Operational storm impact forecast information for the coast

Design, implementation in MorphAn and evaluation of an operational coastal storm impact application

MSc. Thesis in Civil Engineering and Management

Jelmer Veenstra

March 2016

Operational storm impact forecast information for the coast

Design, implementation in MorphAn and evaluation of an operational coastal storm impact application

by

Jelmer Veenstra

in partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering and Management

at the University of Twente,

to be defended publicly on Wednesday 23 March 2016 at 16:00.

Name:	J. (Jelmer) Veenstra	
Student number:	s1006177	
Chair group:	Marine and Fluivial Systems (prof.dr. S.J.M.H. Hulscher)	
Department:	Water Engineering and Management	
Study:	Civil Engineering and Management	
Faculty:	Engineering Technology	
Location and date:	Enschede, 16 March 2016	
Thesis committee:	Dr. K. M Wijnberg	University of Twente
	Ir. J. M. Damen	University of Twente
	Dr. M. Boers	Deltares
	Ir. P. F. C. van Geer	Deltares
	Ir. J. Rietdijk	Hoogheemraadschap van Delfland

A digital version of this thesis is available at essay.utwente.nl

The cover image is an aerial picture of Noorderstrand on the Schouwen-Duiveland island with the Brouwersdam on the left, by Peter Buteijn (March 2010). The Noorderstrand was a former weak spot of the Dutch coast and was therefore reinforced in the fall of 2013.

UNIVERSITY OF TWENTE.

Deltares
Enabling Delta Life

Hoogheemraadschap van
Delfland

Preface

This master thesis reports about my graduation project that finalizes my study Water Engineering and Management at the University of Twente. The project was initiated by Deltares and the Delfland water authority and was mainly conducted at Deltares. It started with a preparatory phase from July to September 2015, in which a literature review and research plan were set up. The literature review was used to explore the possibilities for research topics that are relevant for coastal managers and the development of MorphAn. One of these topics was selected to serve as the scope of the research plan, providing operational storm impact forecast information for the coast. The graduation project itself was conducted from October 2015 to March 2016, during which an operational coastal storm impact application was designed, implemented in MorphAn and evaluated.

I have really enjoyed the period at Deltares and I am grateful for the fact that I had the chance to work in its inspiring and open environment. I would like to thank my supervisors from Deltares, Marien and Pieter, for their enthusiasm and motivation, and for always creating time for me in busy calendars. I would like to thank my supervisor from Delfland, Jeroen, for providing insight in the practical world of a water manager and his enthusiasm about my work. I would also like to thank my supervisors from the University of Twente, John and Kathelijne, for keeping me on a research track, and not to wander too far from my goal to write my thesis instead of only writing a new application. Thank you Joost, for your help with XBeach and your patience. Thank you Marc, for providing access to RWsOS data of Rijkswaterstaat and providing insight in the value of this data source. Thank you Tom, Simone and Caroline for your help with Matroos and giving insight in the data its models provide. I would like to thank my fellow student and great friend, Jonne, for reviewing my entire work and providing me with a readers' view. Lastly, I would also like to thank my fellow students at Deltares, for the great lunch, coffee and walking breaks we had, with great talks about thesis problems, LaTeX opinions as well as the many more less serious topics.

Summary

Dunes protect a large part of the Dutch coast against flooding from the sea. Although most storms will not cause failure of this sea defense, they may still cause a threat to, for instance, seaside towns because of dune erosion and overtopping. Also, high waves and current velocities near the shore may cause damage to coastal structures or property on the beach. Currently, weather, water level and wave forecasts provide coastal managers with timely information about the severity of an approaching storm, but the damaging effects to be expected of that particular storm are usually unclear. Despite ongoing research, no early warning system which incorporates storm impact assessment is currently available at water authorities. In this study, an operational, quick, flexible and easy to use storm impact application is designed, implemented in MorphAn and evaluated. MorphAn is a computer program that is already used for dune assessment and other coastal related analyses by coastal water authorities and Rijkswaterstaat.

There are three main components which are coupled in the storm impact application. These are bathymetry data, water level and wave data as well as an XBeach model. JARKUS transect bathymetry data from MorphAn or alternative 2D grid bathymetry sources like recent bathymetry derived from Argus cameras can be selected and are automatically downloaded. Real-time water level and wave forecast data from Rijkswaterstaat with a 48 hour lead time is retrieved for the location of the chosen bathymetry data. Using this water level and wave data from remote servers eliminates local computational time of large and complicated water level and wave models. Therefore, the storm impact application can be used on a normal laptop and is accessible by water authorities. The bathymetry and water level and wave data is automatically fed into the XBeach model, which calculates the hydrodynamic and morphologic processes that occur during the storm.

The storm impact application in MorphAn provides a Graphical User Interface (GUI) where a user takes several steps in order to obtain a result that provides insight in the effects of the approaching storm on the coast. These effects are for instance dune erosion or breaching, damage of property, high current velocities near the shore and overtopping of dunes or structures. Coastal managers can directly use this result for communication purposes, as well as for decisions about beach and hinterland evacuations or protecting measures of sea dikes or dunes.

The quality of the storm impact application is evaluated with the criteria *Speed*, *Relevance*, *Understanding*, *Robustness* and *Evolvability.* The speed is sufficient to assess approximately 240 1D transects as well as a 2D model with a longshore domain size of 250 to 5000 meter, both within a two hour limit. The relevance of the storm impact application as well as the storm impact information it provides is recognized by coastal water authorities. The understanding is improved by providing a GUI as well as variable output visualization complexities, although there are many improvements possible in the GUI that is currently implemented. The robustness of the storm impact application components is good, because of several different available bathymetry sources, redundant Rijkswaterstaat hardware and an XBeach model as well as a MorphAn GUI that are both locally installed. There are several possibilities to evolve the storm impact application by improving current possibilities as well as implementing international data sets to use the storm impact application elsewhere.

The information provided by the storm impact application is evaluated with the criteria *Accuracy* and *Performance.* The uncertainties of the different bathymetry sources, water level and wave forecasts as well as the XBeach model are assessed. A sensitivity analysis of the uncertainties of water level and wave data provides information about their effect on the result, to be taken into account in decision making. The confidence interval of the dune retreat that is provided by the

storm impact application is approximately 15 meters. This confidence interval can be used by decision makers, to determine whether decisions can be bases on the storm impact application in operational practice.

The storm impact application developed in this study is only useful if it will be used in practice. Evaluation of the seven criteria that were defined in this study provide a promising outlook for operational practice, although many improvements are possible for the GUI. A prototype of a storm impact application was developed, implemented in MorphAn and evaluated. This application uses real-time water level and wave forecast data as well as recent bathymetry. The storm impact application from this study can be used to provide relevant, accurate and timely storm impact information for the coast. Concluding, an operational, quick, flexible and easy to use storm impact application is now available for operational practice and ready to be further developed.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

A large part of the Dutch coast consists of dunes protecting the Netherlands against flooding from the sea. In order to keep the dunes safe, periodic safety assessments of the dunes are conducted by the coastal water authorities for which they currently use the program MorphAn (Lodder and van Geer, 2012). After the storm in 1953, the sea defenses have been drastically improved to withstand once in 2000 to once in 10000 year storms. Although less severe storms will not cause failure of the sea defense, they may still cause a threat of dune erosion and overtopping (Gautier and Caires, 2015).

The storm impact on the coastal area is often unknown (Haerens et al., 2012). However, Dutch coastal managers are generally timely aware of an approaching storm, thanks to weather, water level and wave forecasts. Just a few examples of storm effects could be dune erosion or breaching, damage of property, fast current velocities near the shore and overtopping of dunes or structures. Because these storm impact effects are unknown, coastal managers can only inform inhabitants and emergency services based on expert judgment, but not based on actual predictions of the storm impact. Despite studies about storm impact response, these projects are not made accessible and flexible enough to be operationally used at water authorities. In this study, this problem is elaborated on and an operational, quick, flexible and easy to use storm impact application is designed, implemented in MorphAn and evaluated.

A lot can be gained from an operational storm impact application, because it supports storm impact related decisions such as whether to evacuate buildings, the beach or the hinterland. It also answers safety related questions from emergency services and inhabitants. Furthermore, implementing a storm impact application in MorphAn provides the possibility to use live water data and use recent bathymetry data derived from video cameras. These implementations are both interesting and useful, because they can increase the speed and improve the relevance of assessments in MorphAn.

1.2 Problem definition

This section describes the calamity regulations for coastal areas and existing storm impact projects. It concludes with a problem summary and a motivation why the current storm impact application does have potential to become operational.

1.2.1 Coastal area regulations and authorities of the Netherlands

Some parts of the Dutch coast are natural and undefended dunes, while other parts may have a hybrid sea defense. The beach width ranges from less than fifty meters at narrow sections to hundreds of meters at the Sand Engine. The coastline is sandy and consist of intermediate beaches with sand bars in front of the coast line and breaking waves. The entire beach and dune area has high touristic value, which is reflected in the many beach pavilions and in the activity on the beach. Furthermore, the coastal area is also used for research projects, currently mainly at the Sand Engine nourishment. The dune coast is managed by Rijkswaterstaat and five of the twenty three water authorities (waterschappen) of the Netherlands. These water authorities are the main potential users of a storm impact application and are depicted in Appendix A.

In order to maintain the coastal protection provided by the dunes, the state has provided laws and regulations for the management of primary water defenses. The Water Act (Waterwet) (Ministerie van Infrastructuur en Milieu, 2009) prescribes the prevention or limitation of floods, as well as the prevention and counteraction of landward movement of the coastline. Furthermore, it prescribes a periodic assessment of the primary flood defenses of the Netherlands to ensure dune safety. An overview of reports and assessment guides resulting from this law is provided in Appendix A. The most recent dune assessment guide prescribes dune assessment with the DUROS+[1] model in the software package MorphAn.

Besides the prevention of flooding and landward movement of the coastline, the Water Act (Ministerie van Infrastructuur en Milieu, 2009) also prescribes that water authorities should have a calamity organization and a calamity response plan. If Rijkswaterstaat predicts water levels of NAP +2.20m at Hoek van Holland, a code yellow warning is issued by the WMCN[2] towards coastal authorities. This water level occurs 3.5 times a year. Code orange (NAP +2.80m) occurs once in every five years, code red (NAP +3.65m) once in every 100 years and code MHW[3] (NAP +5.10m) once in every 10000 years. Water authorities take different precautions and measures depending on the warning code. (Ministerie van Infrastructuur en Milieu, 2015)

Although water authorities do not interfere with emergency services or evacuation procedures, they are expected to provide information and knowledge that can be used to advise the decision makers. In the Netherlands, storm intensity, wind, storm surge, water level and wave height forecasts are often available. Usually, it is probable that the dunes will withstand the storm since they are well maintained, but the effects of these meteorological and hydrodynamic events are not assessed on forehand and therefore unknown. These storm impact effects are for instance the morphological changes of the dunes or whether they will breach, as well as possible damage to NWO's like beach pavilions, buildings on a boulevard, or nearshore water levels, wave heights and flow velocities. Insight in storm impact effects can answer questions about whether to and where to evacuate a boulevard, the beach, or beach pavilions, whether it is still safe to walk on the beach, swim or windsurf, or whether a boulevard, dune or levee will overflow with water. Hindcast studies about several of these topic have been conducted in the past, but it would be an improvement if water authorities can act quickly during calamities and provide storm impact information to calamity organizations, building owners and inhabitants on forehand, based on a storm forecast.

