Figure G-2: Example of quadrangular grid-cells near at the mouth of Rio Cobre

G.4 Bathymetry

The bathymetry used initially was based on Admiralty charts. This is old information and the situation can be changed. At first to start up the initial models the old information was used as input. But since the area of interest is Hunts Bay it was also very well possible to do a bathymetric survey on location. This was done on 29th of august 2012. The survey served two purposes. For one thing it would give of course an up-to-date bathymetry. This would give the models then the possibility of what would happen in the current situation. Since Hunts Bay is a morphological dynamic area, the results do have a limited timespan to be valid of course. When episodic events occur in the future the bathymetry might have changed drastically. This needs to be taken into account when considering the models in the future.

The second result is in relation with this last aspect. The old bathymetry has been compared with the new bathymetry. It shows that the dredged channels that used to be in Hunts Bay have virtually disappeared and silted up. Maintenance is overdue if those channels still serve the purpose where they were meant for.

G.5 Sediment

Parallel to the bathymetric survey research was done on the sediment on the bottom of Hunts Bay. 5 samples were taken to assess the type of sediment. It showed that it was very fine muddy material. At the time of the survey the models were already started up and were set to use mud. So this ended up to be a correct assumption. The values used as input for the Mud Module in MIKE were determined from what was seen during the survey related to the advised values by DHI.

As input it was also necessary to know the layering of the bottom. This was done in a rudimentary way. The top layer was a very weak mud layer so a pole could be stuck into it to see how thick it was. Roughly 0.6 meter was found on average. Although it must be stressed that this value hasn't been thoroughly investigated since the resources and time were limited.

What needs to be acknowledged is that more extensive research should be done around the suspended sediments within Hunts Bay and in the Rio Cobre during these events. The type and amount suspended in the river is extremely hard to assess and hasn't been done during this project.

G.6 Simulations

The simulations take a long time in the beginning since the real model adjustments come when the stability problems start to occur. This is a downside of MIKE. It lets you build a model that seems to be able to run. But it might crash halfway. An issue that appeared is the time step. It was initially set at half an hour, but later it was reduced to 15 minutes to avoid stability problems. Those stability problems were hard to find since the CFL values where below 1 at all time. Nevertheless the issues were solved be reducing the time step and increasing the cell-size. This resulted in even shorter time steps.

Running the scenarios took time varying from 3 hours up to 6. Initially it was between 8 and 20 hours. But when fiddling with the mesh-size and the time step, this was strongly reduced.

G.7 Results

The results were as to be expected, namely: Accretion in the deeper areas and erosion in the shallower areas. The phase one expansion shows no real drastic changes but merely another location of deposition and erosion. There for the results needed to be explored in a more meticulous way. Something important to realise about the results is the lack of validation of the sediment transports. Due to the lack of information about sedimentation and erosion processes in the area there was no possibility to calibrate the model to a morphological timescale.

G.8 Comparison

In this part only the way of comparing is described. The actual comparing is done in the report itself.

The issue with MIKE is that comparing two different results with each other is not possible in a direct manner. The output of different simulations is information per grid cell. Since the situation before expansion is compared to the situation after the expansion the grid cells are different, have different cell numbers, and there is a different number in grid cells in general. Henceforth, a separate method needed to be created partially outside MIKE and partially with MIKE. It was found that if an arbitrary mesh could be used to interpolated output of other grids, the output of that arbitrary grid is consistent to all different inputs. It must be said that this is a cumbersome operation and would require close attention not to make mistakes.

When the arbitrary mesh yielded consistent outputs of the two scenarios to be compared the information was ready to be processes by excel for example. Differences could be found ratios and so forth. This information can then be used as input for a new grid based on the arbitrary grid, and the result would be a 2D representation of the information.

Appendix H Modeling in Delft 3D

In this Appendix the design of the Delft3d model is explained and the decisions that are made during the design process are discussed. Because the Delft3D model is to be compared with the MIKE model, the input values and boundary conditions have to be comparable. During the development of the models, the MIKE model had a head start. Therefore the results of the MIKE model about what could be neglected as input conditions were adopted into the Delft3d model so that the models could be compared.

H.1 The grid

A small grid size leads to more accurate results but also to more computation time, therefore a balance has to be found between these two properties. This is done by implementing a nesting grid. This is a grid which is nested in an overall grid and has a smaller grid size than the overall grid. For the Delft3D model a 1-to-5 refinement[6] is applied. The boundary of the nested grid is at the location of Port Royal. With the nesting grid Hunt´s Bay, the area around the expansion and the causeway bridge is modelled in more detail.

The grid has the following properties:

- A spherical grid orientation is used. This is due to the fact that Delft Dashboard can only construct a spiderweb[7] in a spherical orientation
- The nesting grid and overall grid are offline coupled, by using the nesting tool of the Delft3D suite the overall grid makes a time series of the water level at the boundary of the nesting grid
- The nested grid is divided into 10 vertical layers, all with a thickness of 10 % of the whole depth
- The grid properties satisfy the requirements[8] concerning the orthogonality, smoothness and aspect ratio.

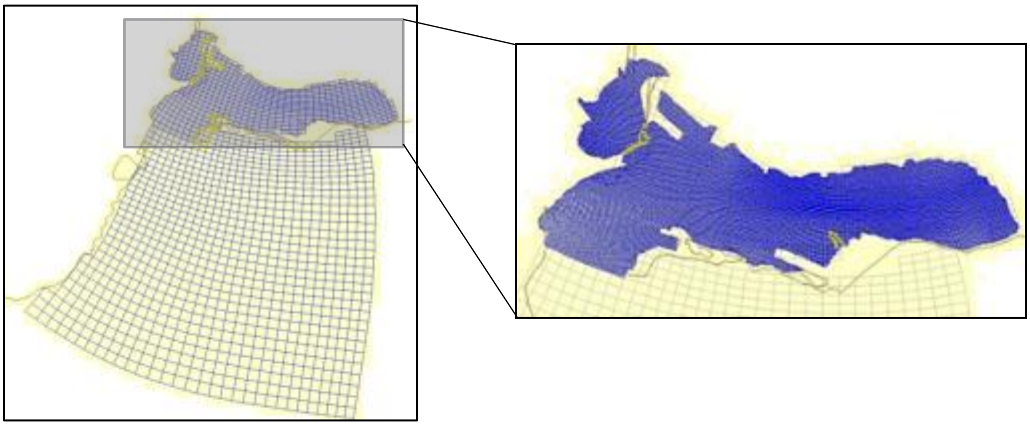


Figure H-1: Overall grid and nesting grid of the Delft3D model

[6] A 1-5 refinement means that the width of a nesting grid is 5 times smaller than that of an overall grid
[7] *spiderweb* is a circular grid with its centre in the eye of the hurricane. It gives the space varying wind and pressure over the grid.
[8] The grid requirements are prescribed in chapter 4 of the Flow manual of the Delft3D suite.

H.2 Bathymetry

The bathymetry of the project area was already available via SWIL, who used admiralty charts and maps to come to the bathymetry. To get good insight into Hunts Bay, a bathymetric survey has been done during this project. These results have been implemented in the bathymetry of the whole project area. One depth point is called a ‘sample’ in Delft3D.

The pre-processing tool Quickin of the Delft3D suite is used to create the depth input file and the thin dams input file. The following guidelines were used for the creation of the bathymetry:

- When there were four or more samples in the grid, the depth was determined with the “grid cell averaging” application
- When “grid cell averaging” was not possible, the tool triangular interpolation was used to designate the depth of a grid cell
- The “internal diffusion” application was used to provide the residual grid cells of a depth.

The increased depth of the access channel and the turning basin is implemented in the bathymetry of the expansion by following the contours of the first expansion plans provided by the Port Authority (Appendix D) and a uniform depth of 17 meters.

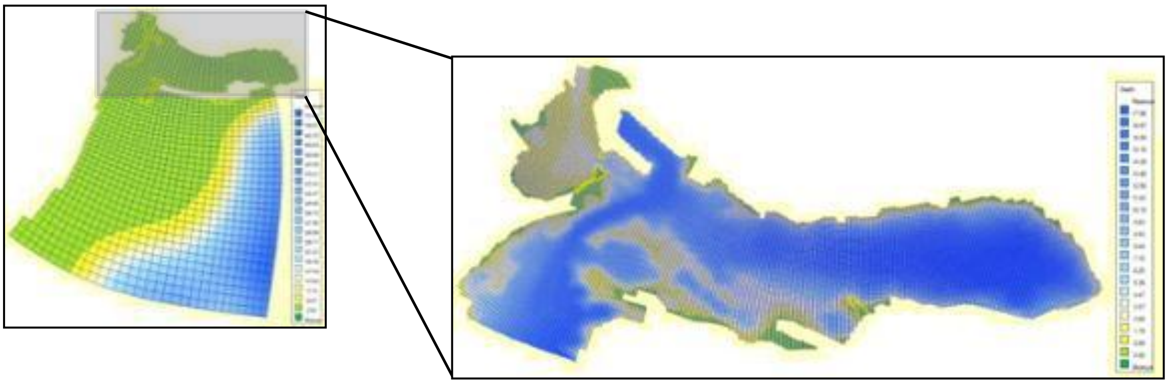


Figure H-1: Bathymetry of the Delft3D model

H.3 Wind

For the wind input of the model the measurements of the Norman Manley Airport [3] and the hurricane tracks and properties of HURWave are used. A spiderweb is being created from the hurricane track by the program Delft Dashboard.

H.4 Tide

The South and Eastern boundaries of the overall model are connected to the open sea, by using the data of the global inverse tide model which is implemented in Delft Dashboard. The tide is imported into the model. This leads to a set of tidal constituents on the sea-boundaries of the model.

H.5 Discharge

Due to the fact that the discharge data is available only in time steps of one day, it makes no sense to linearly interpolate these values. This will lead to an even more flattening of the extreme discharges. Therefore it is chosen to make blocks of 23 hours and to linearly interpolate the discharge to the value of the next day in one hour. This will lead to less abrupt changes in discharge and therefore gives less computational wiggles in the results.

H.6 Morphological changes

The following decisions were made concerning the morphology of the model:

- The morphological changes start after one simulation day. This is due to the fact that the model needs some spin-up time.
- The morphology changes are only computed in the nested grid, this is done to save computation time. This is possible because the influence of morphological changes due to the extreme events in deeper water will not have much influence.
- The morphological factor is set to 1, because the morphological changes cannot be calibrated.
- The Partheniades-Krone sediment transport formula is used. This is done because this formula is implemented in Delft3D and most common to use for cohesive sediments.

H.7 Sediment

For the initial bed composition of the Kingston harbour area there are two sediment fractions defined, these fractions are estimated on the basis of the sediment that was retrieved from Hunts Bay during the fieldwork. The thickness of the layer is also estimated, during the fieldwork a steel pole was pushed into the bottom. Based on the resistance of the pole a rough estimation was made of the thickness of the mud layer.

H.8 Salinity

In the initial state the salinity in the whole model is assumed at 35.8 ppt. This is estimated on the average of the salinity changes over a year in the Jamaican region. The salinity of the river discharge is approximately zero.

H.9 The wave module

The following decisions were made concerning the wave module:

- The same grids were used for the WAVE module as for the FLOW module.
- The offshore grid is offline coupled. It is only using the wind and bathymetry of the FLOW module but does not extend the Flow module. This reduces the computation time and does not have significant influence on the results of the model.
- The nested grid is online coupled to the FLOW module, it uses and extends the water level, the current, the bathymetry and only uses but does not extend the wind.
- No waves enter from the offshore boundaries, all waves are locally generated. This is assumed, since there is no information known about the waves during these events. Also results of the MIKE model show that they do not have much influence.
- Obstacles are used to give the contours of the ‘Thin Dams’ to specify the land boundary more accurate.
- Diffraction is not taken into account. The grid size should be 1/10 of the wave length to get proper results for diffraction. This will lead to an enormous increase in computation time and therefore will not be taken into account.

H.10 Modelling results "Ivan"

H.10.1 Erosion / sedimentation

Due to lack of time and computational time the 4 events could not all be run for the Delft3D model, therefore only one event was run. This are the results of the hurricane Ivan, the first thing that can be noticed when looking at the cumulative erosion and sedimentation of the harbour with and without expansion is that the difference between them is not very significant.

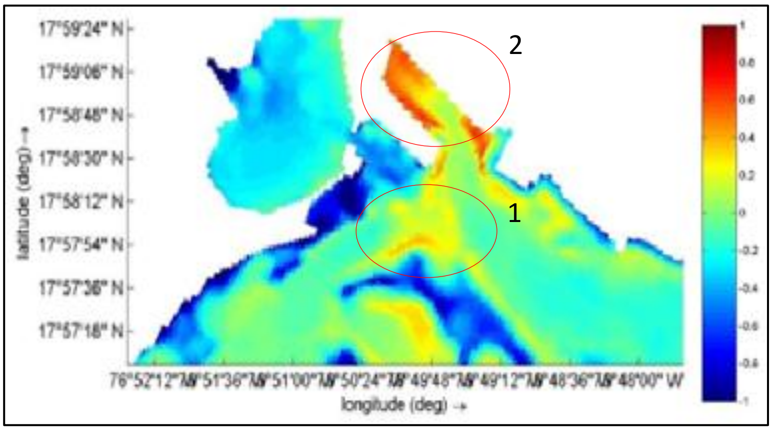


Figure H-2: Harbour without expansion: Cumulative erosion/sedimentation

In Hunts Bay there is some erosion and the outflowing sediment settles widely spread (1) in the harbour in the current situation. It can be noticed that a lot of sediment is brought into the basin of the Fort Augusta container terminal (2) where it settles.

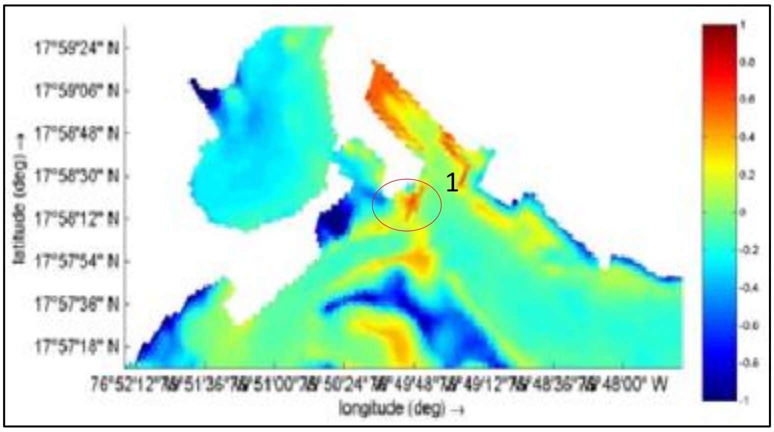


Figure H-3: Harbour with expansion: Cumulative erosion/sedimentation

With the expansion of the Kingston harbour the accretion is more centralized, especially behind the French expansion (1). The settlement inside the basin of the Fort Augusta container terminal has become a bit less but this decrease is not very significant.