1.2.2 Existing storm impact projects

Several storm impact projects were developed as a pilot for operational or research goals, of which three are elaborated on. These projects are currently not used in operational practice, so storm impact information is still not available. The lessons that were learned from the different projects are used to provide criteria and a ideas for the new storm impact application in MorphAn.

HIS-KUST

The HIS-Kust[4] storm impact framework is a web application that used several pre-defined storm conditions for several locations, water levels, wave heights, wave periods and wave directions. The

---

[1] DUROS+: DUineROSie model, an empirical model to determine dune erosion based on a schematized post storm profile. The + indicates the updated model, with improvements like a variable wave period.

[2] WMCN: Watermanagement Centrum Nederland, the Dutch water management center of Rijkswaterstaat in Lelystad.

[3] WHW: Maatgevend Hoogwater, the normative water level for which the levee at Hoek van Holland is designed.

[4] HIS-Kust: Hoogwater InformatieSysteem Kust, Dutch for flood information system for the coast.

application enabled erosion calculation with DUROS[5] for a JARKUS[6] transect profile with five storm frequencies and fifty locations along the Dutch coast. (MX Systems, 2007)

The HIS-Kust application was located on a remote server and it was terminated after the pilot period in 2007. Because the application uses predefined storm conditions, the results were not based on real forecasts and can therefore not be used to provide insight in the actual storm impact. This makes it difficult to use HIS-Kust for decision making.

MICORE

MICORE[7] is an FP7[8] project that was conducted from 2008-2011. The project was a pilot that made morphological storm responses for nine European locations available online, available for anyone through a website (Van Dongeren et al., 2009; Haerens et al., 2012).

Within the MICORE project, Baart et al. (2009) provided a suitable architecture for the design of an early warning system which is a good representation of such a system in general:

Model set-up Beforehand model setup and establishment of input parameters.

Data collection Scripts reading basic data (wind data, pressure data, bathymetric data etc.) from one or more data sources (e.g. using plain text files or OPeNDAP protocol).

Pre-processing Scripts converting the downloaded basic data to the proper input formats for the model engines.

Running model engines Running the numerical implementations of the physical processes using the prepared input to generate predictions.

Post-processing Scripts processing and aggregating the raw model output as well as generating charts with information at the proper level of aggregation.

Visualization or publishing Post-processed modeling results are published visually.

Baart et al. (2009) also reported on the Dutch coast which was one of the nine study areas, specifically the Egmond beach. This Dutch showcase couples four models with decreasing domain size and increasing resolution, depicted in Figure 1.1. These models describe the hydrodynamic, wave and morphologic processes with four nested models:

- The global Wave Watch 3 (WW3) model for water levels and waves
- The regional Dutch Continental Shelf Model (DCSM) is a Delft3D model for hydrodynamics and waves
- The Dutch ”Kuststrook Fijn” coastal model for hydrodynamics and waves
- The XBeach model has the highest resolution and entails the smallest area (the Egmond coast beach), for which it predicts the morphological changes

Baart et al. (2015) studied the morphological forecast skill of the MICORE model train as a function of lead time and concluded that the forecast system gives a three day lead time for morphological effects of water levels under storm conditions.

Besides coupling models, MICORE couples four different data sources for the Dutch part of the project. These are the latest wind speed and direction from online windfield predictions of the HiRLAM project, online water level predictions, a network of wave buoys of Rijkswaterstaat to compare predicted and observed wave heights and annual JARKUS transect measurements to evaluate changes in the coastline.

Some of the results of the nine study locations of the MICORE project are still publicly available. The MICORE project was meant to show the capabilities of coupling models and providing open information about calamities. However, this pilot project does not provide results on arbitrary

---

[5] DUROS: the older version of the DUROS+ model.

[6] JARKUS: acronym for ”JAaRlijkse KUStmeting”, the annual Dutch coastal transect measurements that are provided by Rijkswaterstaat.

[7] MICORE: Morphological Impacts and COastal Risks induced by Extreme storm events.

[8] FP7: the EU Seventh Framework Programme for Research and Technological Development, which was the main instrument for research in Europe from 2007-2013 and has been followed up by Horizon2020 (2014 to 2020).

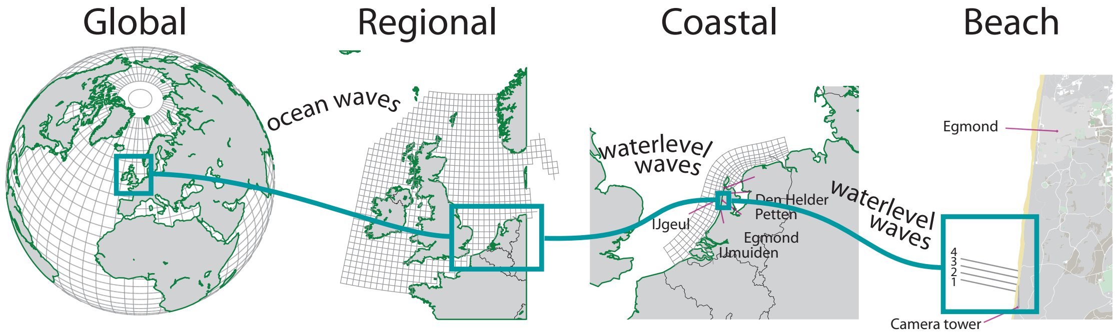


Figure 1.1: The coupled models within MICORE (Baart et al., 2015)

locations along a coast, the models require much computational power and the project is not in development anymore. Therefore, the project is not sufficient for coastal managers to base decisions on and is not used in operational practice in the Netherlands.

RISC-KIT

The MICORE project was followed up by RISC-KIT[9] in 2013, which aims to provide a set of open-source methods and tools (the RISC-KIT) to support coastal managers and emergency decision makers (Van Dongeren et al., 2014). The Netherlands have only provided an example of what is possible for this project, but will not participate further. Also, because this project is still running, it has less visible results than MICORE. Nevertheless, the existence of this follow-up project shows the need for more storm response research.

1.2.3 Storm impact information in MorphAn

Both the calamity regulations and the existing storm impact projects show the demand for storm impact information. According to Baart et al. (2009) and Baart et al. (2015), a storm impact or flood forecast function should provide timely access to relevant information of sufficient accuracy, and information about the confidence of the result. A storm impact application aims to show the effects of the current water level and wave forecast on the coast. Water authorities can use the storm impact application to determine whether a dangerous situation occurs and to make decisions accordingly. It is important that the results are realistic, because unnecessary evacuation due to a false positive or a dangerous situation due to a false negative are both undesirable.

The previous projects were pilots or research projects that were not used in operational practice because of several reasons. HIS-Kust did not provide accurate or complete information because of scenario assessment instead of real time data. MICORE and RISC-KIT provide accurate results but contain complex models which were set-up for both research projects and cannot be executed with limited computing power. Furthermore, these projects were not meant to become operational and there is no guarantee that the existing models will be maintained. All projects have the disadvantage that they are new and unknown programs, with which potential users have to learn to work with.

This study implements an operational storm impact application in MorphAn (Lodder and van Geer, 2012), a computer program where potential users are already acquainted with. A general description of MorphAn is provided in Appendix B. MorphAn provides a clear and simple graphical user interface (GUI) and is the prescribed computer program for dune safety assessment with the DUROS+[10] model at coastal water authorities. Additionally, MorphAn provides the possibility to use Python scripting to access a wide range of advanced functions to expand the standard functions. Several possible MorphAn improvements were defined by Veenstra (2015), of which one was a storm impact application that is further developed in the current study.

---

[9] RISC-KIT: Resilience-Incrasing Strategies for Coasts - toolKIT, the FP7 project that followed op MICORE, which has started in 2013 and will be finished in 2017.

[10] DUROS+: the updated version of the DUROS model, which for instance uses a time-varying wave period

Besides being implemented in a program where potential users can already work with, the storm impact application developed in this study provides realistic results. This is because it uses recent bathymetry data, real-time water level and wave data as well as a hydrodynamic and morphological model calibrated for the Dutch coast.

The relevant storm impact information is for instance described by Baart et al. (2009). This study mentions the indicators overtopping, overwashing, beach and dune erosion, dune breach and localized flooding. Other processes that affect the coastal area are for instance wind, wave heights, tide and surge levels in combination with the (effect on the) initial beach profile (Haerens et al., 2012). The important storm impact information selected for this study is the following:

Bed levels during the storm The initial bed level and the eventual bed level show the erosion amount from the beach and dunes as well as whether buildings are becoming unstable due to erosion around the foundation.

Water levels, wave heights, run-up Water levels typically increase towards the shore, wave heights decrease due to dissipation. Visualizing the combination of both water levels and wave heights shows whether dunes are likely to overtop or overwash. It also indicates whether the water level, waves or the wave run-up reaches the buildings.

Building locations In order to show the impact on buildings, their location must be available.

Current velocities Fast currents affect swimmer safety and buildings.

1.3 Research objective and research questions

The research objective of this study is:

"Provide coastal managers with relevant, accurate and timely storm impact information for the coast, by developing, implementing and evaluating a prototype of a robust and operational storm impact application in MorphAn, based on real-time water level and wave forecast data as well as recent bathymetry."

The research questions that have to be answered to achieve the research objective are the following:

1. *What are necessary storm impact application components to acquire relevant storm impact information?*
2. *How can the storm impact information be provided using a storm impact application in MorphAn?*
3. *What is the quality of the storm impact application?*
4. *What is the accuracy and performance of the storm impact application results?*

For each research question, a separate research approach step and a corresponding report chapter is defined.

1.4 Methodology

There were several choices made prior to the study. The storm impact application that is designed uses live water and wave data, combined with recent bathymetry data as input for a morphological model. The choices that were made, will be briefly described here.

1.4.1 1D and 2D bathymetry data

As stated in the MorphAn description in Appendix B, annual 1D JARKUS measurements are often used in the Netherlands as bathymetry data. This is sufficient for areas with low longshore variability and straight coastlines. When longshore variability is higher however, 1D JARKUS transect measurements cannot represent the entire coastal bathymetry due to their large spacing. The morphological models that use this 1D bathymetry cannot accurately calculate morphological processes along curved coastlines, because longshore transport is not taken into account. Also, situations where waves obliquely approach the shore can cause 30-50% more erosion because of this longshore transport (Den Heijer, 2013). Furthermore, 2D models enable assessment of the spatial effects of a dune breach or an overwash of a barrier island. For these reasons, also 2D models and bathymetry were considered. First, the 1D version of the storm impact application was made operational. This was followed by further developing the storm impact application such that it also supports 2D grid bathymetry and models. More details about different bathymetry data sources will be provided in Chapter 2.2.

1.4.2 Water and wave forecast data

The choice was made to use water and wave data from RWsOS[11] as input, instead of using a computational expensive model train as in the MICORE project. The latter is more work to implement and maintain, and RWsOS is an already existing and robust system. Furthermore, using RWsOS does not require much computational power. This makes it possible to run the storm impact application on a general laptop, which makes it accessible for coastal managers. The RWsOS system and data will be described in Chapter 2.3

1.4.3 Morphological model

Up to now, two morphological models were mentioned, DUROS+ and XBeach. XBeach is used in the storm impact application because it models both the hydrodynamic as well as the morphological processes. It is a widely used and validated model for storm impacts on sandy coasts. It also performs better in modeling morphological change then DUROS+, due to the fact that it models the actual processes and does not assume a relatively simple equilibrium dune profile that DUROS+ uses. Because processes are modeled, it is also possible to see the progress trough time, instead of only the eventual result. The fact that it also models the hydrodynamic processes provides insight in water level and wave height variations over the cross shore domain, and thus also near the shore. XBeach can model 1D as well as 2D domains and three modes are available (stationary, surfbeat and non-hydrostatic). Deltares (2015c) derived suitable default settings by validating XBeach with a series of tests for the Dutch coast. These settings were also used in the storm impact application, so it can be applied to the Dutch coast. More details about the XBeach model will be provided in Chapter 2.4.