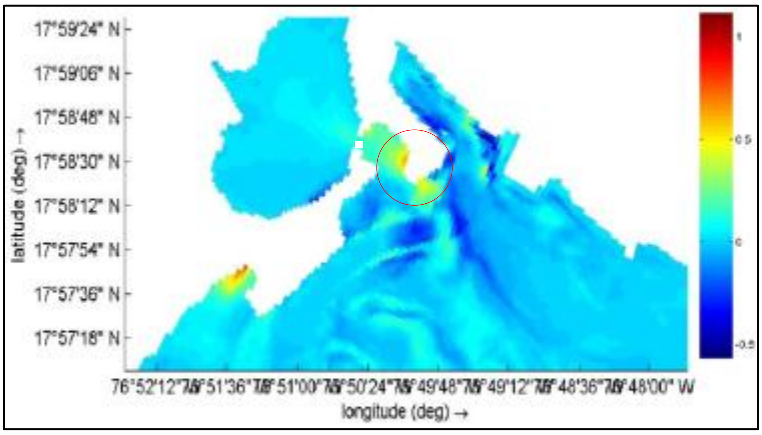


Figure H-4: Kingston harbour: Difference cumulative erosion/sedimentation

When looked at the difference between the harbour with and without the expansion the only notable thing to notice is the accretion around the French expansion (1).

H.10.2 Flooding

When looking at the water level difference for the harbour with and without the expansion, it can be noticed that the change in water level is not very significant. It has an order of magnitude of a few centimetres. Therefore the flooding risk of the area around Hunts does not indicate any significant change when looked at the consequences of hurricane Ivan.

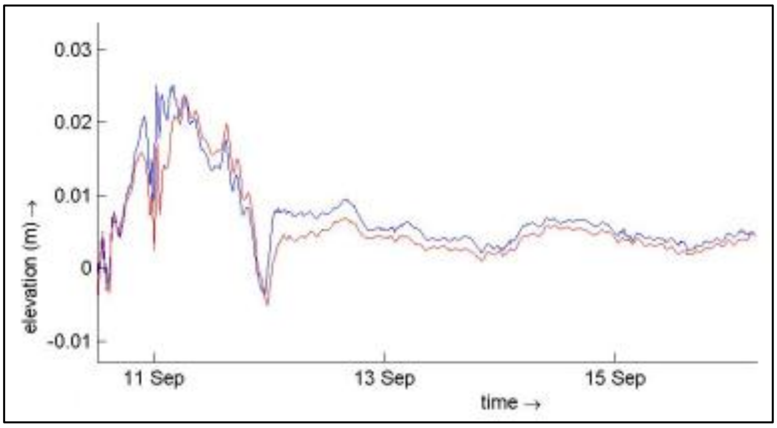


Figure H-5: **Red** Water level difference in the middle of Hunts Bay. **Blue** Under the Causeway Bridge

Appendix I Calibration of the models

In order to increase the credibility of the model, calibration needs to be done. Calibration yields the comparison between the outcomes of the model and measured data, the real situation. With this approach one needs to bear in mind that the measured data is from a scenario with many boundary conditions it is exposed to. On contrary the model is a simplified representation of reality lacking most of these boundary conditions. So in short the model needs to be equipped with most boundary conditions. And one needs to accept that full correlation is impossible to achieve without very extensive research on boundary conditions. This full correlation is with no means necessary to come up with answers to our specific question about sediment transport. Flow velocities are very important. In this case one will see that two different aspects need to be regarded. There will be a trade off in maximum velocities and residual flow. The discussion about this will be represented in the conclusions of both models.

First there will be an elaboration on the measurements and the model output data. In the part where the comparison will be done the differences and contradictions will be indicated.

I.1.1 Validation measurements

In the past not much is measured in Hunts Bay and the Kingston Harbour. For a project about the Fort Augusta container terminal [12] a current meter was installed underneath the Causeway Bridge. This measured for 1 month the water level elevation and the velocities, a whole tidal cycle. This data consists of several time series and is used for the comparison with the model.

The data on current velocities are decomposed in the two main directions (Northing: north-south and Easting: east-west). Since all these velocities are lined up in a clear time series, they can easily be compared to other time series such as one from a model. For a more reliable calibration it is recommended that at more locations data will be gathered, since it is now only done for one point. When there are at least two measurement locations, the phase lag of the tide between those stations can be calculated. This is not possible with the present data. This lack of data has serious consequences for the robustness of the model.

The measured path consists of the tidal velocities including the conditions during the measurements. Therefore the measurement doesn’t consist of purely tidal velocities, but with high fluctuations due to the wind and wave conditions. For an accurate calibration the input values of the model should be as close as that of the conditions occurring during the measurements. Since no data about wind and waves on that local and accurate scale on that time is available, only the velocities due to the tide are taken into account. A section of the measured data, for the Easting velocities in this example, can be found in Figure I-1.

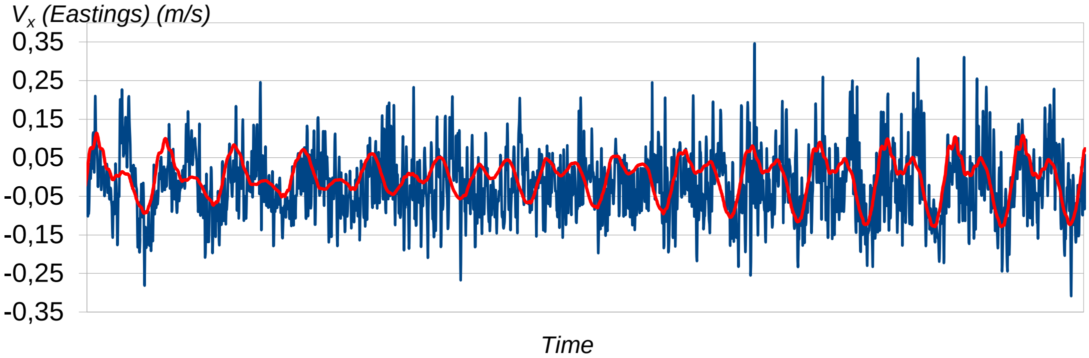


Figure I-1: Section of the Easting velocity. **Blue line** Measured data. **Red line** Example from Delft3D

I.1.2 Model output

The model had to be set up in such a way that its results could be compared to the measurements. This was done by modeling the area with just a tidal boundary condition. This tidal boundary causes velocities under the Causeway Bridge, and is even the major contributor to it. This is of course not the only contributor. But it must be said that all the other contributors causes minor changes compared to the tides and with respect to the currents and water level elevations. Since the measured data was gathered by measuring from one point, the model output is done by a point measurement under the Causeway Bridge as well. An example of the modeled velocities can be found in Figure I-1. The data is calibrated by using excel and the software program *Grapher*[9].

[9] *Version 8.8.957*. Grapher is a software program that is able to create 2D and 3D graphs from simple and complex equations. In this case used for the calculations of the mean and deviation of the available data.

I.2 Calibration in MIKE21

For the output the start was with the basic parameters. The first run was with a roughness with a Manning value of 32. This resulted in quit good results but investigation needed to be done on improvements. It has been known that increased tidal elevations result in better flow velocities. But of course this will make the model deviate in the matter of water levels. This is a concession that can be done in this case since we are looking at sediment transport. For sediment transport flow velocities are by far more important than water levels. With this assumption the tidal range has increased with 20%. This yielded better results for the velocities under the Causeway Bridge.

I.2.1 Comparison

As has been said in the introduction the focus in the comparison is on flow. And within that, the trade-off between residual flow and maximum flow. Several methods were used to assess the differences of the times series in a quantitative way. By eye one can only make a first estimate. Below one can see an easy way to compare the residual flow on a long term basis in the 2 basic directions, and the accompanying standard deviations representing the spread in maximum velocity. The latter is important to the sediment since the higher velocities, hence the deviation, cause far more sediment transport. So in this representation one can see that the increased tide really improves the flow velocities in the model compared to the measured values. One can also see that there is a flow into Hunts Bay according to the measurements. A full explanation hasn't been found yet. But with a velocity of 2 cm per hour it is not really contribution to the sediment transport.

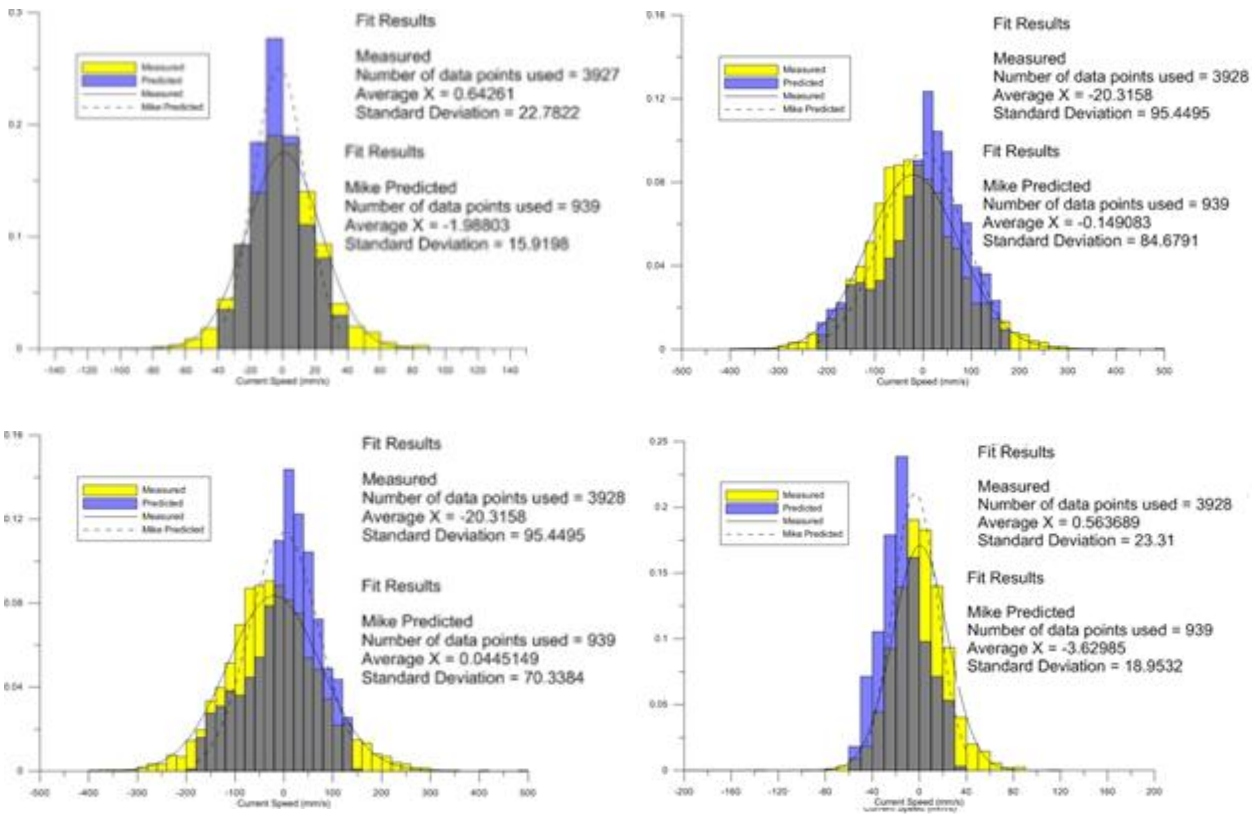


Figure I-2: **Top left** Northings. Manning 32. Normal tide. **Top right** Easting. Manning 32. Normal tide. **Bottom left** Easting. Chezy 65. Increased tide. **Bottom right** Northings. Chezy 65 increased tide

Another way to compare velocities is a scatterplot to shows the spread in combinations of the two main directions. Below one can see the result. It shows a good correlation for the direction. And the extreme velocities are in check when the first few time steps of the model are left out. The direction corresponds quite well. For the increased tide scenario one sees that the extreme velocities match indeed a little better.

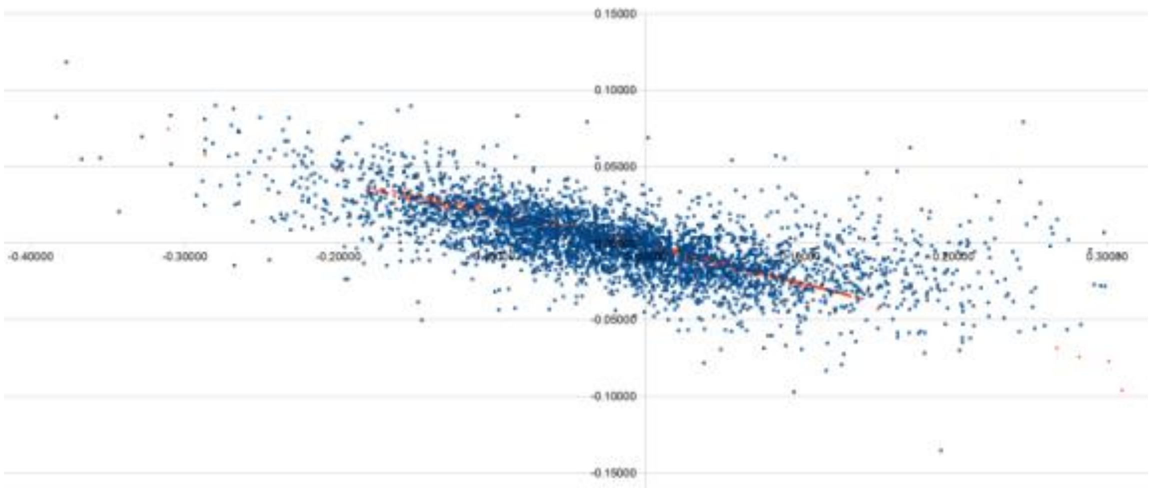


Figure I-3: Scatter plot with Manning=32 and normal tide

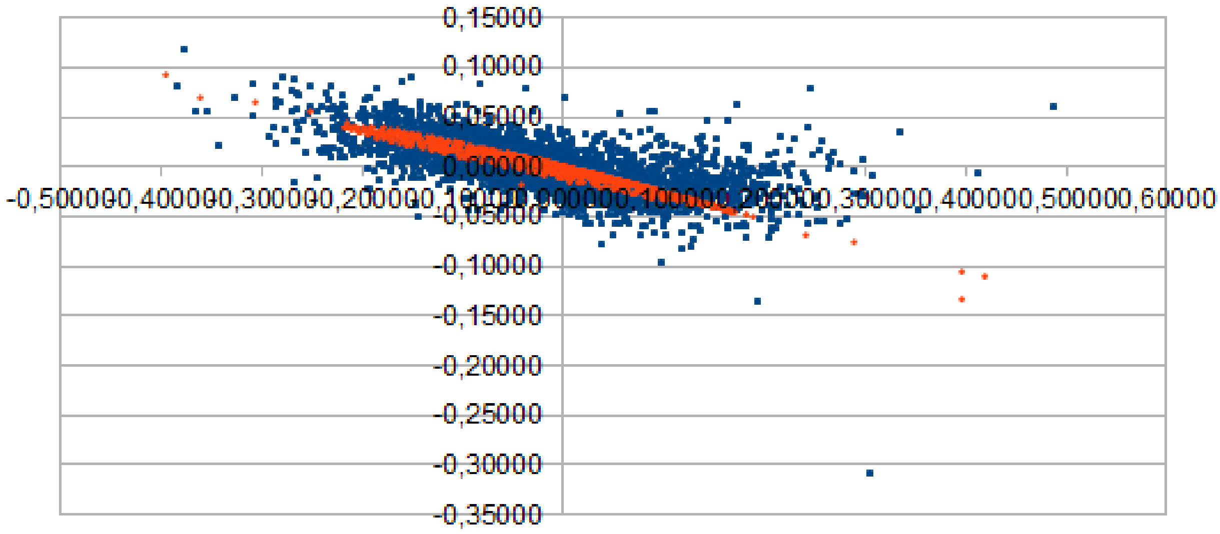


Figure I-4: Scatter plot with increased tide

The third and last way to compare the two scenarios with the measured data is a progressive vector analysis. This is adding every time step multiplied by its velocity vector. This results in a cumulative path. It also represents the residual flow of each. As discussed before the residual flow is of less importance than the higher velocities.