1.4.4 Evaluation

The demands and limitations for making the storm impact application operational at water authorities were assessed with seven criteria, depicted in Table 1.1. According to Baart et al. (2009), a storm impact or flood forecast function is only useful if it provides timely access (*Speed*) to relevant information (*Relevance*) of sufficient accuracy (*Accuracy*). Baart et al. (2015) added that it is also important to provide information on the confidence of a forecast (*Performance*). Furthermore, for a storm impact application to become operational, its components have to be robust (*Robustness*), because it should not be dependent on unavailable resources in case of a storm calamity. Also, the results must be clear in order to use them operationally (*Understanding*). In order to keep the storm impact application up to date and flexible, it must be able to evolve (*Evolvibility*). The seven criteria were evaluated with for instance literature, a sensitivity analysis and a survey. The different evaluation methods for each of the criteria will be further elaborated on in the relevant steps of the research approach in Chapter 1.5.

---

[11] RWsOS: Rijkswaterstaat Samenhangende Operationele Systemen, the operational flood early warning system of the WMCN of Rijkswaterstaat, which also provides water level and wave forecasts for the North Sea.

Table 1.1: Evaluation criteria

Criterion	Description
Speed	Is storm impact information available within a sufficiently small amount of time?
Relevance	Relevant information for supporting coastal managers?
Understanding	Is the storm impact application and the information it provides easily understood by the technical user and decision makers?
Robustness	How robust are the different components of the storm impact application?
Evolvability	Is it suitable for or easy to adapt to other input data or other study areas?
Accuracy	What is the accuracy of the different storm impact application components?
Performance	What is the erosion volume sensitivity predicted by the storm impact application when assessing the component uncertainties?

1.5 Research approach

The approach that was used for each of the research questions is described in this section. The execution of each of the four research approach steps is elaborated on in a separate chapter.

1.5.1 Define the storm impact application components

The components of the storm impact application are several bathymetry data sources, RWsOS water level and wave data and an XBeach model. For the bathymetry component several data sources are acquired and the resolution, coverage, accessibility, retrieval method and data format were assessed. The result provides an overview of bathymetry data that is available for the storm impact application. The RWsOS component was assessed by describing the model setup of the data provided through RWsOS, the data format and the retrieval method. The XBeach model component was defined by comparing the three modes of the model, the areas of application and the wave calculation method in both 1D and 2D model domains. The three storm impact application components are described in Chapter 2.

1.5.2 Implement the storm impact application in MorphAn

The storm impact application in MorphAn combines the RWsOS (water and wave) and bathymetry input data with an XBeach model. Python scripting provides access to a lot of functions and tools in the C# code and this was used to embed these three components into MorphAn. A storm impact application design was made, which encompasses the input data sources and their format, the model and model settings that were used and a design of the operations that the storm impact application in MorphAn performs.

The resulting design was discussed with the developer of MorphAn to decide how to implement the function using scripting in Python and how to comply with the used standards and existing functions in MorphAn. This discussion contributes to a more efficient process and also makes the script more general usable, for example in further new functions within MorphAn or DeltaShell.

In order to increase understanding, the scripts were concealed with a GUI which is also implemented with the scripting function. The GUI enables the user to gather and visualize the relevant input data from several sources, start the XBeach model with the input and visualize the relevant storm impact information from the input and the model output. The storm impact application implementation in MorphAn is described in Chapter 3.

1.5.3 Evaluate the quality of the storm impact application

Criteria for the storm impact application were defined with literature in the Methodology in Chapter 1.4. The first five criteria were used to assess the storm impact application itself. *Speed* was evaluated by comparing the model runtime to the approximately two hours that are available for a storm impact analysis according to coastal managers. *Relevance* of the storm impact application and its results were evaluated with a survey of coastal managers. *Understanding* was described and discussed with coastal managers. The criterion *Robustness* elaborates on the robustness and availability of the different components of the storm impact application (input, model, hardware, access). The criterion *Evolvability* describes the input availability outside the Netherlands and the expandability of the storm impact application. All these criteria define the quality of the storm impact application in Chapter 4.

1.5.4 Analyze the results of the storm impact application

Where the first five criteria are about the storm impact application itself, the actual results that are provided by the storm impact application were assessed with the latter two criteria. The *Accuracy* of the different storm impact application components was determined with literature. The *Performance* of the storm impact application was assessed by conducting a sensitivity analysis of the component accuracy, with erosion volumes as indicator. These two criteria determine the quality of the results of the storm impact application in Chapter 5.

Chapter 2

Components of the storm impact application

The storm impact application in MorphAn provides a Graphical User Interface (GUI) where recent bathymetry data and RWsOS water level and wave forecasting data can be easily selected and automatically retrieved from the internet and used as input for an XBeach model.

2.1 Schematization of the storm impact application

Figure 2.1 shows the schematization of the storm impact application in MorphAn. The white blocks are already existing parts. A description of MorphAn itself is available in Appendix B. For instance, MorphAn contains a GUI and a scripting function, both depicted as white blocks in Figure 2.1. These contain the parts that are added to the GUI and implemented with the scripting function. Again, the white blocks are existing components *Bathymetry data*, *RWsOS forecast data* and the *XBeach model*, that are combined in the storm impact application. Each of these three existing components will be elaborated on in a different section of this chapter.

The three existing components join together in MorphAn via the blue blocks, created in this study. The blue rounded blocks are processes implemented with scripting and the blue rectangle blocks are users actions in the GUI, which affect the process. The bathymetry files and RWsOS raw data is selected by the user in the GUI, it is downloaded and converted to XBeach input files in the background, depending on the user-defined grid size in the GUI. The XBeach model runs and creates output in the background, which is visualized with and in the GUI by the user. The new blue blocks will be elaborated on in Chapter 3.

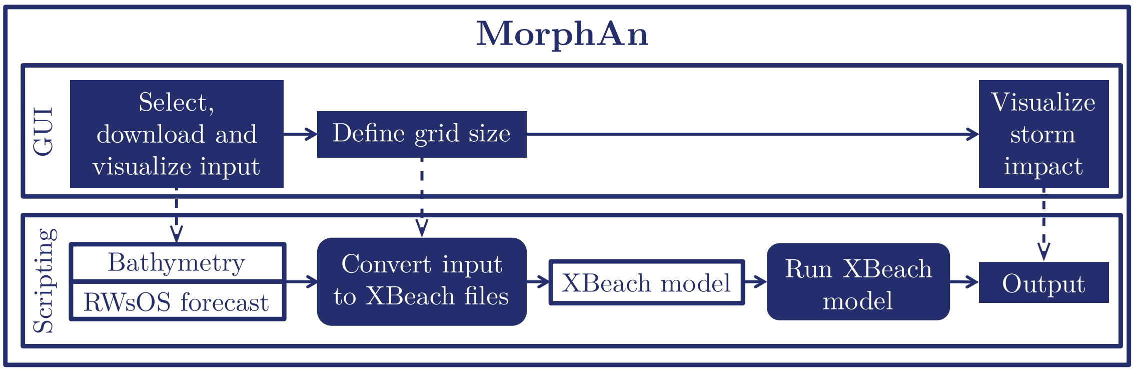


Figure 2.1: Schematization of the storm impact application components (white blocks), processes (blue rounded blocks) and GUI actions (blue blocks) that are used by the GUI in MorphAn.

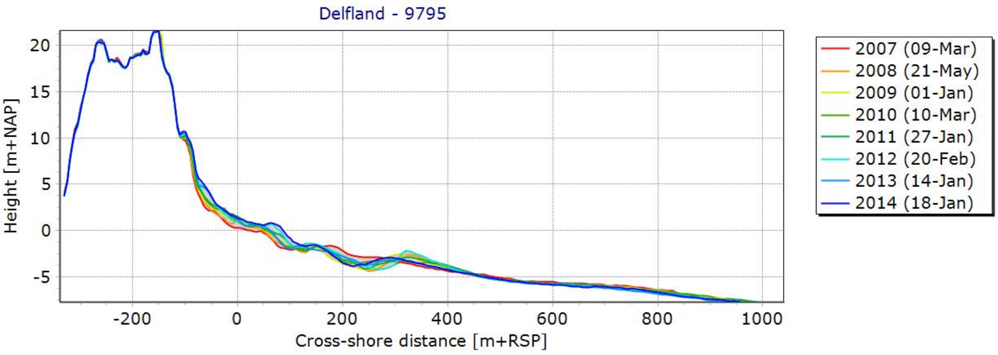


Figure 2.2: JARKUS data of raai 9795 from 2007 to 2014

2.2 Bathymetry data

2.2.1 Transect bathymetry data

A JARKUS transect is a combined data set of dry and wet measurements. Wet bathymetry data is collected by ships that collect this data on each coastal transect. Dry transect beach data is derived from grid data with a resolution of 5 meters, yearly collected with laser altimetry (Lidar) equipped airplanes. These wet and dry datasets are combined and interpolated for the intertidal area. These transects are made every 250 meter along the Dutch coastline, but this spacing is smaller at several locations. The cross shore resolution is 5 meters on dry land and close to the coast, and 10 meters in deeper water.

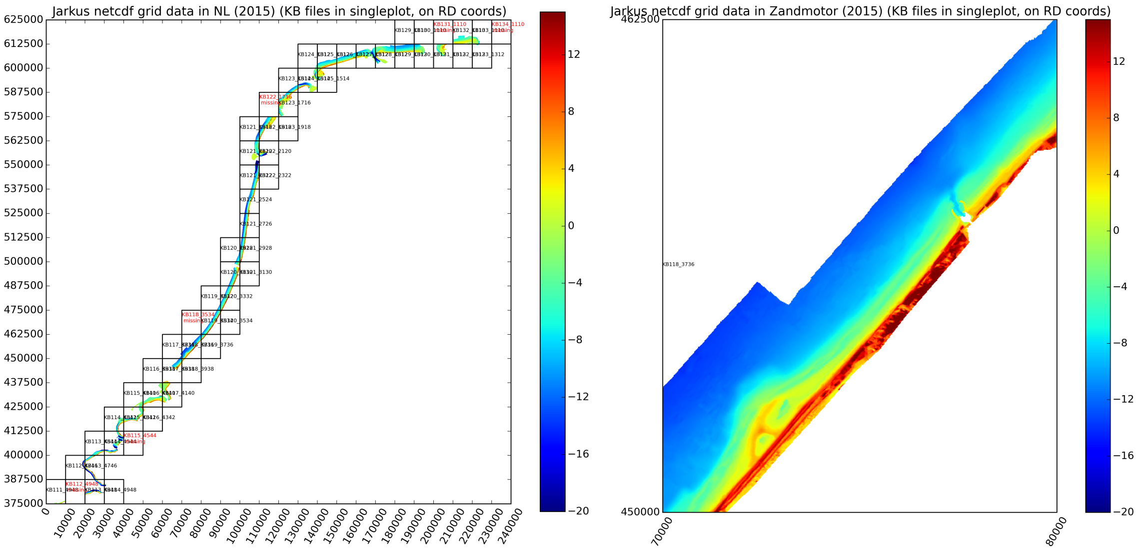
The yearly measured JARKUS transect dataset is large and is therefore divided into sixteen coastal sections for which data is collected from 1965. The raw JARKUS data of these coastal sections are made available by Rijkswaterstaat as *.jrk files (plain text) on the Open Earth Raw Data (OERD) repository. These data contains some duplicate cross shore locations due to overlapping wet and dry measurements and is written in a format that is somewhat difficult to read automatically with a program. At Deltares, the JARKUS transects are also converted to a large NetCDF[1] file. This file contains the filtered JARKUS transect data, without duplicate or missing values. It also includes for instance coordinates for every location on a transect. The NetCDF file is openly available at the Deltares OPeNDAP server and are easier to read into a program than the raw transect files. However, MorphAn releases are equipped with the raw JARKUS transects of the entire Dutch coast up to the year of the release, which makes also these raw files easy to use within MorphAn itself. Both the raw JARKUS transect data from MorphAn as well as the NetCDF file can be used as input bathymetry for the operational 1D model. For the latter however, a Python installation is needed on the users computer, because MorphAn (DeltaShell) does not yet provide the functionality to get a small amount of data from a large online NetCDF file.