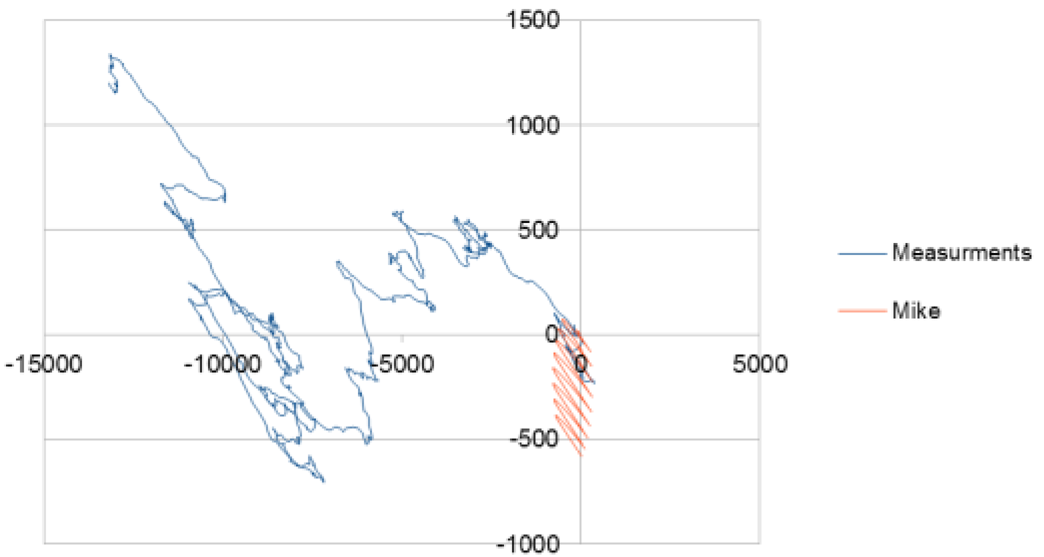


Figure I-5: Progressive vector analysis of the increased tide

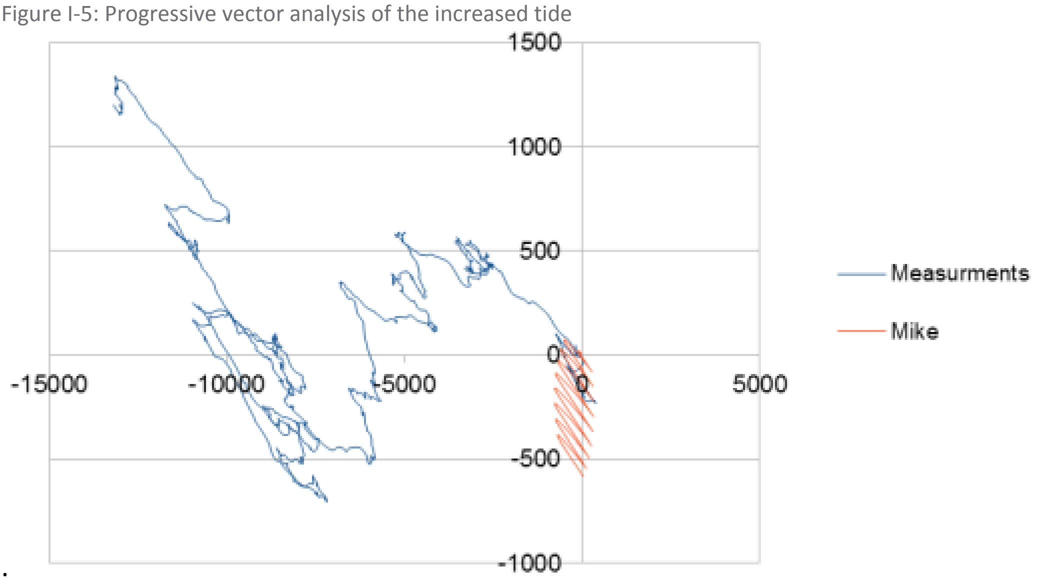


Figure I-6: Progressive vector analysis of the normal tide

There is no apparent difference in the progressive vectors of the normal and increased tide. There is on the other hand a big difference between the measurements and the model output. At first the thought was a residual flow from the rivers Rio Cobre and Sandy Gully. But then the direction would have to be opposite. So far no apparent reason has been found yet. But it must be said that the influence on sediment transport will be negligible. Nevertheless it is good to know that this residual current is apparently there.

I.2.2 Conclusion

After using the 3 different methods for comparison it is decided that the increased tide yields the most accurate flow field around the measurement point under the Causeway Bridge. It does on the other hand have no good representation of the water level although this hasn't been investigated thoroughly how large the differences are since there is no need of knowing the models behavior on water levels. This compromise needs to be taken into account when using this model for other purposes.

I.3 Calibration in Delft3D

First a directional scatterplot is made, to check if the measured and computed velocities have the same net direction. After that a progressive vector analysis is done, which shows the path of a particle over time (with the Causeway Bridge as starting point). Finally the velocities in both Eastings as Northing direction are compared

I.3.1 Directional scatterplot

The measured and the predicted velocities, in both northings and easting are elaborated into a graph for the comparison of the resulting direction of the velocities. This scatterplot, with eastings on the horizontal axis and northings on the vertical axis, can be seen in Figure I-7.

It can be seen clearly that the measured values are spread very widely. From the figure it can be seen the Delft3D prediction follows the path of the measured values. There is a small difference in angle visible; the Delft3D path is a bit steeper than that of the measured one. This can be explained by the fact that the grid used in Delft3D model causes a slightly different boundary orientation at the causeway bridge, compared to the real situation.

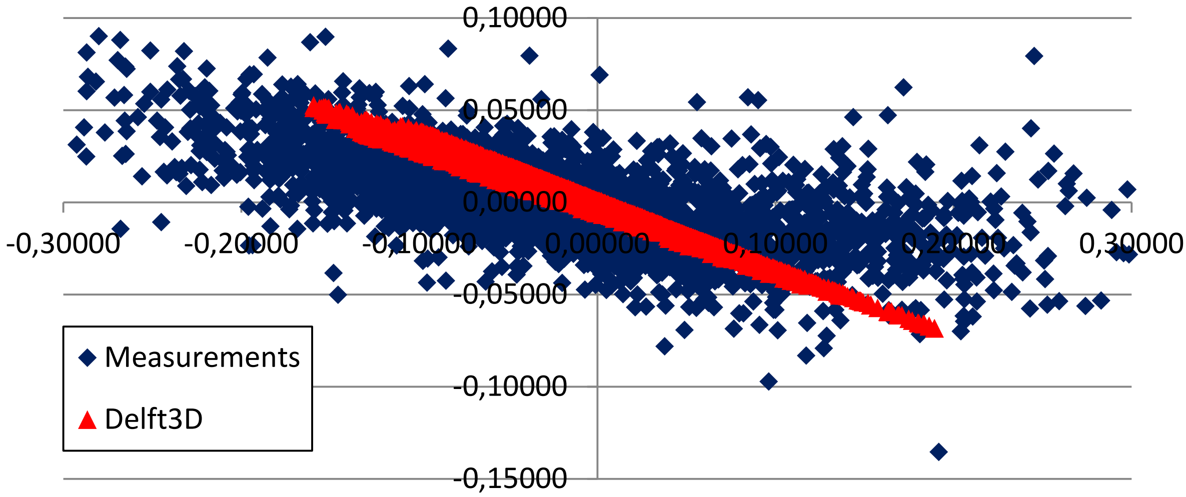


Figure I-7: Directional scatterplot

I.3.2 Vector analysis

In a progressive vector analysis, the path of a water particle is calculated. This is done by multiplying the velocity, in both northings and easting, by the time step. So after every time step the location of a particle (underneath the Causeway Bridge) is determined. This is done for both the measured data and the modeled ones. The outcomes can be seen in Figure I-8. It can be seen that the measured data gives a resulting path towards the west, which is also concluded from the histogram comparisons with Grapher. The three different models follows a path which is significant different; a net direction towards the south is the result. As it can be seen from the figure, the model with the increase in tide has a bigger range, so a bigger error is expected, and this one will not be seen as the favorable model to use. This spread in variety can also be seen when the manning coefficient is used, although it is a small difference. For all the three models, the direction of the particle, through the starting point [0, 0], is conform that of the measured ones. So there is no difference. From this, it can be concluded, the model fits the best with the reality for both the Chezy = 65 as the Manning = 0.03 option.

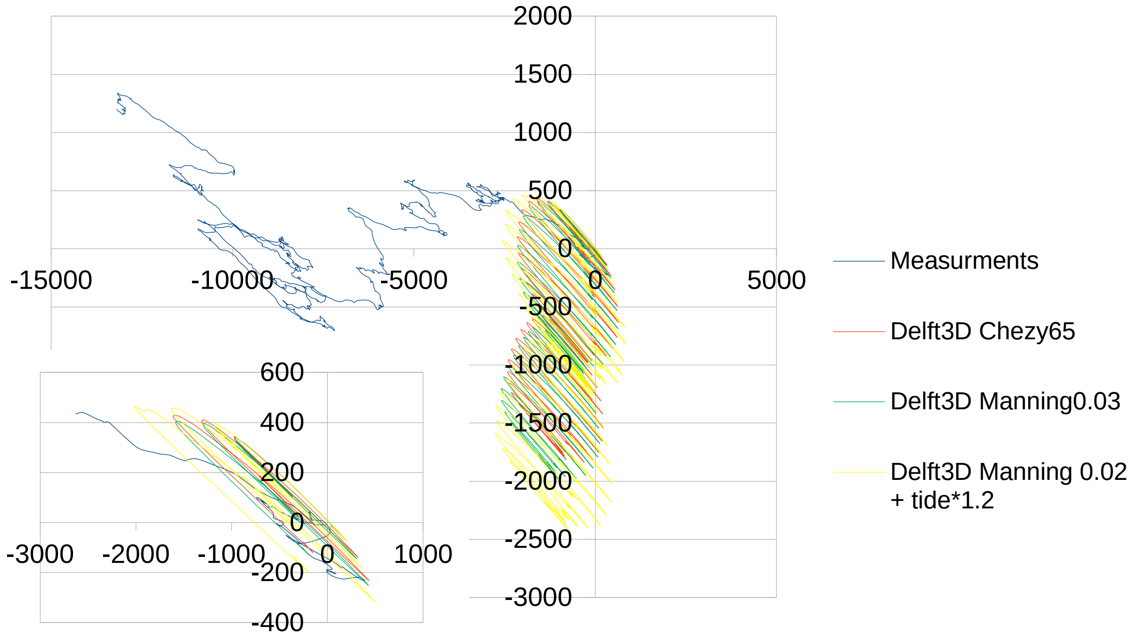


Figure I-8: Progressive vector analysis for Delft3D with in the left bottom the graph of the first 400 values

I.3.3 Histogram comparison

The goal of this calibration is not to fit exactly with that of the measured data, but the path of the sinusoidal part of the tidal velocities in the measurements should be fit as accurate as possible. An example for this can be found in the red line in Figure I-1.

For every chosen model a probabilistic plot is made and compared with the measured data. For this the software *Grapher* is used. This is only done for the water level due to the tide, so without the influence of the rest, like wind. For both the easting- and the northing velocities, these calculations are done. The results are shown in Figure I-9. *It must be noted that the values are notated in mm/s*.

The results in the boxes on the top are the results for the measured data. A resulting velocity towards the west of 20 mm/s is the result. This is also concluded from research done in 2007 on the Fort Augusta terminal [12]. What also can be seen is the standard deviation of 94.9 mm/s for the Easting direction. It must be noted that this deviation includes the high fluctuations, which is not included in our modeling. Therefore it is chosen that the deviation doesn't need to be as close as possible to the measured deviation. What also can be seen on the calculated data is that the averages of the models are not close to the measured data. This is already treated in the paragraph about the vector analysis. Again it can be seen that the increase in tide is less favorable than the other options (NB. The deviation should not be very close to the measured data).

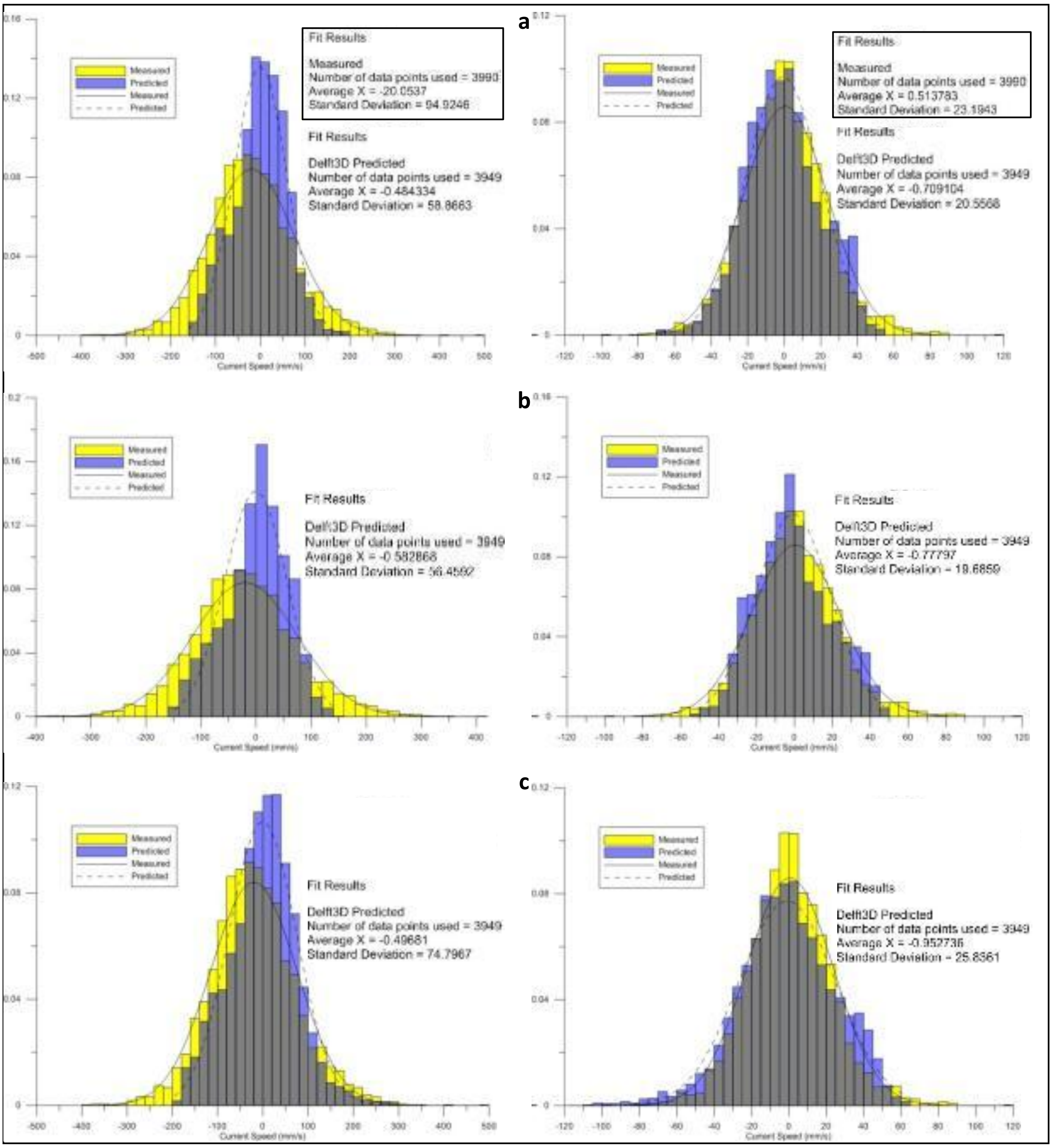


Figure I-9: Histogram comparisons for measured (yellow) and predicted (blue) values. **a.** Chezy = 65 for eastings (left) and northings (right) **b.** Manning = 0.03 for eastings (left) and northings (right) **c.** Manning = 0.02 and increased tide for eastings (left) and northings (right)

I.3.4 Conclusion

In both the vector analysis as the histogram comparison the configuration with the increased tide doesn't seems to be the best option to choose. Therefore the Chezy and Manning options remain. Since the Chezy configuration consists out of a lot of wiggles, it is decided to choose the Manning coefficient of 0.03 for the computations in Delft3D. Then again, it must be said that the Chezy value indicated a smoother bottom than the compared Manning value. For sake of time and lack of measured data no further optimization was done for the bottom friction. For both the Chezy and the manning methods an optimized value can be found, depending on the preferred method.