2.2.2 Grid bathymetry data

Grid bathymetry data is available as well. The most accurate bathymetry data are the vaklodingen, which have an accuracy up to approximately 0.5 meters in x and y direction, depending on the collection method (Wiegman et al., 2005). Unfortunately, vaklodingen are collected irregularly, which makes it an unreliable data source for automatic bathymetry retrieval. The lidar beach data is collected each year, but often does not cover all dune rows of the sea defense and no bathymetry at all. Lidar dune data is collected approximately every five years (De Graaf et al., 2003). It would also be possible to combine these data sources with general topographic data of the Netherlands (AHN, Actueel Hoogtebestand Nederland) if the landward extent of the coastal topographic data is not sufficient. However, all of these sources do not provide a reliable and complete data source for automatic bathymetry retrieval yet, and are therefore not used within this study.

---

[1] NetCDF: a file format which is widely used to store self-describing, machine-independent and array-oriented data. This data can be easily read and interpreted with programs like Matlab, Python, ArcGIS and DeltaShell.



(a) Dutch coast, rectangular boxes are the file borders **(b)** Sand Engine and Scheveningen Harbour

Figure 2.3: JARKUS grid bathymetry data for **(a)** the Dutch coast and **(b)** a more detailed selection of the Sand Engine. This data is available for the entire Dutch coast and originates from the Deltares OPeNDAP server.

A more stable grid bathymetry data source is JARKUS grid data, which is the interpolated version of JARKUS transect data of Rijkswaterstaat. This data has a regular squared grid with a resolution of 20 meters. These NetCDF grid files are also openly available on the Deltares OPeNDAP server, just like the NetCDF transect files. Both the JARKUS transect as well as the grid data files are created almost immediately after Rijkswaterstaat has made the raw JARKUS transect data available on the OERD repository. An example of the JARKUS grid bathymetry data is given in Figure 2.3.

2.2.3 Real-time bathymetry data

Because the JARKUS grid data is interpolated between the original JARKUS transects, this data is often only sufficient for longshore uniform areas, where analysis of several transects might also suffice. However, Figure 2.2 shows that the non-uniform Sand Engine area is an exception, which is due to a small spacing between transect measurements of sometimes only 50 meters. Nevertheless, many non-uniform areas cannot be represented by the available transect measurements. Furthermore, JARKUS data is collected once a year during the spring, and often already several months old when used for winter storm models. According to Cohen et al. (2009), the bathymetry strongly varies trough the year and the winter profiles contain significantly less volume than the spring profiles. This will be elaborated on in Chapter 5.1. This outdated bathymetry can affect the model output. This can partly be solved by modeling every storm that has occurred since the last bathymetry, and use the output bed level as the input bed level of the next storm, but this can be quite devious for successive storms over a period of multiple months. Furthermore, bed level prediction errors are passed on to the next model and could be amplified with every storm. Therefore, different grid data sources are elaborated on which do not have the above problems.

There are possibilities to collect near real-time bathymetry with image or video cameras. These can be used to derive the current topography of the beach (Vousdoukas et al., 2010) or the current state of the intertidal beach bathymetry (Uunk et al., 2010). These Argus cameras can also be used to derive an estimation of the nearshore bathymetry with a method called Beach Wizard, which uses wave roller dissipation, intertidal variations and wave celerity observations that are derived from camera images (Van Dongeren et al., 2008). The accuracy of camera derived bathymetry can be increased by deriving wave celerities with radar data (Van Dongeren and Cohen, 2006). Radar data can also be used as a standalone source for bathymetry data estimations (Friedman et al., 2014). Both grid and transect bathymetry data can be derived with this Beach Wizard method.

A newer method to derive bathymetry from camera images is cBathy (Sembiring, 2015). According to Sembiring et al. (2014), cBathy performs better than Beach Wizard in estimating bathymetry, compared to reference jetski bathymetry measurements. However, cBathy is developed for rip current prediction and therefore is used to produce bathymetry data between the shoreline and a water depth of eight meters. The cBathy longshore resolution is 10m and the cross shore resolution is 3m (Sembiring, 2015). The beach and dune bathymetry are not taken into account, which is important for erosion during storms. Nevertheless, cBathy can be combined with other datasets to provide a complete bathymetry.

These real-time bathymetry data sources are often only temporarily available for only some locations and not for the entire Dutch coast. Also, none of the above systems is currently operational or has measurements that are publicly available. However, the necessary equipment for a measurement station can be installed quite easily as well as on arbitrary locations and can therefore be considered a potential bathymetry data source for the storm impact application.

2.3 RWsOS water level and wave forecast data

A Flood Early Warning System named Delft-FEWS North Sea is developed at Deltares, which is operational at Rijkswaterstaat as the RWsOS system. It produces forecasts of the water levels and wave data like the wave height, direction and period. This system automatically runs four times per day (every six hours) and produces forecasts for 48 hours. It consists of models that predict water levels and wave data.

Water levels are predicted with a flood forecasting model for the Northwest European Shelf and North Sea, the Dutch Continental Shelf Model (DCSMv6). This model uses the air pressure and wind forecasts from the HiRLAM[2] model of KNMI as boundary condions, which also runs four times per day. (De Kleermaeker et al., 2012)

Wave data is generated by a SWAN model for the Dutch Continental Shelf (SWAN-DCSM) and the Southern North Sea (SWAN-ZUNO). The original SWAN wave model was developed by Booij et al. (1999) for computing random, wind generated waves in coastal regions. It is operational at Rijkswaterstaat as a part of RWsOS since 2015. This model consist of two nested grids, depicted in Figure 2.4. The larger DCSM grid has a resolution of 3.6 km and contains the entire Dutch continental shelf, with exception of the Nordic fjords and the Irish sea, to reduce computational time. This model makes use of water levels and current fields from the DCSMv6 model, wind fields from the HiRLAM model and wave boundary spectra from the operational global WAM wave model of the ECMWF[3]. The DCSM model provides boundary conditions for the ZUNO model. The ZUNO model entails of the Southern North Sea area and has a curvilinear grid with a variable grid size of 2km offshore to 200 meters nearshore.

The output of these RWsOS models is available for registered users via the MATROOS[4] database at matroos.rws.nl. The output of the models is checked for outliers with automatic filters, but experts at Rijkswaterstaat also manually check and correct the output. Therefore the RWsOS output can be considered validated and can be used directly. Detailed SWAN wave spectra are calculated and used within the SWAN model, but these are only stored for a very limited amount of locations near harbors. This makes the data source not flexible enough for a storm impact application, and time series of wave characteristics are uses instead. The RWsOS database is used to extract timeseries of water level data (in meters w.r.t NAP[5]) with a timestep of ten minutes

---

[2] HiRLAM: High Resolution Limited Area Model, a Numerical Weather Prediction model provided by the Royal Dutch Meteorological Institute KNMI.

[3] ECMWF: European Centre for Medium-Range Forecast.

[4] MATROOS: Multifunctional Access Tool foR Operational Oceandata Services. The operational version of this database is available at Rijkswaterstaat (matroos.rws.nl), for which access is provided by Marc Philippart of RWS-WVL, operational manager of RWsOS. A research version of MATROOS is available at Deltares (matroos.deltares.nl).

[5] N.A.P.: Normaal Amsterdams Peil (Amsterdam Ordnance Datum), a vertical datum based on the historical average summer flood reference.

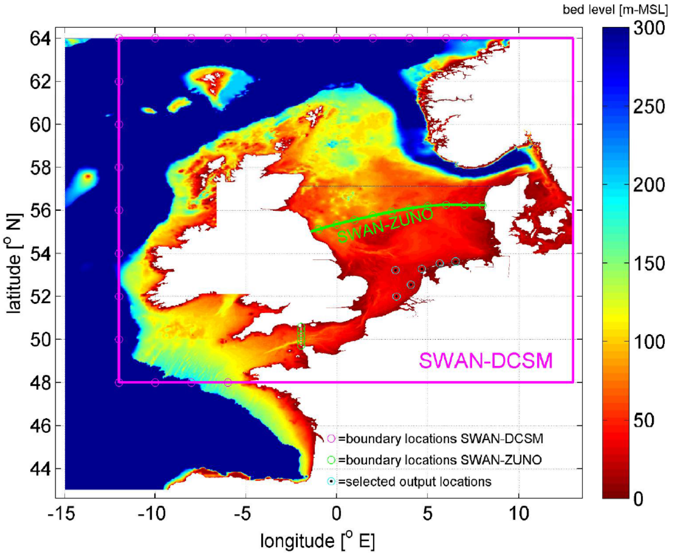
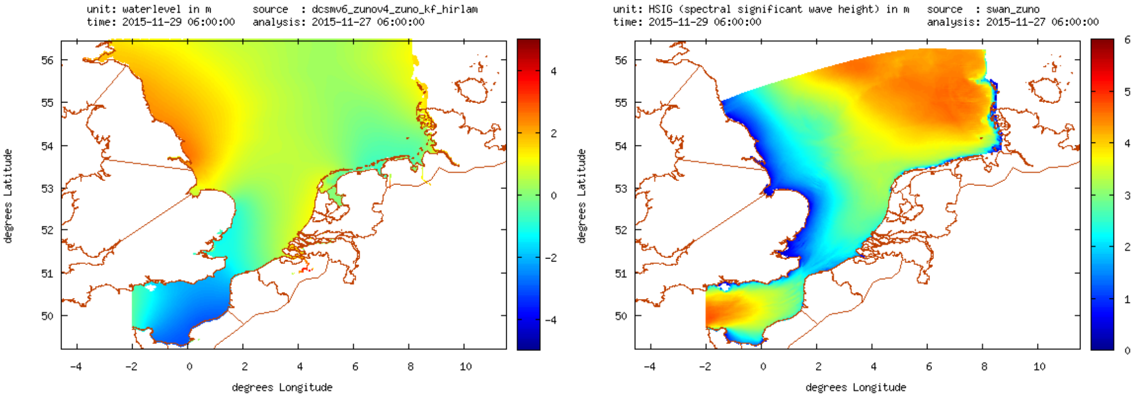


Figure 2.4: SWAN operational model area (Gautier and Caires, 2015)

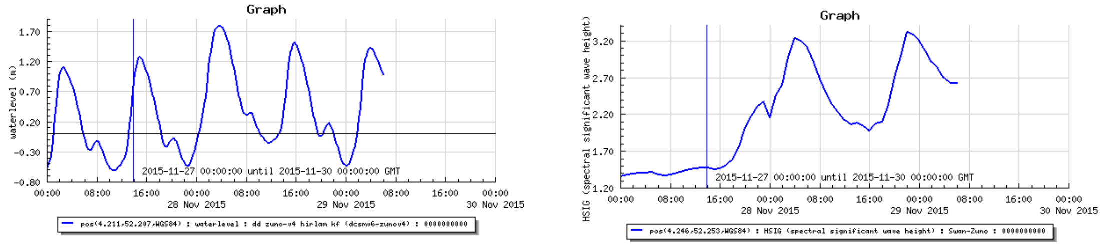
to one hour from the DCSMv6 model and timeseries of wave characteristics with a timestep of one hour from the (SWAN-ZUNO) model. This wave data is the significant wave height (H_{m0}), the main wave direction (angle w.r.t North), the spectral wave period ($T_m^{-1.0}$) and the swell wave height (swell H_{m0} or H_{E10}), which is defined as the significant wave height based on the frequency domain 0.03 Hz - 0.10 Hz (Gautier and Caires, 2015).