Appendix J Model analysis

J.1 Introduction

As already succinctly discussed in Chapter 5, the obtained results can be divided into three different sections.

The first section is the equilibrium situation before the expansion. This one shows depths and flow patterns in present situation, without exceptional weather conditions. The second section displays the results of the extreme events introduced in chapter 5. It will both discuss the highlights during and after the extreme event has passed. In the third set of results the new situation is implemented. Remarkable differences will be pointed out accompanied by an illustration showing the relative erosion / sedimentation for the existing situation versus the new situation.

In the conclusion, a summary of all data will be given including possible relations between events. This will be the opening data used to come up with a solution for the sedimentation problem.

The discussion of the results will be accompanied by an illustration of the increase or decrease of the top layer height at the end of each model run, when the extreme event is over. Based on the fieldwork done in Hunt´s Bay (See Appendix B) the silty top layer is modeled with 0.6 m thickness.

To clarify names and locations that are used in this project, a map is given that shows them all in Figure J-1.

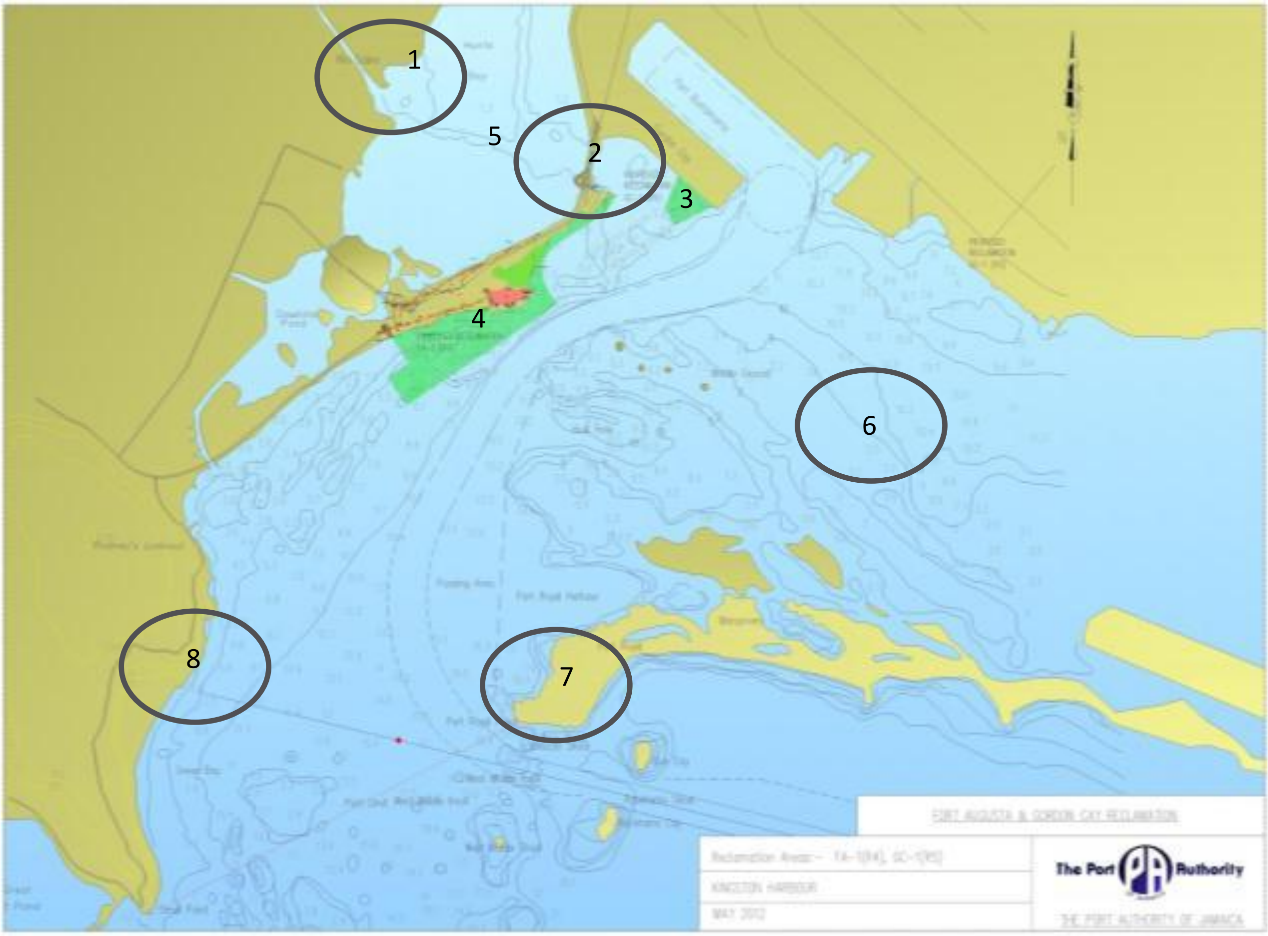


Figure J-1: Overview of area

Table J-1: Locations of interest in the project area

1	**Mouth of the Rio Cobre**
2	Causeway Bridge
3	French expansion added to the existing Kingston Container Terminal. Part of Phase 1
4	Chinese expansion. Part of Phase 1
5	Hunts Bay
6	Kingston Harbour
7	Port Royal
8	West bank of the Kingston Harbour. Hellshire Beach is just visible in the bottom left corner.

Note that the numbers in the illustrations are not realistic on the actual processes, but purely for comparison between the models, since these values have not been calibrated with real data.

J.2 Present situation

This illustration shows the area of interest in equilibrium. The flow is concentrated in the gullies in Hunts Bay, congregating near the Causeway Bridge and flowing out into the Kingston Harbour area. The figure showing this situation is one of the first in modeling an extreme event. This is to illustrate the outflow and accompanying erosion due to scour (although this is a small amount). At the start of the model run, this would be zero everywhere, not representing the reality.

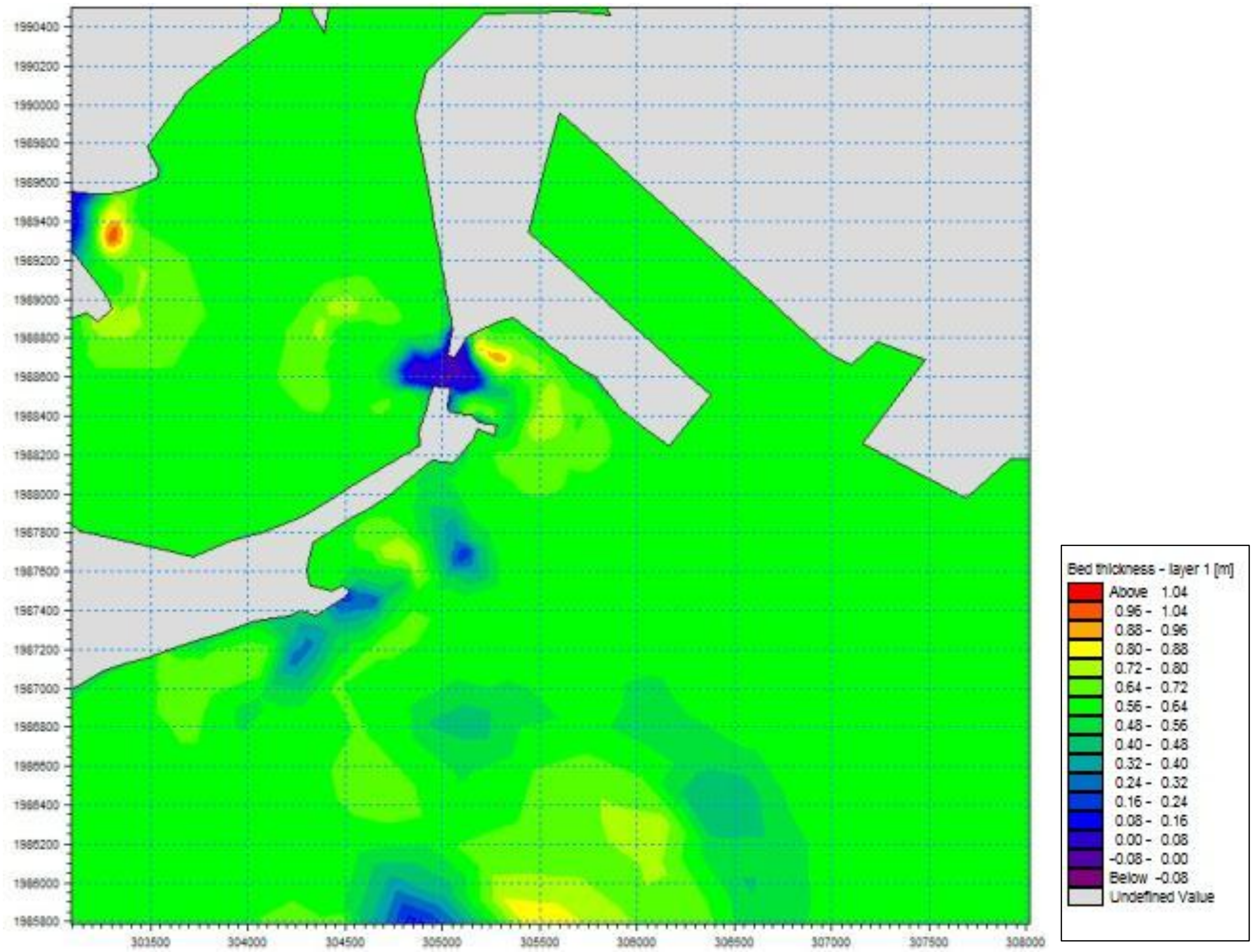


Figure J-2: The situation before the extreme events

J.3 Ivan

The modeling process has been summarized around 300 frames which show the deposition on that given time. To get an idea of the processes going on during the time the hurricane ravaged over Kingston, these frames have been studied to see any changes.

J.3.1 Without expansion

During the first hours of Ivan, erosion is visible at the mouth of the Rio Cobre, the West bank of the harbour and under the Causeway Bridge. At September 10th, no clear deposition is visible yet. However, at 4.30 in the morning of September 11th a lot has changed. The peak discharge coming out of the Rio Cobre causes erosion in the entire Hunts Bay and the “jet” of flow is clearly visible well beyond the Kingston Container Terminal (KCT) into the Kingston Harbour towards the East. Sediment is deposited on both sides of this jet and a significant amount inside the shipping lane, right down before the exit of Hunts Bay. Other erosion is observed along the West bank of the Kingston Harbour and the North coast of the Port Royal. These processes continue until Ivan has passed. When the hurricane has passed and the discharge reduced, deposition can be found at a shoal just north of the Causeway Bridge and serious deposition in the entire shipping lane. In the model, the entire top layer of Hunt´s Bay has been eroded away, including substantial erosion along the West bank of the Kingston Harbour all the way up to Hellshire Beach.

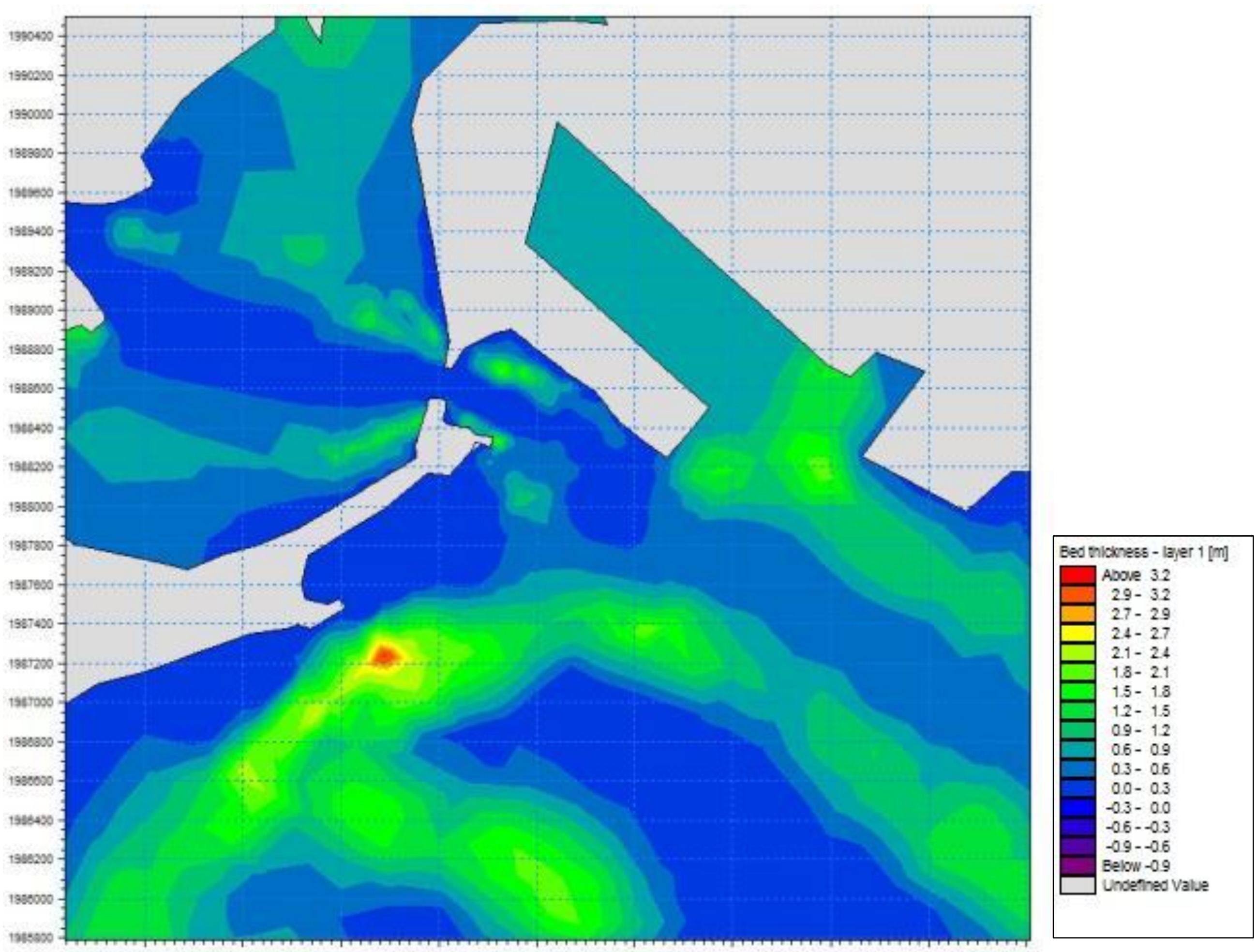


Figure J-3: The situation after Ivan passed, without expansion

J.3.2 With expansion

With expansion, the steering of the flow by the bend in the Northeast terminal is immediately visible. The flow is more diverted to the Southeast towards the North shore of Port Royal. Deposition starts at the corner of the Chinese expansion, the shipping lane and a shoal forms at the tip of Port Royal. Remarkable difference is the limited erosion inside Hunt´s Bay; the flow seems much more concentrated in the gully towards the exit. Also the Eastern part of the harbour basin undergoes much less erosion, compared to the old situation.

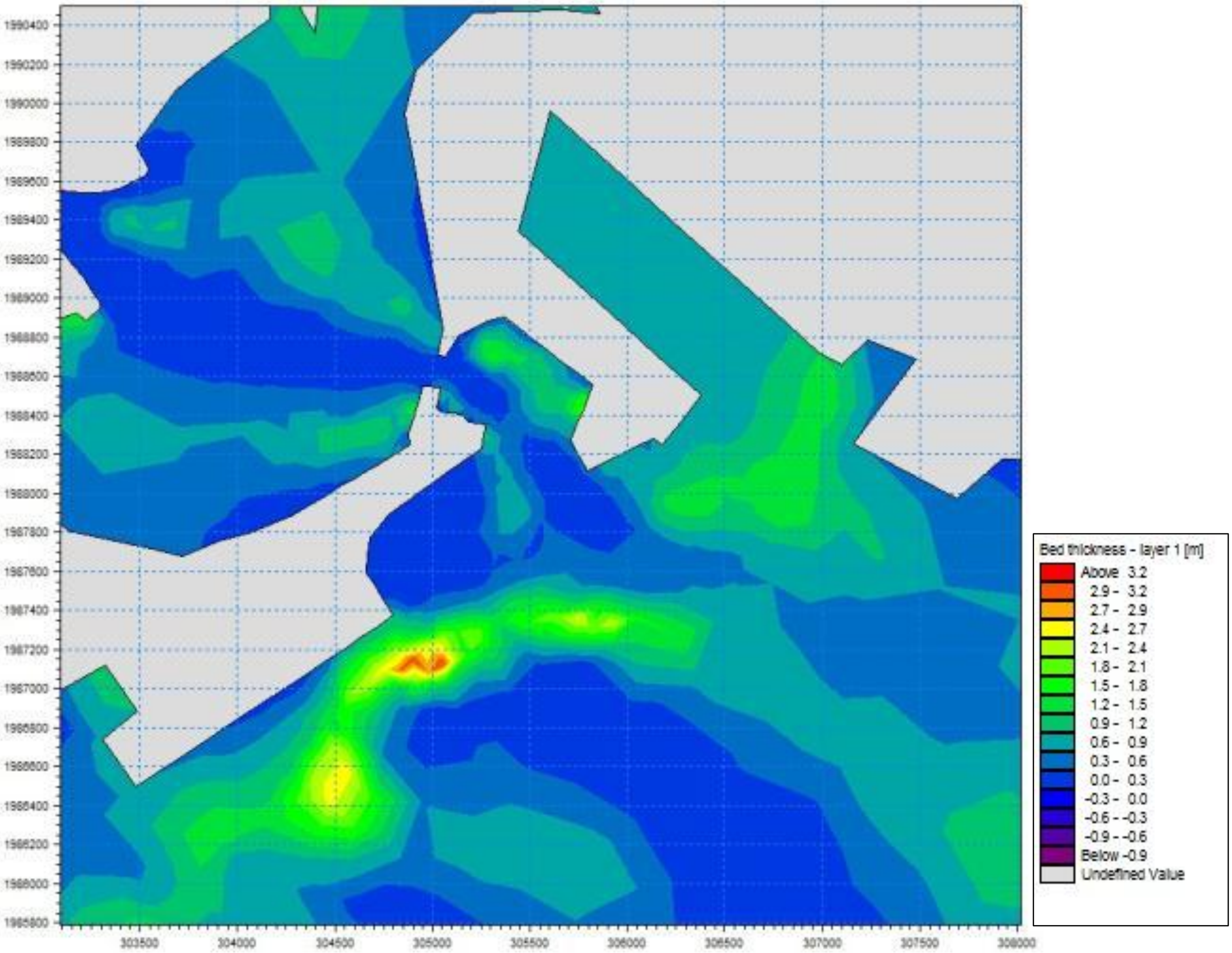


Figure J-4: The situation after Ivan passed with expansion

Concluding it can be said that the deposition in the shipping lane is more intense (twice as much as in the existing situation) but more concentrated at a smaller part of the channel. Hunts Bay experiences almost no erosion except in the gullies. The shoreline towards Hellshire Beach undergoes a lot of erosion (up to 1.0 meter of bottom layer disappeared in the model). With the expansion, at the little peninsula just North of Hellshire Beach the peak erosion is 30% higher compared to the old situation. However, this is just a small stretch of shoreline. The majority of shoreline experiences no significant differences.

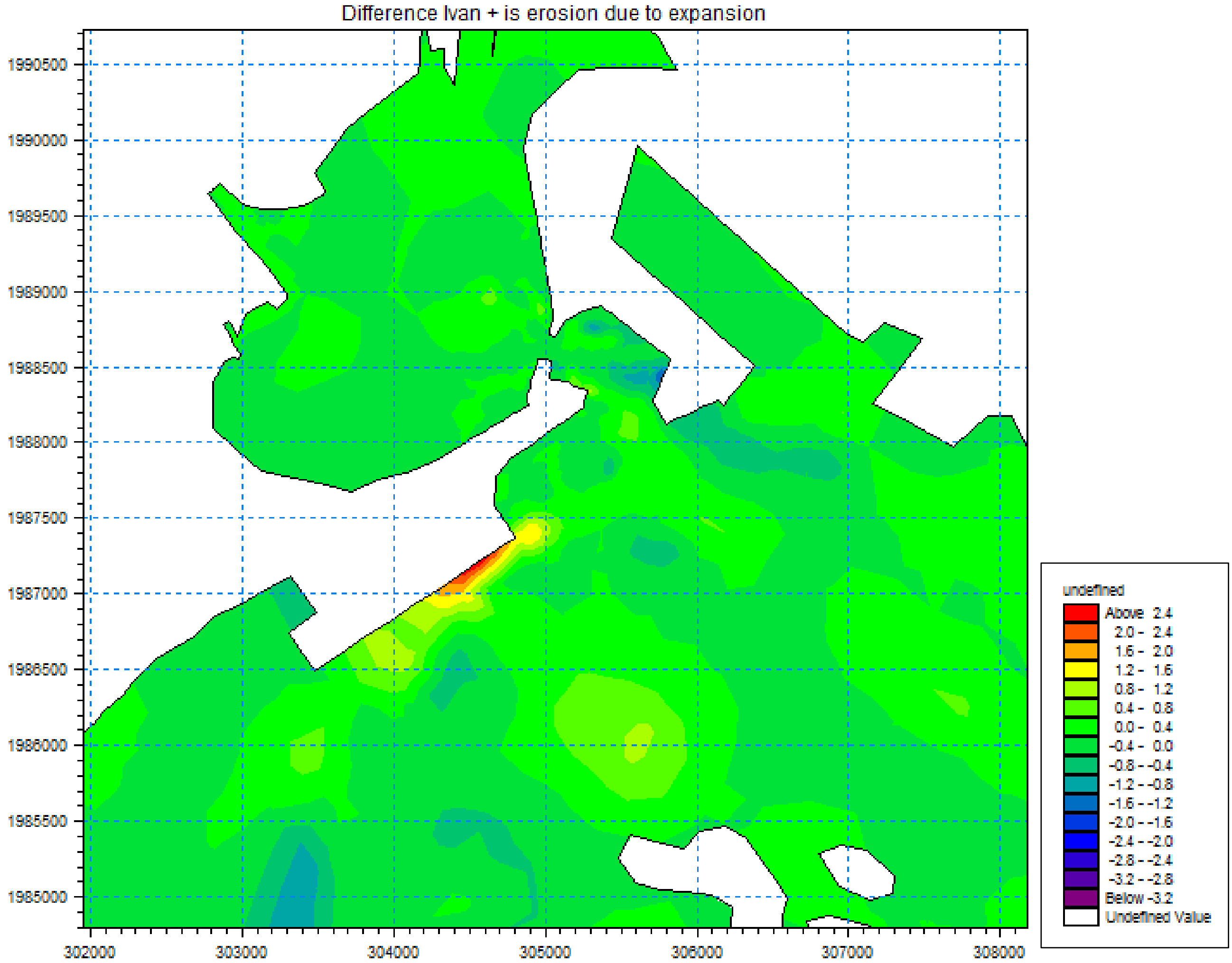


Figure J-5: Erosion / sedimentation due to Ivan in the new situation compared to the existing lay out

J.4 Gustav

J.4.1 Without expansion

At the beginning of the storm on the 28th of August at 14.30, the model shows little erosion in Hunts Bay, as well as formation of a shoal East of Hunts Bay. Some erosion is starting where the flow is constricting under the Causeway Bridge. The next observation time is 5.30 on the 29th of August. Clearly visible is the sediment settling in the shipping channel in the Kingston Harbour. The initial erosion continues near the Southern end of Hunts Bay while the center part of the bay is still experiencing some accretion. An explanation for this erosion would probably be stirring up by the wave action due to the winds coming from the North. Around noon the 30th of August, a shoal is forming in the Kingston Harbour, at the tip of the KCT. The flow coming out of Hunts Bay entering the large water mass is this location forms an eddy, where lots of sediment will settle down. Due to a change in flow and waves, this eddy is starting to disappear the same evening. Meanwhile, serious accretion is continuing in the shipping channel. The eddy formation at the exit of Hunts Bay due to the “jet” flow underneath the Causeway Bridge is responsible for two shoals near the exit of Hunts Bay at the harbour side. The changes are decreasing as the hurricane has passed and the system is starting to form itself into a new stable situation.

The situation after the hurricane is illustrated in Figure J-6. The major changes, in comparison to the start, are erosion at the West bank of the Kingston Harbour area and the south end of Hunts Bay. Accretion formed two shoals at the Causeway Bridge and severe sediment deposits in the shipping lane. The shoal at the end of the container terminal is reduced in size but still clearly visible.

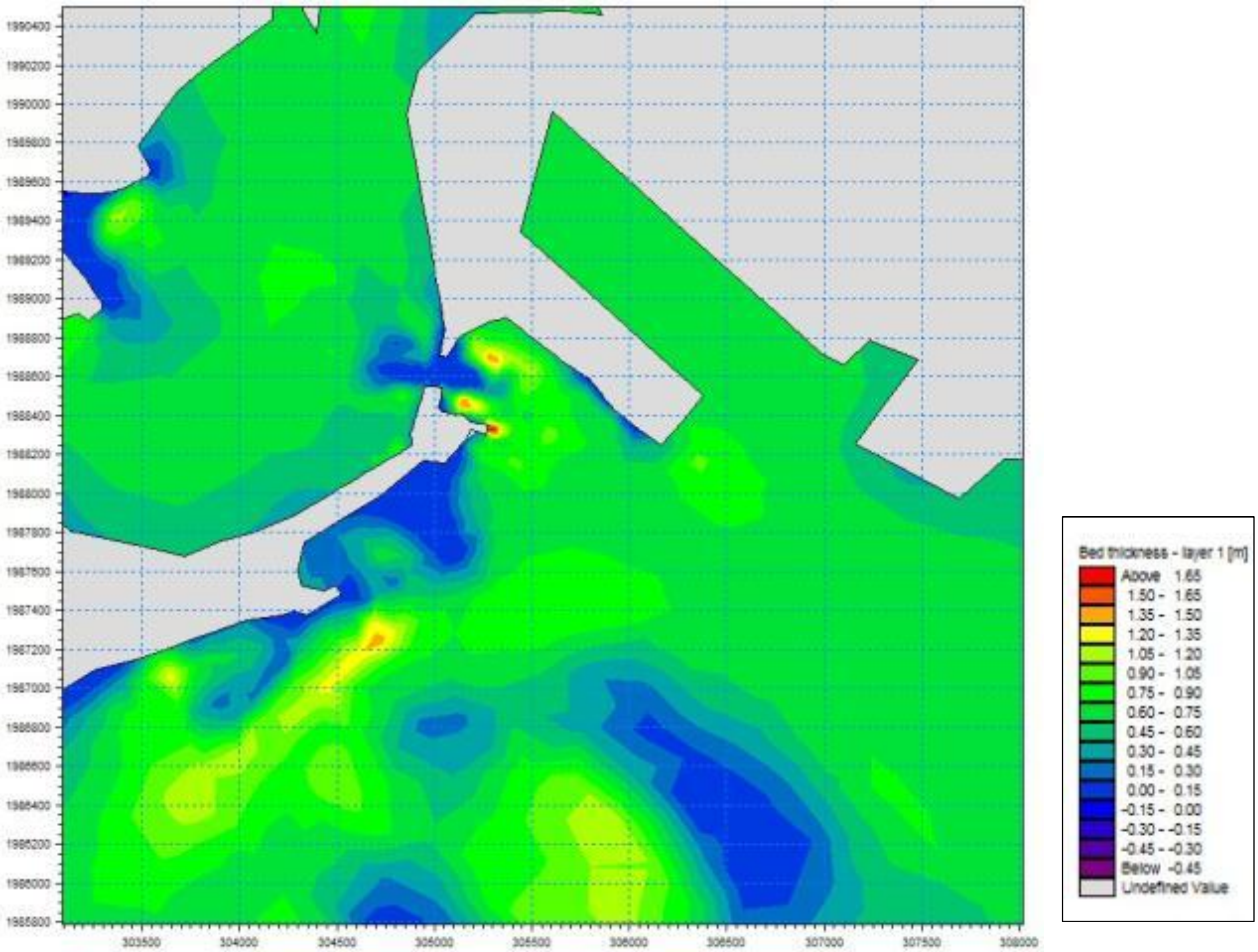


Figure J-6: The situation after Gustav passed without expansion

J.4.2 With expansion

The situation looks different for the expansion at 28th of August around 14.30. Under the Causeway Bridge, accretion is happening. On the sharp corner of the Chinese expansion, accretion is starting, due to the sharp turn in flow and therefore calm area where sediment will settle. The French expansion to the KCT can be seen as the outer bend of a river. The highest flow velocities can be found here, which explains the erosion on this corner. At the next observation moment, again 5.30 at the 29th of August, directly under the Causeway Bridge, erosion is starting to show, but still accretion occurs just before and just after the passage. Around the Port Royal peninsula, two large erosion areas are detected. Also along the southwest coast of the Kingston Harbour including the southwest expansion, significant amounts of erosion are visible. This is probably caused by increased flow along the coast. This process is visible during the entire event: erosion along west bank, and the eastern bend of the terminal, with as most important observation: In the shipping lane is not a significant amount of sediment deposition, this happens far more offshore, beyond the lee of the Port Royal Peninsula.