All this data is available on arbitrary coordinates within the RWsOS model grid, which is sufficient to be used as boundary conditions at locations several kilometers from the Dutch coast. Timeseries on the boundary of the model domain are retrieved as text files. It is also possible to retrieve the entire NetCDF file of the different models, but this is not necessary and takes more time. A visual example representation of the RWsOS data is given in Figure 2.5.



(a) DCSMv6 model area

(b) SWAN-ZUNO model area



(c) DCSMv6 waterlevel timeseries

(d) SWAN-ZUNO Hm0 timeseries

Figure 2.5: Two RWsOS data model areas and timeseries on an arbitrary coordinate within the models. The model runs are from 27-11-2015 6:00 and provide a forecast of 48 hours. The data is retrieved on 27-11-2015 at 14:00, indicated by the vertical blue line.

2.4 XBeach model

XBeach (Roelvink et al., 2015) is an open source depth averaged (1D or 2DH) numerical model, developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometers and on the time scale of storms. Within XBeach, there are basically three general levels of detail to choose:

The stationary mode is a simplified mode for long term simulations and only solves wave averaged equations. It neglects wave-group variations and thereby infragravity motions. Therefore, the stationary mode is not suitable to model storms.

The surf beat mode is the standard XBeach mode and solves short-wave variations and swash of long waves. This is necessary in the swash zone, where time-averaged currents and setup are insufficient. The surf beat mode assumes that long waves are more important during storms than short waves and therefore only calculates the energy that is contained in the short waves, but not the characteristics or form of every individual short wave. Because the individual short waves are not taken into account, this mode cannot calculate short wave runup levels, as well as overtopping and overwash amounts. However, it does calculate long wave runup levels (swash) and also provides an indication whether a dune will overtop or overwash.

The non-hydrostatic mode solves all equations with variable pressures, so there are no assumptions needed for long or short waves. However, because each short wave is taken into account and it has to comply to the Courant condition, it requires a very fine grid and small time steps. This results in a significant increase in the computational time compared to the other modes. The advantage is that wave runup for both long and short waves and therefore also overwash amounts can be modeled.

The *stationary mode* is insufficient for a storm impact application because it is not suitable for storms. The *non-hydrostatic mode* is expected to be too computationally expensive for the time available for a storm impact application run. Also, Deltares (2015b) showed that the non-

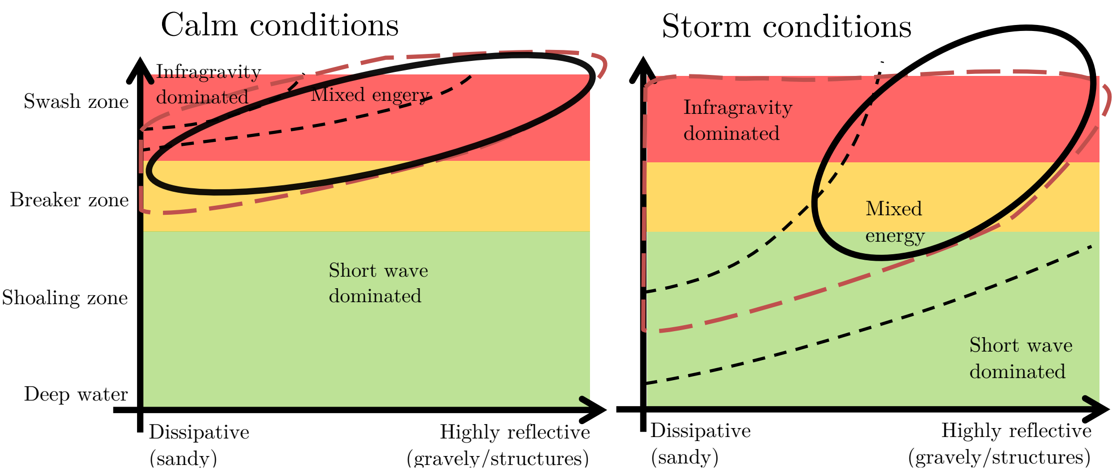


Figure 2.6: This figure from Deltares (2015b) shows calm and storm conditions: the dominant wave processes (black dashed lines), the dynamic zone where morphologic changes occur (brown dotted line) and the short wave parameterization performance (well/green, okay/orange, poorly/red). The black circle denotes their overlap: the area where short waves are relevant, its parameterization is insufficient and there are morphologic changes occurring. These areas should be modeled with the non-hydrostatic mode. Dissipative beaches in storm conditions can be modeled well without it.

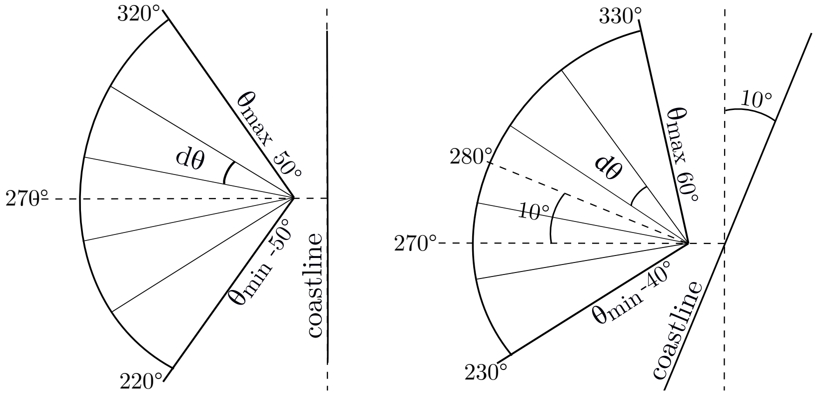


Figure 2.7: Wave angles and bins for different coastline rotations. In the left example, only waves from 220°to 320°with respect to the North can enter the model. In the right example, the coastline rotation of 10°allows waves from 230°to 330°with respect to the north to enter the model. The values for θ_{min} and θ_{max} are with respect to the baseline of 270°with respect to the north.

hydrostatic mode is not necessary for storm conditions on dissipative beaches (Figure 2.6). Therefore, XBeach is used in the *surf beat mode*. The XBeach executable uses multiple input files that contain input parameters, x and y coordinates, initial bed levels, water level time series and wave characteristic time series. The contents of these files are described in Appendix C.

XBeach works with wave bins of which the range is defined by θ_{min} and θ_{max} and the number of bins is derived from $d\theta$. Figure 2.7 shows an example of a coastline with an orientation of 0°with respect to the North. θ_{min} is -50°and θ_{max} is 50°with respect to a line perpendicular to the coastline. $d\theta$ is 20°, which results in five wave bins. These waves enter the model and can only propagate within the wave bins. If they refract, they switch from one bin to another. More wave bins increase the computational time, and a larger absolute value for θ_{min} and θ_{max} increases the amount of waves that can enter the model. Values of -90°and +90°would include all the waves in the direction of the coast line. To save computational time in MorphAn, θ_{min} and θ_{max} are currently limited to -50°and +50°, with a $d\theta$ of 20°, as in Figure 2.7.

In 1D mode, wave propagation and refraction of oblique waves is estimated with a quick Snell's law estimation. This causes all waves to refract in cross shore direction, where the longshore component of the wave energy is lost. The Snell's law estimation results in less realistic hydrodynamic processes and is therefore not used in 2D mode. With the applied 2D XBeach settings, the waves only enter the model domain trough the offshore boundary. This means that some of the oblique waves cannot reach the entire shoreline of the model domain, which results in a triangular shadow zone at the side boundaries of the model domain. The hydrodynamic and morphological results are less reliable in these shadow zones, so the area of interest should not be located there. In order to overcome this problem, the model domain is extended so all waves reach the area of interest, Chapter 3 elaborates this solution.

Chapter 3

Implementation in MorphAn (coupling of the components and GUI)

The schematization in Figure 2.1 briefly summarizes the new functions that were implemented for the storm impact application. A Graphical User Interface (GUI) is designed and partly developed to make the storm impact application prototype operational for coastal managers, by providing the functionality without having to use the Python script. The steps that the user takes in the GUI are elaborated on in this chapter and can therefore be used as a user manual. Because the current storm impact application is a prototype, not all functionality is implemented as described in this chapter yet, but these are marked with a star (⋆). Chapter 3.5 will briefly elaborate on the differences from the ideal and the current GUI implementation. The base of the GUI is a project tree (⋆), depicted in Figure 3.1. This screen is divided in input and output, which both have sub-items that will be elaborated on in this chapter.

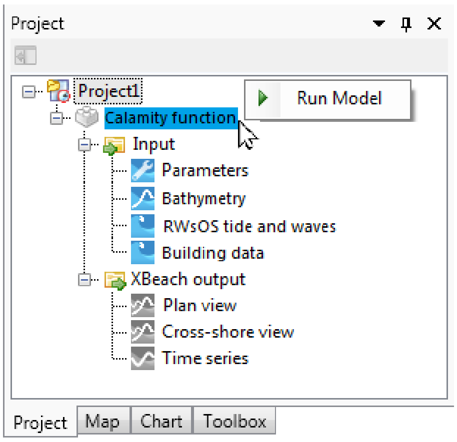


Figure 3.1: Project tree screen (⋆)

3.1 Technical prerequisites

There are some technical prerequisites in order for the storm impact application to work:

- ▷ Windows computer with MorphAn 1.4 or higher installed, including the optional components *Scripting* and *XBeach*
- ▷ XBeach Kingsday release (v1.22 or later, including NetCDF) executable to replace the MorphAn XBeach Groundhog Day release (v1.21) executable in the MorphAn installation folder
- ▷ storm impact application scripts (from the SVN repository) in the MorphAn scripting folder
- ▷ RWsOS MATROOS credentials (or a Deltares connection for Deltares MATROOS)
- ▷ An internet connection for RWsOS data and for non-MorphAn bathymetry data
- ▷ Optional: a Python (Anaconda) installation, if JARKUS data is retrieved from OPeNDAP
- ▷ Optional: building data in *strandtenten.txt* (Appendix C)
- ▷ Optional: building data in a shapefile (⋆)

Appendix D elaborates on how to get the (installation) files, how to install and where to apply for credentials.

3.2 Input

3.2.1 Parameters

The current storm impact application prototype has several input options of which the most important are described here. The input parameters can be filled in by the user, currently in the pop-up screen in Figure 3.2. This input screen will be embedded under the *Parameters* button in the project tree in Figure 3.1 (⋆). The input options are divided into Bathymetry related options, RWsOS related options and options for the XBeach model grid and result plots.