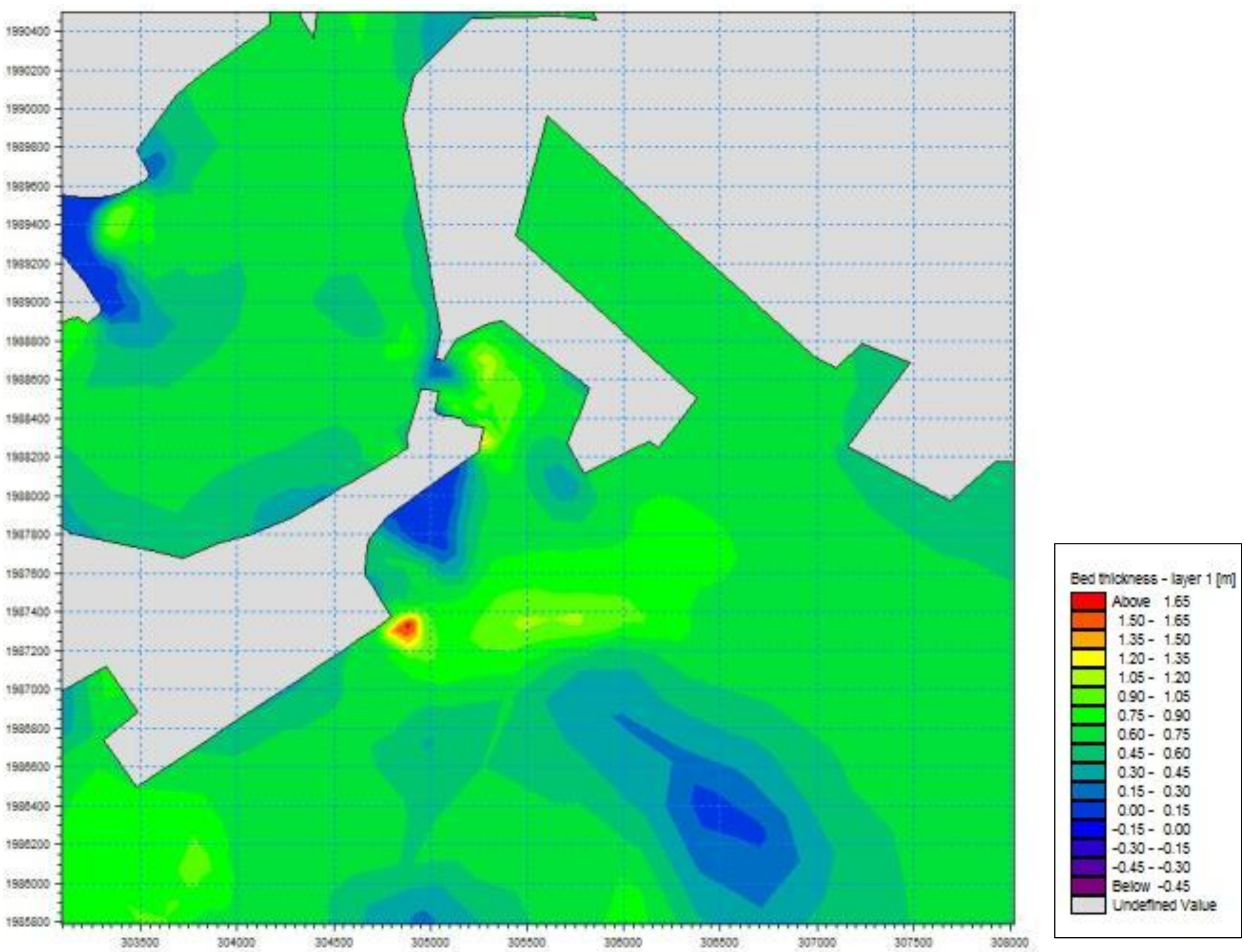


Figure J-7: The situation after Gustav passed with expansion

So concluding the most important difference between the old and new situation are accretion right before and after the Causeway Bridge, less erosion under the bridge itself, erosion along the west bank and sediment deposit further off shore. As well as during Ivan, significant erosion is visible around Hellshire Beach, but differences between the old and new situation are negligible.

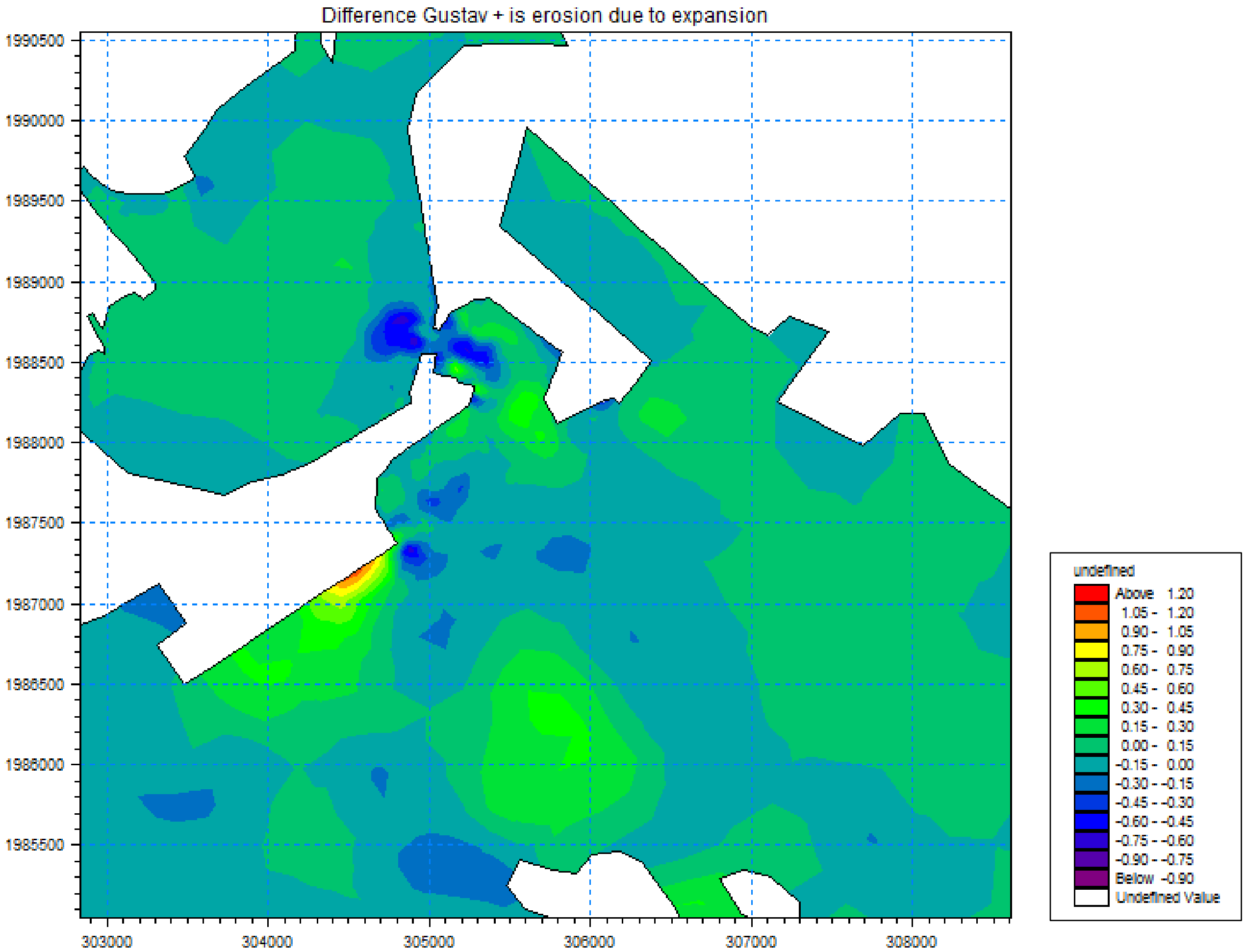


Figure J-8: Erosion / sedimentation due to Gustav in the new situation compared to the existing lay out

J.5 Nicole

J.5.1 Without expansion

During the first day of Nicole, nothing special happens. At the end of the afternoon of 29 August, the same process as during Gustav is visible: a large shoal forms at the end of the container terminal and erosion under the Causeway Bridge. In the shipping lane, no deposition is found yet and this stays the same after Nicole has passed. Erosion occurs in the mouth of the Rio Cobre and under de Causeway Bridge. Sediment accumulates at a shoal at the end of the container terminal.

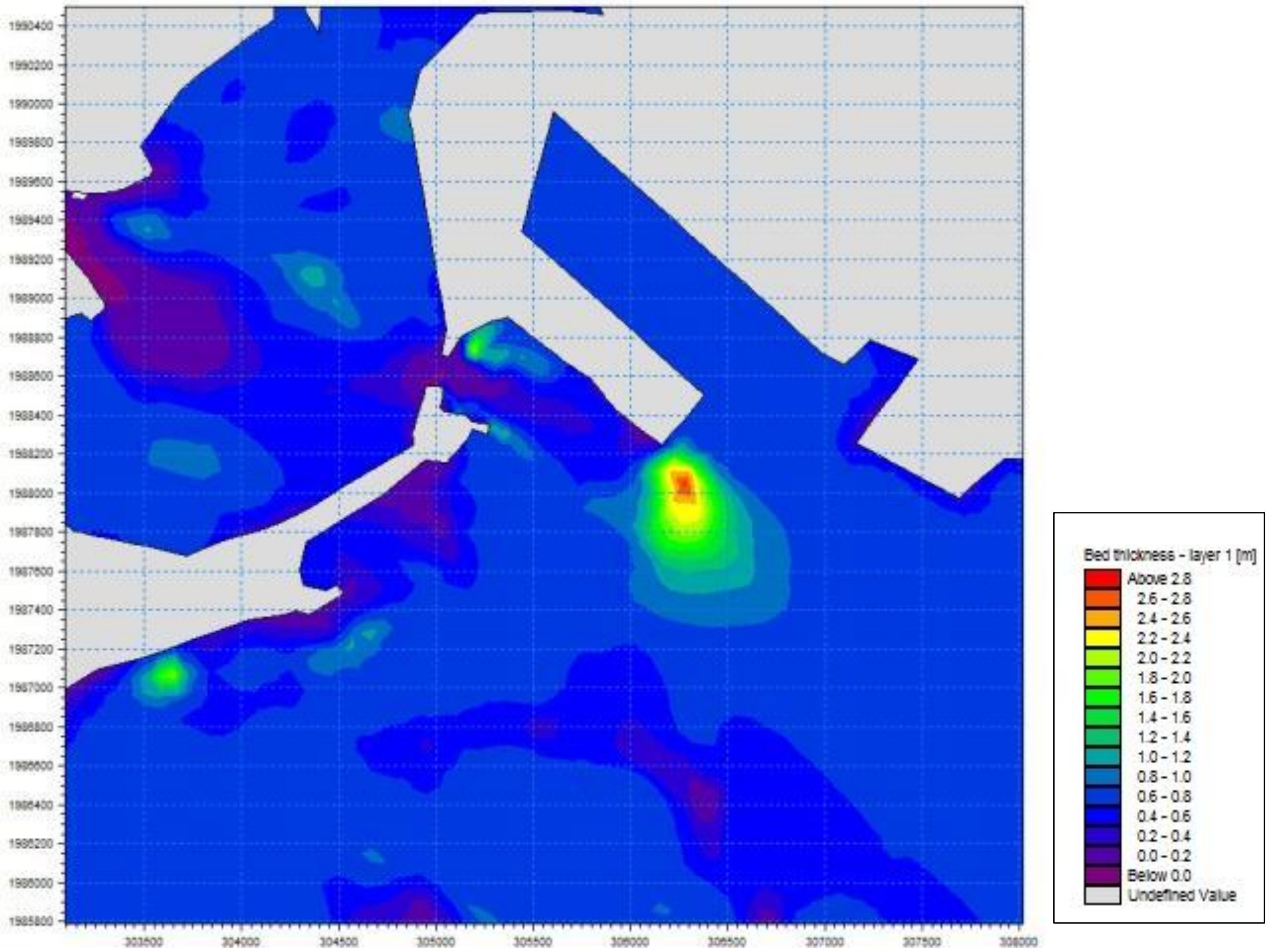


Figure J-9: The situation after Nicole passed without expansion

J.5.2 With expansion

The situation is almost the same with the expansion implemented. The only difference is the location of the shoal. This is more towards the southwest in front of the entrance of Hunts Bay in the shipping lane. The rest of the shipping lane doesn't experience substantial.