For the bathymetry, a choice between 1D and 2D sources can be made (*bathy*). Four types of bathymetry are now implemented: JARKUS transects from MorphAn, JARKUS transects from OPeNDAP, JARKUS grids from OPeNDAP and Beach Wizard grids. Furthermore, the year for which to retrieve the bathymetry is necessary, which will often be the most recent measurement year (*year*). The list of transect numbers or area to analyze is selected at the bathymetry input (*raailist*). More on the bathymetry input data is elaborated on in Chapter 3.2.2.

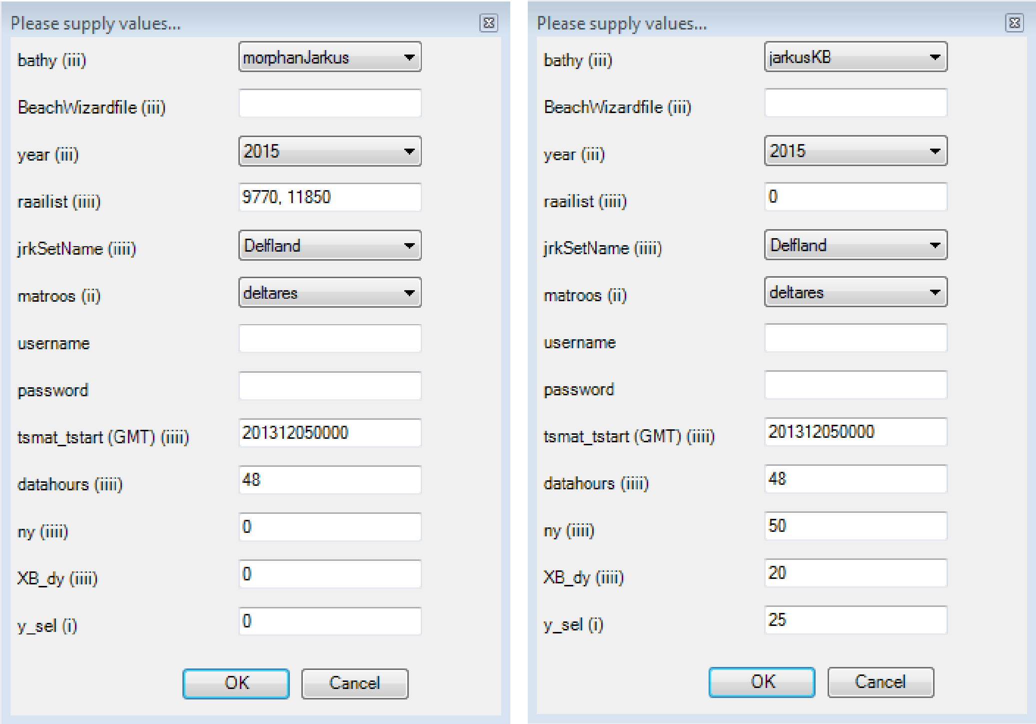
The RWsOS related options entail the source server (Deltares or Rijkswaterstaat, *matroos*), the start date and time of the analysis (*tsmat_tstart*, in the format yyyymmddhhmm) and the period for which water level and wave data is retrieved from the server (*datahours*, in hours). The geographic location for which the RWsOS data is retrieved, is automatically determined by the selected bathymetry input. More on the RWsOS input data is elaborated on in Chapter 3.2.3.

The XBeach model grid options are the number of grid cells in longshore y-direction (*ny*) and their size (*XB_dy*). The number of grid cells in cross shore x-direction (nx) and their size (dx) is automatically determined at the bathymtery input and is therefore not user defined. The cross shore transect of the model grid that is visualized is defined by *y_sel*. The XBeach model run itself elaborated on in Chapter 3.3.

After the input parameters are provided, a folder structure is created where files will be stored later on. Folders are created for the bathymetry, RWsOS data and the XBeach model.

3.2.2 Bathymetry

In the 1D mode of the storm impact application, the transect locations and the measurement year that will be analyzed are selected in a map or from a list like Figure 3.3 (⋆). The JARKUS transects will be retrieved from the MorphAn installation or from the Deltares OPeNDAP server. The resolution of these transects is high enough for XBeach and is therefore not optimized. JARKUS



Please supply values...

bathy (iii)	morphanJarkus
BeachWizardfile (iii)	
year (iii)	2015
raailist (iiii)	9770, 11850
jrkSetName (iiii)	Delfland
matroos (ii)	deltares
username	
password	
tsmat_tstart (GMT) (iiii)	201312050000
datahours (iiii)	48
ny (iiii)	0
XB_dy (iiii)	0
y_sel (i)	0

Please supply values...

bathy (iii)	jarkusKB
BeachWizardfile (iii)	
year (iii)	2015
raailist (iiii)	0
jrkSetName (iiii)	Delfland
matroos (ii)	deltares
username	
password	
tsmat_tstart (GMT) (iiii)	201312050000
datahours (iiii)	48
ny (iiii)	50
XB_dy (iiii)	20
y_sel (i)	25

(a) 1D example input **(b)** 2D example input

Figure 3.2: Pop-up input screen

Figure 3.3: 1D JARKUS bathymetry selector ($\star$)

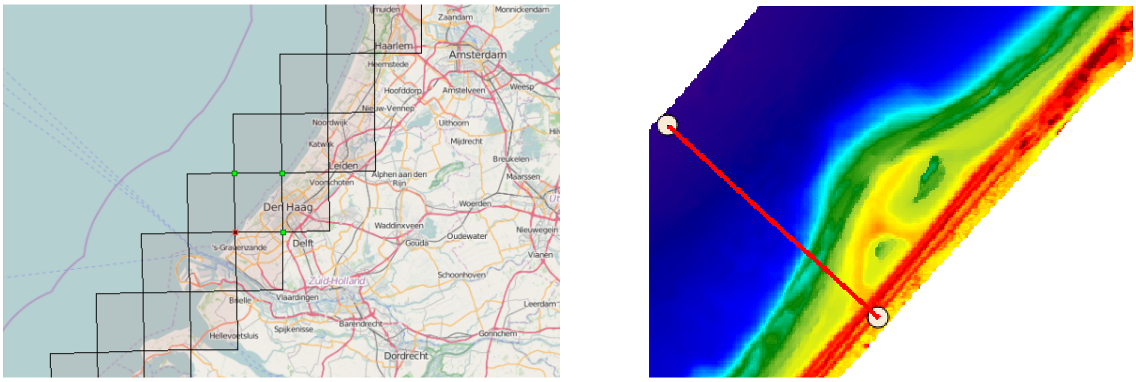
transect bathymetry often reaches to a depth of approximately NAP -10m, which is extended with a hard coded constant slope of 1:50, to a depth of NAP -20 meters in order to allow the long waves to travel into the model domain without disturbance. The coordinate of the new seaward boundary of the transect is used as location where the RWsOS data is retrieved. The coordinates of the transect points and the bathymetry on these points is written to several XBeach input files (Appendix C).

When the 2D mode is used, 2D JARKUS bathymetry files can be selected in the window in Figure 3.4a. This file of approximately 150MB will then be downloaded from the Deltares OPeNDAP server. It is also possible to use other types of grid bathymetry files like Beach Wizard data, but then the file must be downloaded manually and the filename must be provided.

The bathymetry data is displayed in a map, where a baseline for the model grid is drawn by the user, perpendicular to the coastline (Figure 3.4b). This baseline is part the left border of the model grid, as seen from the coast. Subsequently, a grid is automatically created based on the baseline and the user-defined number of gridcells in longshore direction (ny) and the cell width (dy). Figure 3.5 shows how this grid is defined. The origin (x_{ori}, y_{ori}) is in RD[1] coordinates (e.g. 70000, 460000). The rotation α is positive in clockwise direction, which corresponds with the coastline rotation

---

[1] RD: RijksDriehoek coordinate system used mainly in the Netherlands with its reference point in a church Amersfoort (155000, 463000) and its apparent origin in France. RD is a rectangular coordinate system where x and y values are distances in meters.



(a) Bathymetry selector **(b)** Baseline coordinates

Figure 3.4: GUI interface where **(a)** a 2D JARKUS bathymetry file is selected and downloaded and **(b)** any 2D bathymetry is shown in a map where the boundary coordinates for the XBeach grid baseline can be selected.

with respect to the North. The RD values for all (x,y) coordinates are defined in Equation 3.1 and 3.2, where x' (y') is the x-distance (y-distance) from the origin of the grid (x_{ori}, y_{ori}) in meters. The origin is near the seaward coordinate of the user-defined baseline.

$$x = x_{ori} + y' sin(\alpha) + x' cos(\alpha) \tag{3.1}$$

$$y = y_{ori} + y' cos(\alpha) - x' sin(\alpha) \tag{3.2}$$

It is also possible to use the 2D bathymetry data for a 1D transect analysis by providing ny=1 (one grid cell in longshore direction, two 'transects') and the 1D wavebin settings (snells=1, $d\theta$=100 and no extended grid) ($\star$).

The number of grid cells in cross-shore direction (nx) and the variable length of these grid cells (dx) are automatically determined. The nx is kept as low as possible to reduce the model runtime, while keeping the Courant number (Equation 3.3) just below $C_{\max} = 0.9$ in order to keep the explicit numerical scheme of XBeach stable. This optimization function is already embedded in MorphAn.

$$C = \frac{u\,\Delta t}{\Delta x} \leq C_{\max} \tag{3.3}$$

The variable dx is determined on every grid cell in cross shore direction by using a default value for Δt as well as a calculated velocity u (which is calculated with a fixed water level, a fixed wave height and the given bathymetry). During the model run, the dx of each grid cell and the actual velocity are used by XBeach to determine a suitable time step Δt. When the Courant number is small ($C < 0.5$), the time step Δt will be small and the runtime will increase. When the Courant number is too large ($C > 1.0$), the larger time step Δt might cause instability in the numerical scheme.

Furthermore, waves must be able to enter the model domain without disturbance which would cause initial energy loss. This is only possible if the seaward boundary is in deep water, which is defined as a water depth equal to or larger than half of the wave length. Therefore, in both the 1D as well as the 2D mode, the bathymetry is extended in seaward direction with a constant slope of 1:50, to a depth of NAP -20m. This depth is often used in XBeach models (Roelvink et al., 2015).

The data of the underlaying bathymetry layer is evaluated to the curvilinear model grid. When the bathymetry layer has a coarse resolution, like for instance the JARKUS grid data (20x20m), the four surrounding values are interpolated by inverse distance weighing. The coordinates of each of the gridpoints, the evaluated bathymetry and the grid dimensions are then written to different XBeach input files (Appendix C). It is possible that the resulting grid (Figure 3.6) is not satisfactory. It for instance covers a too small or too large domain, the resolution is inadequate or the grid does not follow the coastline. Then, the input values for ny and XB_dy can be changed or a new baseline can be drawn, after which a new grid can be created.

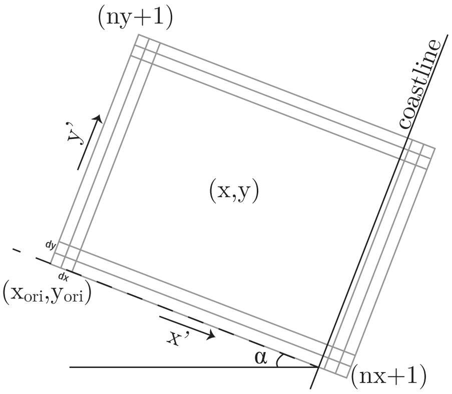


Figure 3.5: XBeach grid coordinates

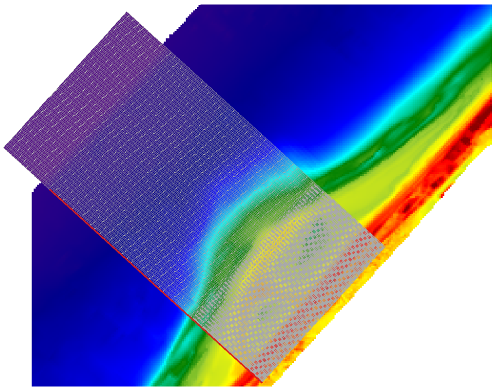


Figure 3.6: GUI interface where the XBeach grid is generated with interpolated values from the bathymetry layer.

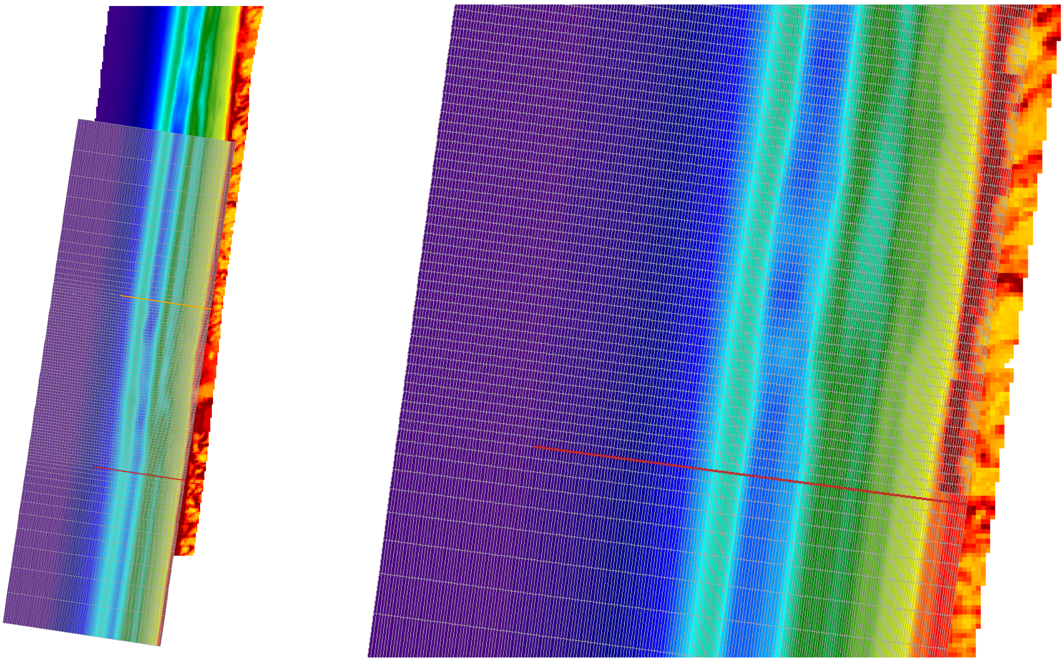
Oblique waves entering the model grid in Figure 3.6 would cause shadow zones that possibly cover the entire coastline of the area of interest. Therefore, the model grid is extended automatically in longshore direction, as depicted in Figure 3.7, a technique developed and implemented in this study. The longshore extension length for both sides of the grid is determined by an angle of 50°, which is $tan(50°) = 1.19$ times the cross shore length of the grid. The cell width (dy) of the extension increases with 20% towards the side of the grid, so the amount of cells and therefore the computational time is not increased too much. The bathymetry of the red and orange baseline is repeated in the extended grid. This results in several transects with the same bathymetry at the sides of the model grid, which ensures a stable XBeach model run. This also implies that some extension is necessary, because constant bathymetry is needed at the sides of the model grid for the XBeach model. Using the extended grid ensures that the waves are able to enter the model grid and also prevents the sides of the area of interest to be sacrificed for constant bathymetry transects.

3.2.3 RWsOS

The storm impact application has brought MATROOS data to the user. The relevant data is automatically loaded into MorphAn and used as input for an XBeach model. RWsOS water level and wave data forecasts are retrieved from the Deltares or the Rijkswaterstaat MATROOS server, based on the provided start time and duration. In 1D mode, the seaward coordinate of the transect is used and in 2D mode the seaward coordinate of baseline of the model grid. The retrieved timeseries can be viewed in a single graph or individually, as shown in Figure 3.8. This figure shows data of the Sinterklaasstorm of 5 to 7 December 2013, with a waterlevel increase of 2 meter and wave heights up to 4.5 meter. If forecast data is retrieved, the chart also displays the retrieve time and the current time, to provide insight in how recent the data is and the remaining forecast time. The timeseries that are retrieved from RWsOS will be used as a boundary condition on the offshore boundary of the model domain and written to an XBeach input file (Appendix C). The wave characteristic timeseries are used to create JONSWAP[2] wave spectra, which can be used as XBeach input. Because the JONSWAP spectrum works with a peak wave period (T_p), the RWsOS spectral wave period ($T_m^{-1.0}$) is multiplied by 110%, which is valid for not too shallow water and single peaked wave spectra (Van der Meer, 2002). The wave characteristics are written to an XBeach input file (Appendix C).

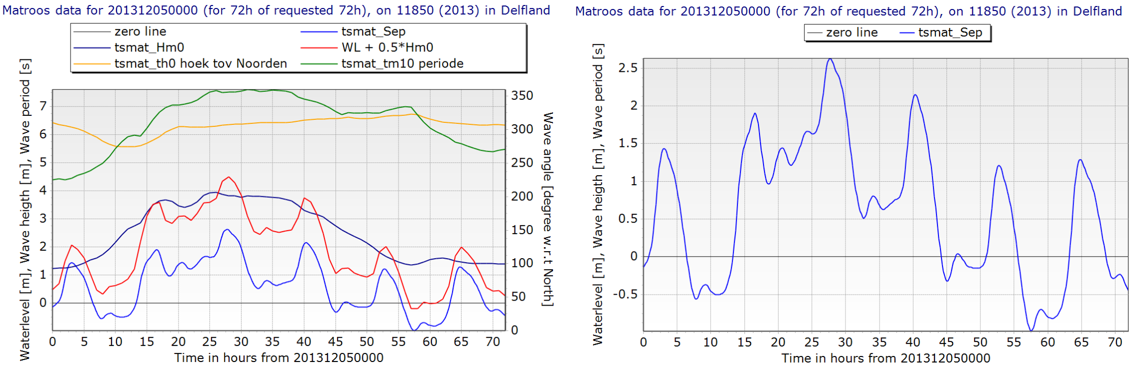
---

[2] JONSWAP: Joint North Sea Wave Project, an empirical relationship for a wave spectrum that defines the distribution of the wave energy frequency (Hasselmann et al., 1973).



(a) Grid with extensions **(b)** Detailed view of the transition

Figure 3.7: The grid is extended in longshore direction in order to prevent a shadow zone in the area of interest. The extensions of the grid have an increasing dy to save computation time, the bathymetry is the same as on the red and orange baselines.



(a) Default data view **(b)** Simple data view (water level only)

Figure 3.8: The water data that is retrieved from the RWsOS database, these figures show 72 hours of data from the Sinterklaasstorm at transect 11850 in Delfland. The data consist of the water level (light blue, *Sep*), wave height (dark blue, *Hm0*), wave direction (yellow, *th0*) and wave period (green, *tm10*).

3.2.4 Building data

Data about locations of buildings are necessary to assess if buildings like hotels or beach pavilions are influenced by for instance dune erosion or a high water level and waves. Building location data can currently be provided via a text file with the relevant transect and the seaward and landward distance from the RSP[3] line. Sattelite images in MorphAn can be used to collect this data manually. The seaward distance is used to determine the elevation of the initial bed level. This is not very precise, but it gives an indication. Furthermore, because it depends on transect numbers, this data can only be visualized for results of a 1D model run.

An alternative is to provide building data in a geo-referenced shapefile (⋆). This file contains x, y, z locations and dimensions of buildings like hotels or beach pavilions. This information can be used to visualize the buildings in both plan view (for 2D analysis) and cross-sectional view (for 1D and 2D analysis). Besides visualizing, the buildings can be implemented as hard structures in the XBeach model, to assess their effect on erosion (⋆).

3.3 XBeach model run

With input parameters, bathymetry, waterlevel, wave data and building location data available, the XBeach model is now completely set up. When the user runs the storm impact application, information is provided about the progress and the remaining runtime. An XBeach model runs on it own processor core and multiple models will automatically run parallel on a different cores of the processor. The speed decreases if there are less processor cores than XBeach models. In 1D mode, there is one model per transect and they will run parallel. In 2D mode, there is often only one model per area, which only uses a single processor core. The XBeach model calculates the minimum and maximum water level, the maximum wave heights and the maximum absolute flow velocities along the model domain. Furthermore, it calculates the bed level trough time. All the output is written to a NetCDF file.

3.4 Output

To view the output from the model run, a map view is opened (⋆). For 1D this map shows a plan view of the analyzed transects and for 2D it shows the bed level trough time (with a time slider) (⋆). Both maps also show the maximum water line and the buildings in the area (⋆). In 1D mode a transect can be selected and in 2D mode each of the cross shore lines of the model grid can be selected as a transect (⋆). Clicking a transect gives an overview of the retrieved RWsOS water data and a cross-sectional view of the XBeach model (⋆).

With the current implementation in MorphAn, the relevant storm impact information is provided. This relevant information in the cross-sectional view chart of the XBeach model output are described in Table 3.1 and depicted in Figure 3.9.

Figure 3.9 shows that the maximum water level has significantly increased towards the shore, with levels up to 4.3 meter and run-up levels up to 5.2 meter with respect to NAP. The water level at the boundary of the model domain is approximately 2.5 meter, depicted in Figure 3.8b. This boundary is located approximately 3.5 kilometers from the RSP point, which is not visible in Figure 3.9. The maximum wave height decreases from approximately 4 meter offshore to less than 1 meter near shore. This wave dissipation mainly happens closer to the shore, where the water depth quickly decreases, the part that is visible in Figure 3.9. The current velocities increase from 1 meter per second offshore to 3.5 meter per second closer to the shore. A large volume of beach and dune erodes, there is a fifty meter retreat at NAP +3m. Furthermore, the beach pavilion that is currently located on the beach would have been affected by this storm, by the water level and waves as well as the erosion of its foundation. This erosion might seem severe for a storm with an offshore water level of NAP +2.5m.

---

[3] RSP: RijksStrandPalen, a fixed location at every transect that can be used as a reference point.

Table 3.1: Cross-sectional chart model output description, the terms in the left column are explained in Figure 3.9.

Output variable	Description
zb	Bed level (change represents dune erosion) on for instance ten timesteps during the simulation, with a maximum of one step per 30 minutes.
max uv abs	Maximum absolute flow velocity (and maximum u and v velocity)
zs_min, zs_max	Maximum and minimum water levels over the cross shore domain
H	Maximum wave height (H_m0) around the maximum water level
WLpoint	Highest water line from long wave runup (swash), which gives an indication of the actual runup (of both long and short waves)
buildings	Buildings based on a distance form RSP for x, where the z level is derived from the bathymetry level of the seaward position of the building. This currently only works for a 1D transect model run.