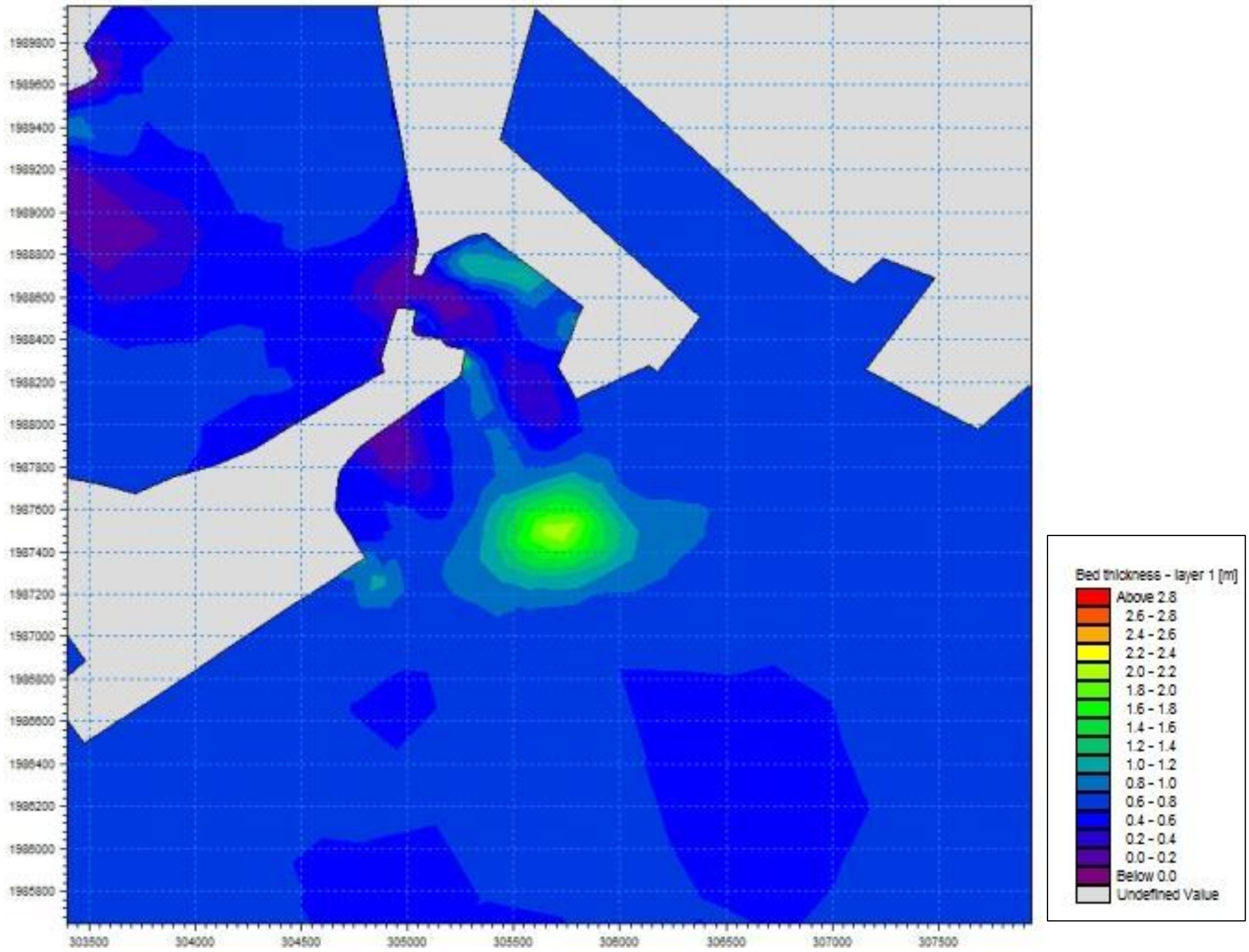


Figure J-10: The situation after Nicole passed with expansion

Conclusion of this comparison is that only the location of the sediment deposit changes a little. The magnitude of accretion stays the same. No shorelines outside the area are damaged.

J.6 Floods

J.6.1 Without expansion

At the beginning of the process, 22nd of May 2002 at 5.00, nothing exceptional occurs with respect to the bed level. In time a lot of erosion happens in the river mouth. After about 5 hours from the start, erosion starts under the Causeway Bridge. This is caused by the fact that constriction causes an increase in velocity. In time the erosion plume propagates further more into Hunts Bay and causes local accretion in the middle of Hunts Bay, at this stage the erosion whole reaches its position where it doesn't propagates eastward anymore. Underneath the Causeway Bridge the erosion hole becomes a lot deeper.

What also can be seen is the formation of two shallows just east of the Causeway Bridge. These shallows have been formed because of the decrease in velocity by the widening of the section. In the shipping channel a small around accretion occurred. But this can be seen as negligible.

Besides the phenomena discussed above, there are no significant changes of morphology around Hunts Bay due to the Flood event.

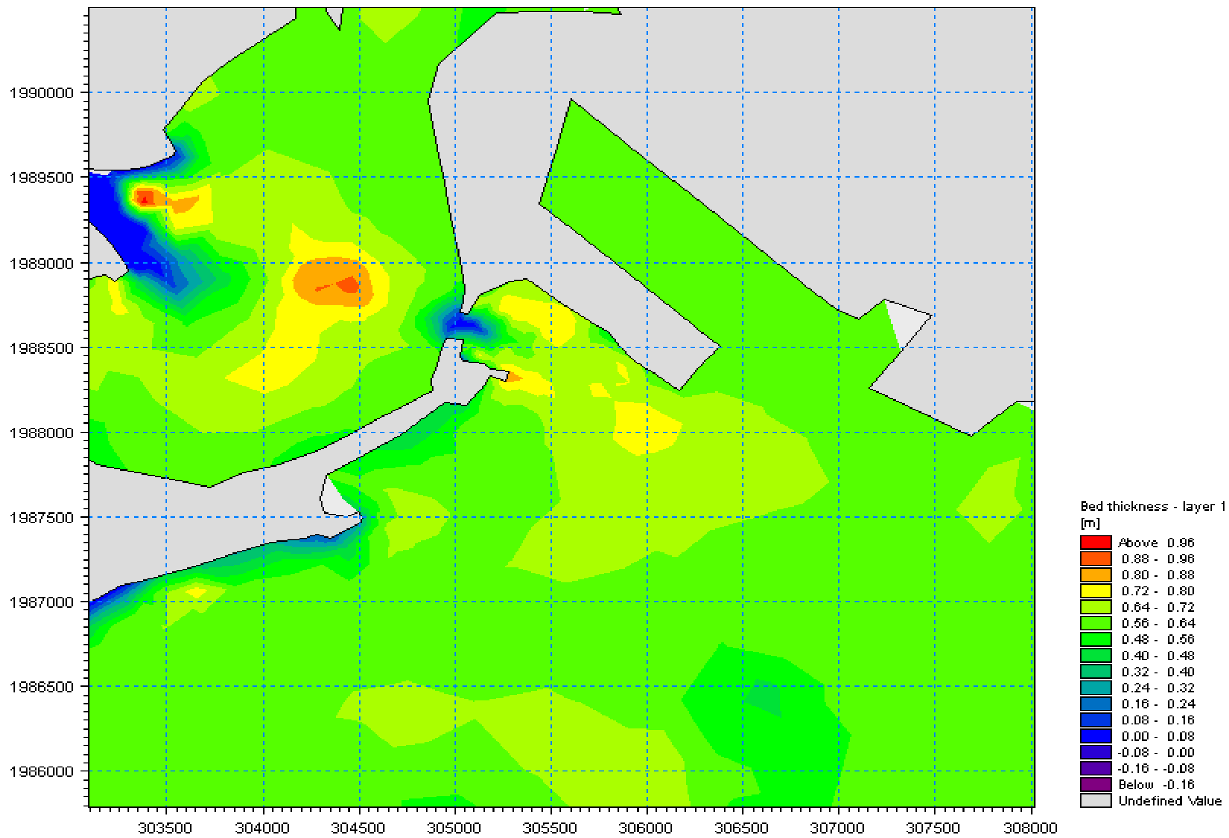


Figure J-11: The situation after the flooding without expansion

Around Port Royal no change is visible due to the Flood event. Along the west bank of the harbour area, some erosion can be found. It will therefore be expected that the coast is eroded as well slightly after this event. .

J.6.2 With expansion

For the situation with the first phase expansion the processes inside Hunts Bay are mostly the same. In the final stadium again a lot of erosion occurs in the river mouth. Also the formation of a small shallow in the middle of Hunts Bay can be seen. Underneath the Causeway Bridge an erosion hole is formed as well, with the same order of magnitude, than for the case without expansion.

Furthermore it can be seen that just eastward of the Causeway Bridge some siltation occurs, due to the widening of the flow area. The lay-out of the expansion causes the outflow (from Hunts Bay) to act like it is in a bend. The consequence for this is the change in velocities in the curve, and therefore local erosion spots become visible along both the French and Chinese expansion quay walls. When the flow has passed this curvature, it reaches the channel. A small, concentrated siltation area can be found, where the sediment settled, because of the sudden deepening of the water.

Further southward a small erosion hole can be found on the west of Port Royal. Near Port Henderson, locally a lot of erosion on the beach occurs.

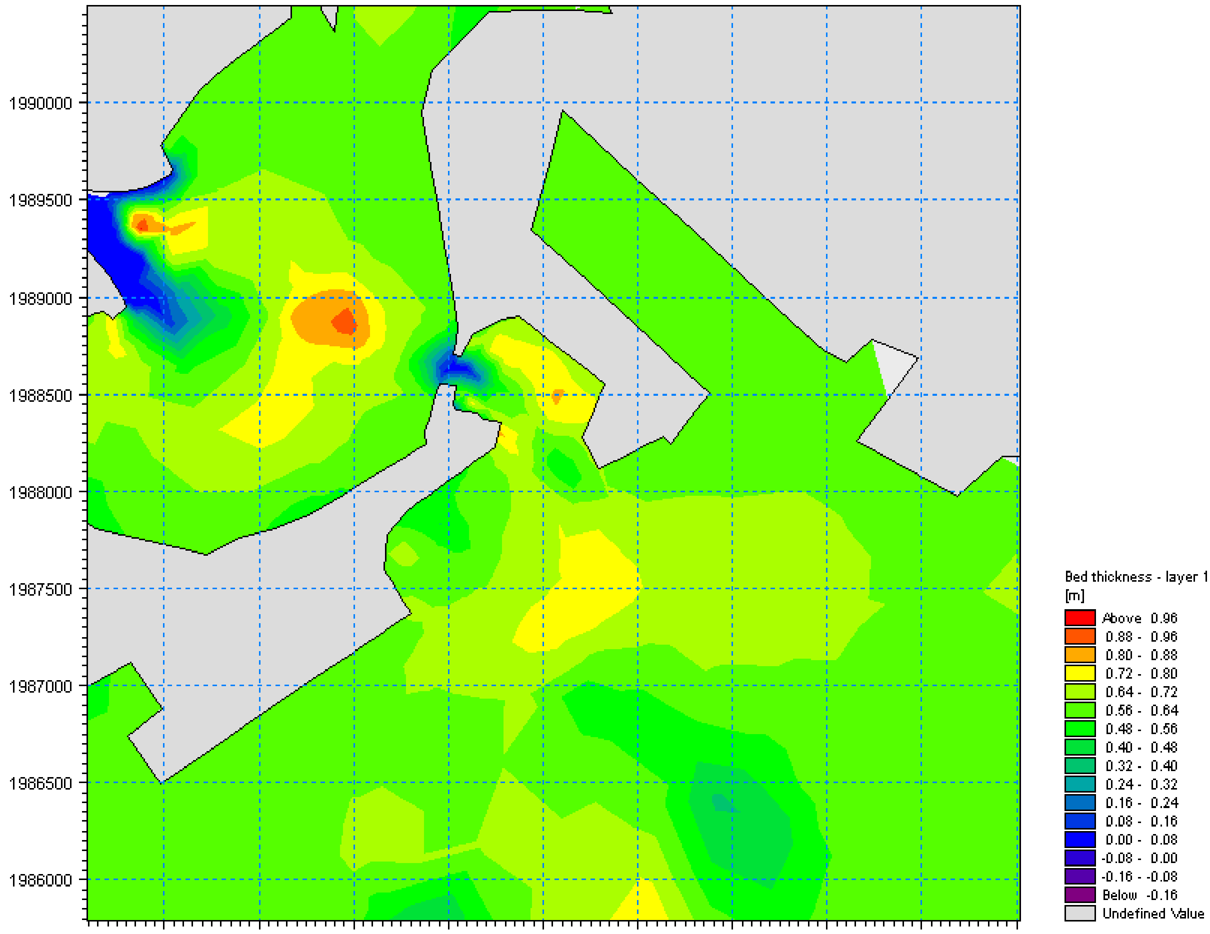


Figure J-12: The situation after the flooding with expansion

Appendix K Sedimentation problem improvement

As a part for the research the initial goal was to find the problems within the existing design. In general the problems of siltation in the access channel do not grow but more or less just move to a different place within the channel. This is important to know. Still the siltation takes place within the channel. The differences were assessed by looking at the changes during Ivan with the existing lay out and the planned lay out as described earlier. This is done with the incomplete French expansion. The situation with phase 2 (the complete French expansion) hasn't been assessed in combination with the improvement due to a lack of time.

K.1 Problem definition

The problem to be recognized is that the access channel silts up fast during a major sediment exporting event. The access channel is supposed to navigable at all times, with exception during these extreme events of course. Navigation depth is one important thing for that matter. If the channel is deepened the attraction of siltation will most likely become stronger and starts to act as a sink. Something that is found with the simulations is that the constriction of the flow from the Causeway Bridge up until the channel causes a steep drop of suspended sediment load after widening of the flow. This would be right at the side of the access channel. This will occur not as severe as it sounds with the phase one expansion. Here the problem will merely move to a different place. This can be seen in the report where these are both compared.

Another issue is the increase of maximum water level due to expansion 2. This can cause serious issues with flooding around Hunts Bay. The basin will fill up during an extreme discharge. Due to lack of information and measurements about discharges into Hunts Bay it is hard to say what can happen the coming 50 years for example. What can be said is that expansion 1 doesn't make the situation worse flood wise. Expansion 2 as suggested in this report is reason to investigate those consequences with more information. Mitigation might be required.

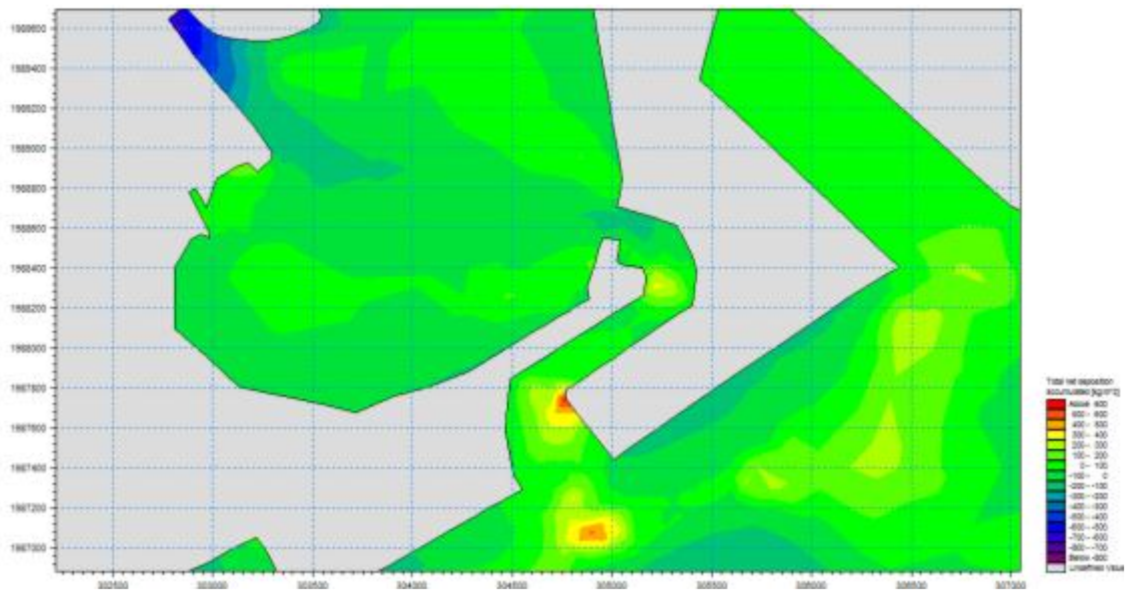


Figure K-1 : Total net deposition accumulated during Ivan with the Hunts Bay - Harbour canal depth at 12m in phase 2

On the matter of the phase 2 expansion the result is clear. Only at the outflow there is accretion to be found. This is very severe and the bottom here will rise for almost 3 meters. This is a very strong focus of siltation. In the existing situation it is a more diffuse process and requires less maintenance. This will change due to this specific location that is affected. Also this channel needs adequate maintenance is will be discussed in the chapter on phase 2

The issue at hand in both situations is that the access channel silts up because the channel is right at the new exit of Hunts Bay. With narrowing the corridor between Hunts Bay and the access channel more carrying capacity for sediment from Hunts Bay and the access channel becomes available.

K.2 Solution method

There are a few solutions to the siltation problem. One category is based in removing sediment from the flow before it reaches the channel. This can be done with a sediment trap. Another idea is making the flow a lot more diffuse before it reaches the channel. This would be done by moving the expansion away from the flow area as it is planned right now. The latter option is the most complicated and is impossible to assess here in this report. There for the focus was on the sediment trap. This method can basically be applied in 2 ways: Inside and outside Hunts Bay. Both have disadvantages. Inside Hunts Bay the area is more difficult to access with bigger vessels because the Causeway Bridge is fixed. But putting the sediment trap outside Hunts Bay gives problems for the phase 2 expansion and is very limited in space. Besides when applying a sediment trap there it would require very expensive bank protections since the underwater slope would be very steep and preferably vertical to acquire maximum volume for the sediment trap. Nevertheless both were modelled to see if there were big differences.

The second problem related to the flooding scenario of Hunts Bay is not solved except when moving the second phase expansion away from the Causeway Bridge. This is a whole new idea and is not investigated as a solution since the actual consequences of flooding hasn't been investigated as well. There for the only focus is on sediment control further on.

K.3 Results sediment trap

Both sediment traps were modelled albeit in different scenarios (Ivan and Gustav) with only the phase 1 expansion.

K.3.1 Sediment trap outside Hunts Bay

The first attempt to find a solution was the sand trap outside Hunts Bay. This was based on the accessibility for dredging vessels. The results however were appalling. It hardly made any difference and siltation in the channel was still occurring as can be seen below. The lighter green areas are silting up. This is exactly within the shipping channel. So this solution had it down sides before but is now also found to be inadequate. The situation used for this example is Ivan.

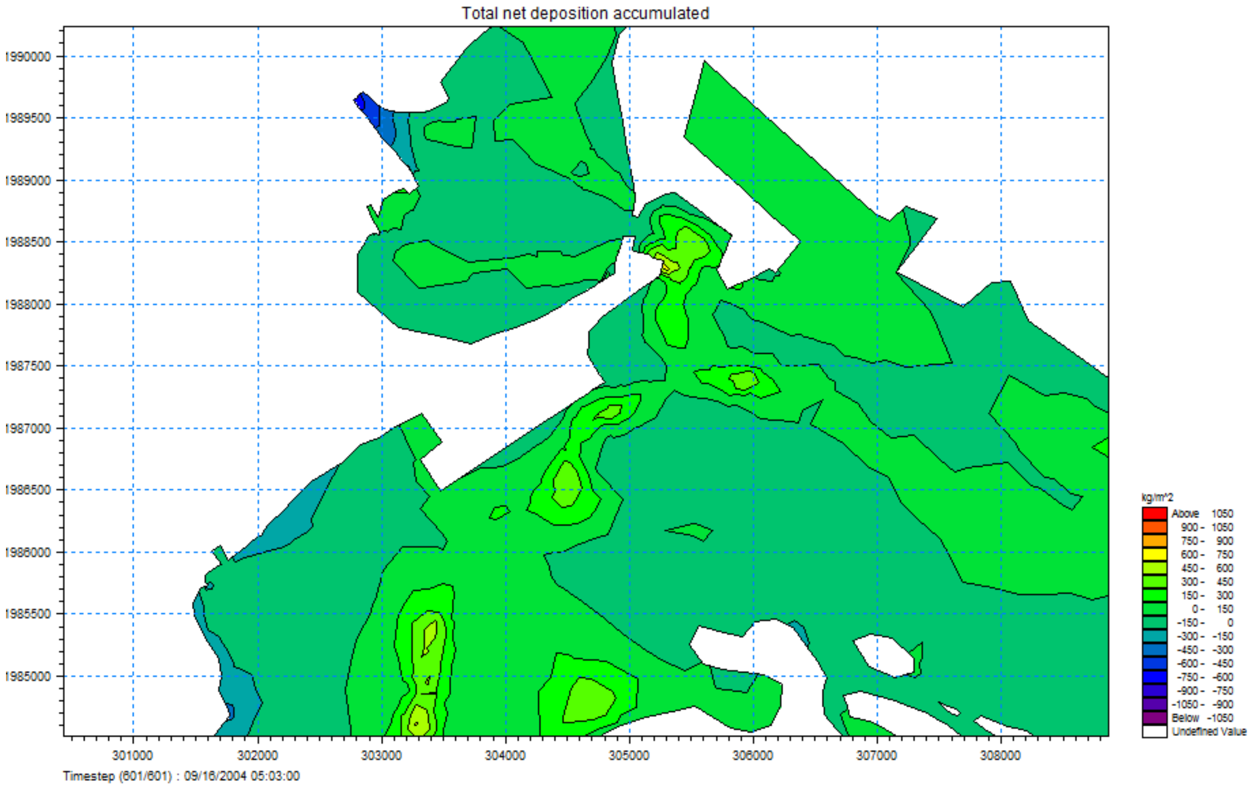


Figure K-2: Total net deposition accumulated during Ivan with sediment trap outside Hunts Bay

K.3.2 Sediment trap inside Hunts Bay

The next scenario is a sediment trap inside Hunts Bay. The downsides were mentioned before. But since the outside sediment trap doesn't work, it is worth to investigate. Inside Hunts Bay there is a lot more space. This means it is possible to make the sediment trap less deep which is less costly and could be done by local dredging companies since it doesn't require large capacity because dredging can be done all year round if necessary. The results can be seen below. It looks very promising. In the orange area there is hardly any deposition at all. This is on strong contrast with the sediment trap outside Hunts Bay. On all points this design performs better and should be the way to go if the dredging vessels required for this, can access Hunts Bay through the Causeway Bridge.

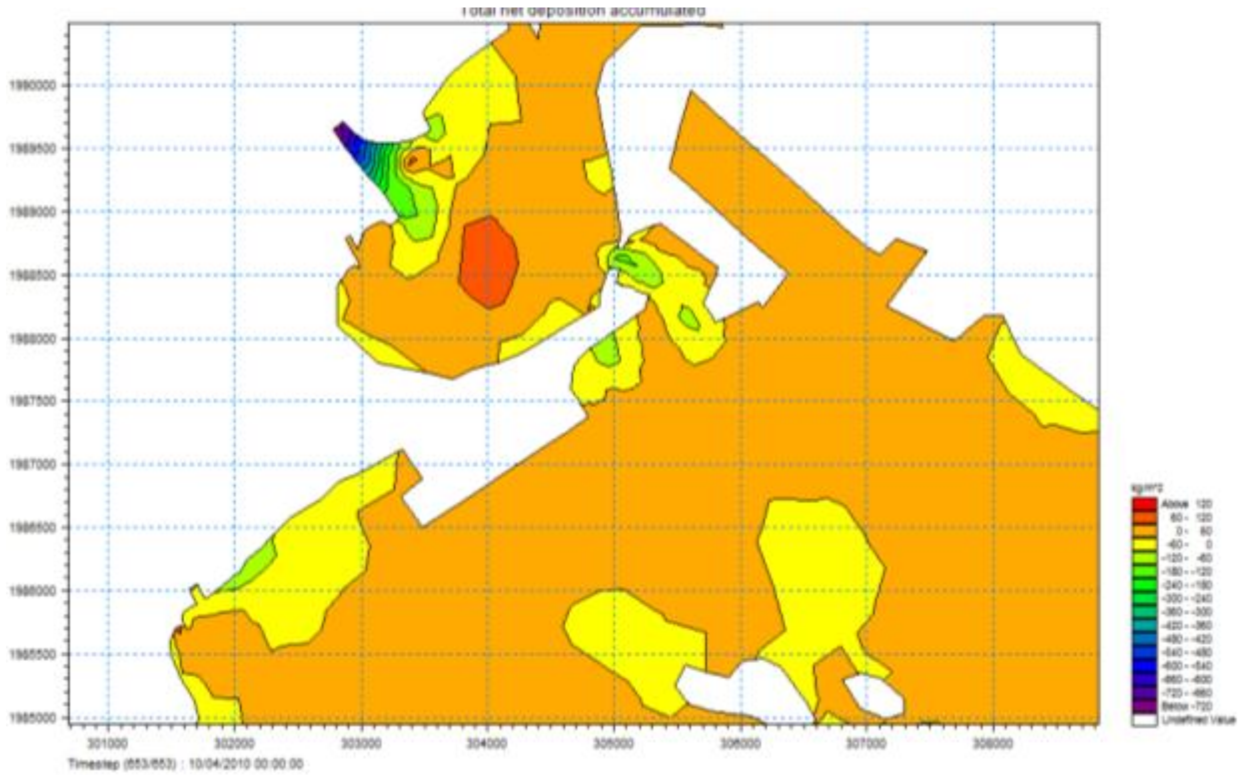


Figure K-3: Total net deposition accumulated during Ivan with sediment trap inside Hunts Bay

Appendix L Comparison of MIKE vs. Delft 3D

A request came from SWIL to model the Kingston harbour with two different programs, namely Delft3D and MIKE. By doing this, insight is created in the possibilities of the different programs and the programs can be compared to each other.

When the results of MIKE and Delft3D are compared it can be noticed that the models give different results.

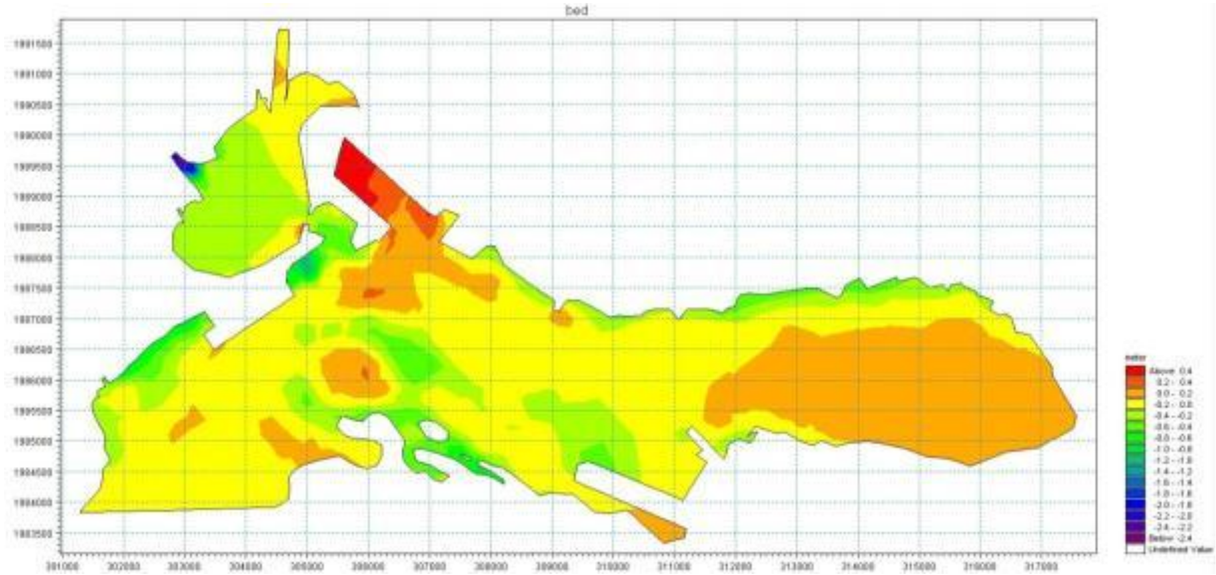


Figure L-1: Bed level change Delft3D for hurricane Ivan without expansion

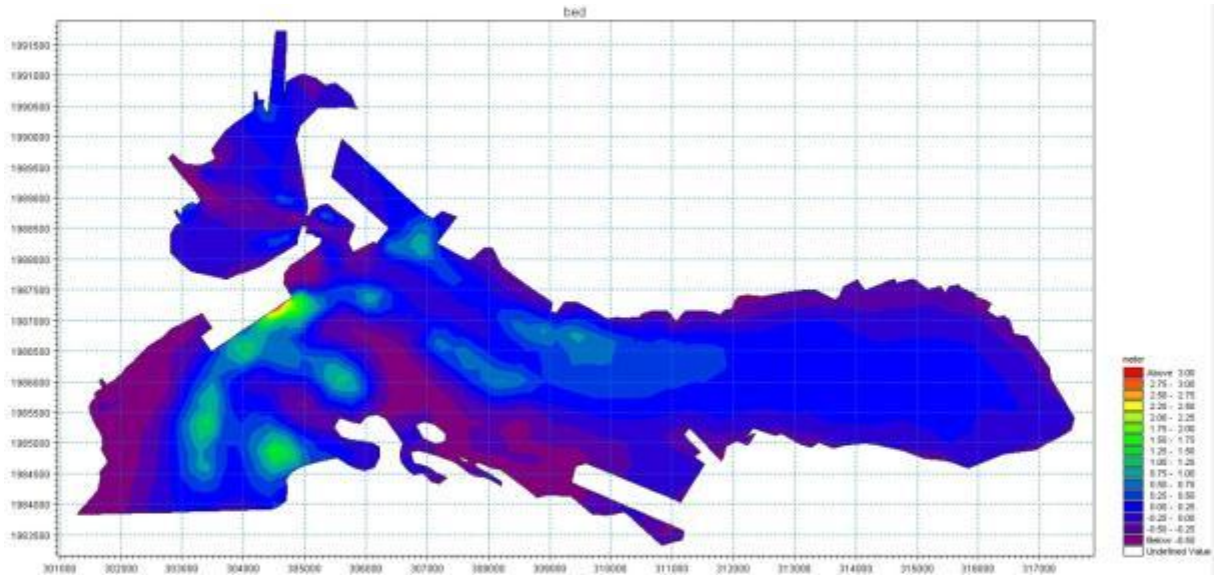


Figure L-2: Bed level change MIKE due to hurricane Ivan without expansion

The results of the models do not look like each other. There is probably a mix-up in the settling velocity or the amount of turbulence. The Delft3D shows much more settling in areas with low energy than the MIKE model. Due to the fact that SWIL has experience with the sediment transport modules of MIKE it is chosen proceed with the MIKE results. This will lead to more reliable results.

Also the fact that the MIKE model was in a further state of development than the Delft3D model and the limited amount of time resulted in using the MIKE program for the results played a role in this.

The results of the models have to be compared to the real situation in order to check which of the sedimentation areas of the models are in line with the real situation. This is also under recommendations. Both models do however not show a significant increase of sediment due to the expansion. So it still can be concluded that the first phase expansion during these events does not lead to an increase of problems.

Additional differences that were experienced are plenty. It must be stressed though that the models were built by two different people. Computation time, stability and user friendliness are a few of them. Both can be a result of personal choices made along the process. The most troubling issue was the big difference in output. If just the amounts were different the problem wouldn't be that big. But about 30% of the area showed erosion in one model en accretion in the other. This was a disappointment but the fact that MIKE was built with a lot of in-house expertise it was considered the most reliable. Both models have the downside that when it comes to the details, experience is required.

Appendix M List of Figures

Appendix N List of tables