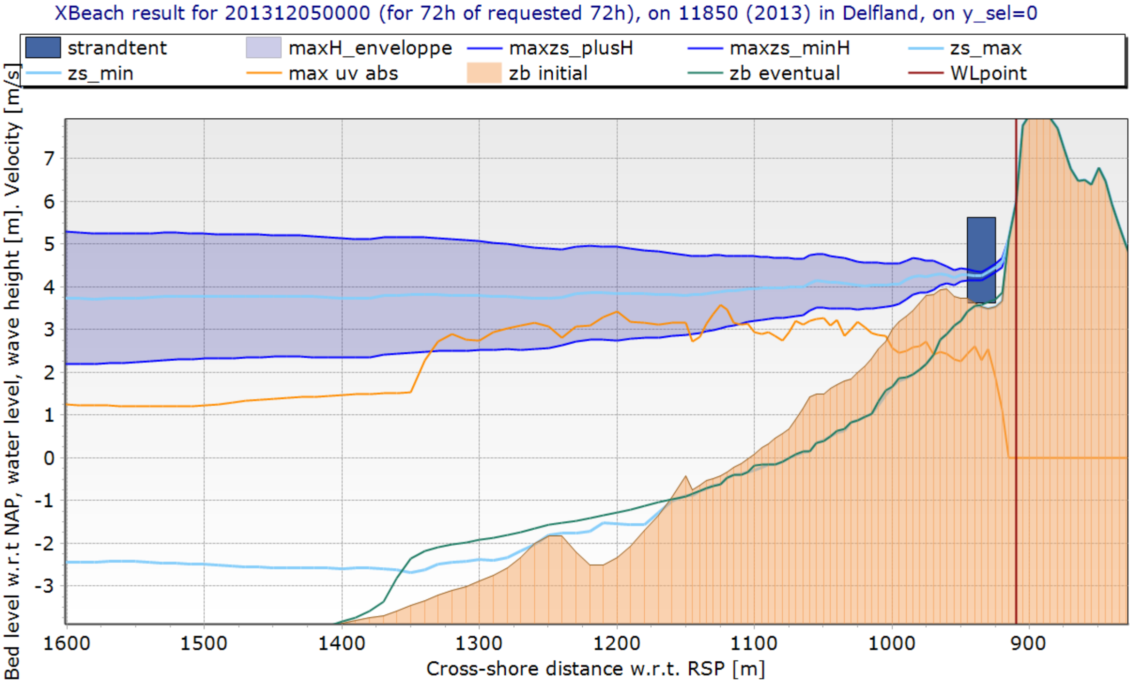


Figure 3.9: XBeach result with the minimum and maximum water levels during 72 hours (tides and set up, light blue lines, *zs*), the maximum wave heights on top of the maximum water level (dark blue lines and area, *maxzs_H*), the maximum absolute velocities (orange, *max uv abs*), the initial bed level (sand colored area, *zb initial*), the bed level at the end of the run (dark green, *zb eventual*, the GUI also provides the bed levels trough time), the most landward water set up line (dark red, *WLpoint*) and buildings (dark blue square, in this example beach pavilion 'T Puntje, *strandtent*)

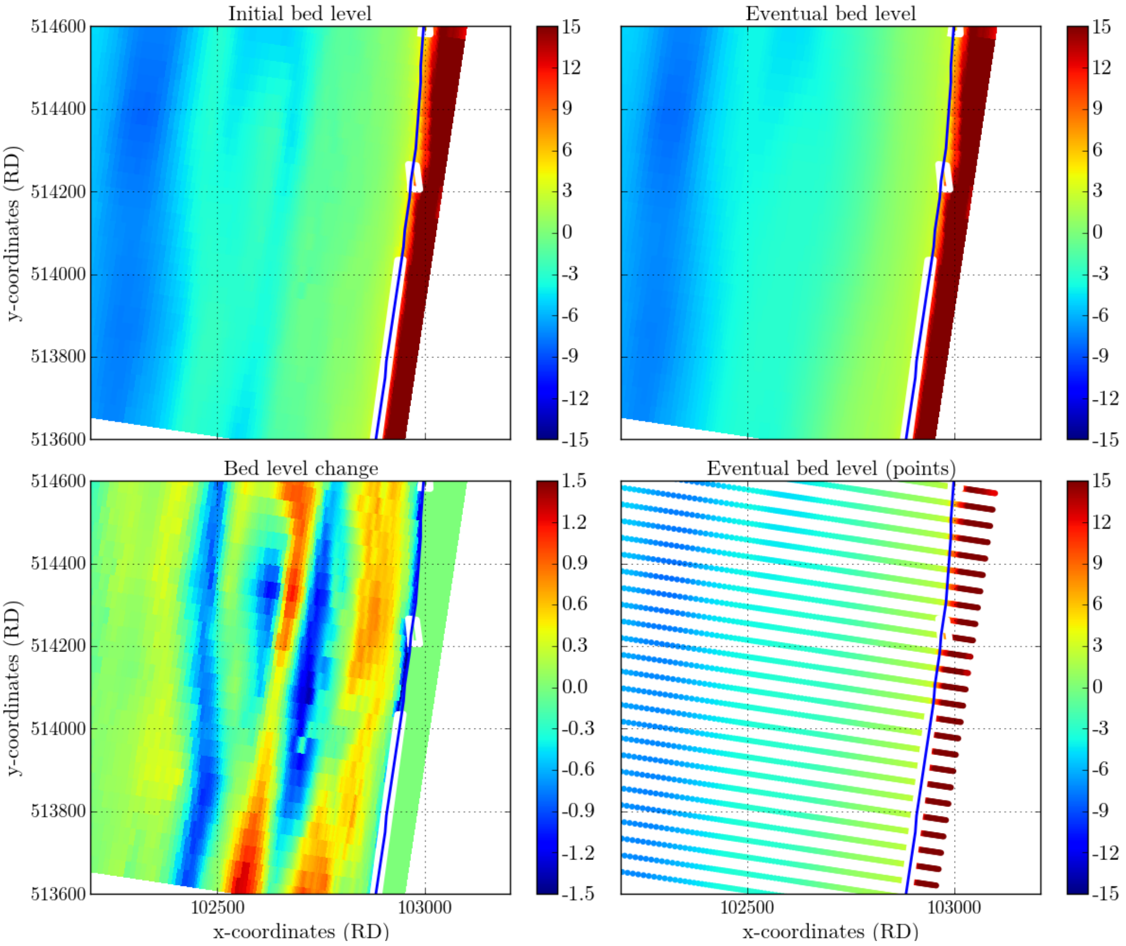


Figure 3.10: 2D XBeach output visualization (⋆): bed levels, maximum water line (blue) and buildings (white). **(upper left)** shows the initial bed level with bars and troughs (summer profile) and **(upper right)** shows the bed level after a 48 hour storm (winter profile), where the bar trough system has partly vanished. **(lower left)** shows the bed level change with erosion of the bars and sedimentation in the troughs. **(lower right)** shows the 'transects' of the model grid, which can be visualized in the cross-shore view (⋆).

Plotting the results of the 2D XBeach run is not yet implemented in MorphAn (⋆). A potential visualization is depicted in Figure 3.10. It shows the bed level (change), buildings and the maximum water line. The water line as well as the dune erosion reaches some of the buildings. Furthermore, current velocities, wave heights and water levels can be visualized. Since the output is available on several time steps, the progress of all output can also be visualized trough time (⋆). The 'transects' depicted in the figure can also be visualized in a cross-shore view like Figure 3.9 (⋆).

3.5 Current prototype method

Most of the functionalities from the storm impact application are operational in the current GUI. The project tree view is not yet implemented and is substituted by a ribbon with shortcut buttons. This ribbon appears when running the main script and is shown in Figure 3.11. Because the shortcuts execute parts of this script, the user does not have to use or even look at the script any further. Each part of the script that is executed when clicking the different shortcut buttons is described in Table 3.2. Several checks are built in to give feedback to the user about for instance unavailable RWsOS data or forgotten input. This prevents the storm impact application prototype from crashing when mistakes are made.

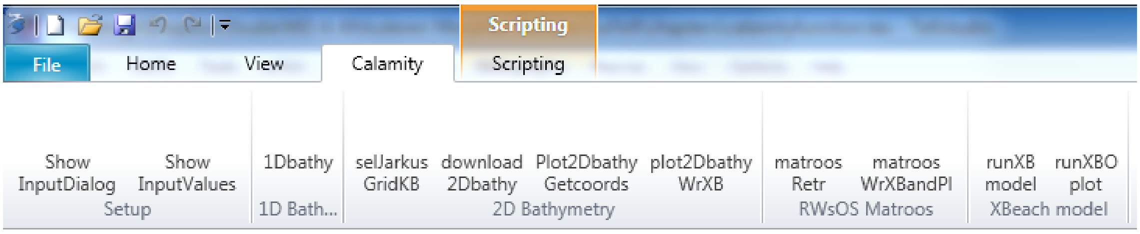


Figure 3.11: Storm impact application shortcut buttons in the MorphAn ribbon. The buttons are divided into four groups.

Table 3.2: Ribbon shortcut functions

Shortcut	**Function description**
ShowInputDialog	Display an input dialog which writes the users input to local variables. Besides the parameters from Chapter 3.2.1, also the bathymetry source and an optional list of JARKUS transects that should be analyzed can be provided.
ShowInputValues	Display the input values in a pop-up screen.
1Dbathy	Get selected JARKUS transect data from MorphAn and write to XBeach input files. If MorphAn transects are used, a workspace with transect data must be added first, for which the MorphAn manual provides instructions (Deltares, 2015a). This also enables the user to see for which transects data is available in a certain year.
selJARKUSGridKB	JARKUS grids can be selected from a map (Figure 3.4a), enter is pressed to confirm the selection.
download2Dbathy	The selected JARKUS grid files are downloaded from the Deltares OPeNDAP server.
Plot2DbathyGetcoords	A line can be drawn that serves as the baseline for an XBeach grid (Figure 3.4b).
plot2DbathyWrXB	A grid is created with the baseline coordinates (Figure 3.6) and the coordinates and the interpolated bathymetry values of the grid points are written to XBeach input files.
matroosRetr	RWsOS data from the seaward corner of the XBeach grid or transect is retrieved form the Deltares or Rijkswaterstaat server and stored in files.
matroosWrXBandPl	The RWsOS data is plotted in a chart (Figure 3.8) and written to XBeach input files.
runXBmodel	The XBeach model runs in a command window which shows the progress.
runXBOplot	A cross-sectional view of the 1D or 2D XBeach model output is displayed in a chart, together with available building data for the 1D XBeach model output.

Chapter 4

Quality of the storm impact application

This chapter evaluates the quality of the storm impact application, by evaluating five of the evaluation criteria.

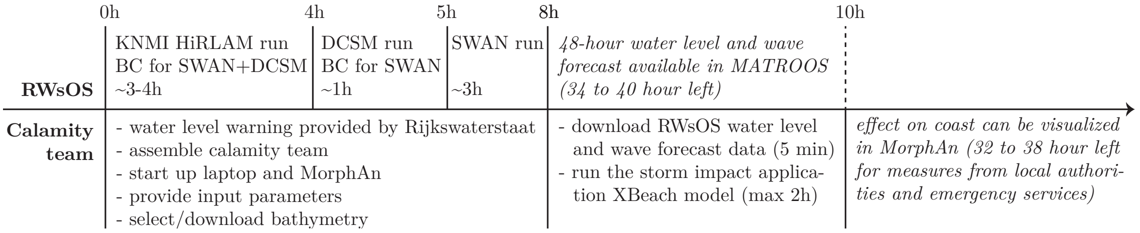
4.1 Speed

A storm impact application is only useful if it is fast enough to provide timely access to relevant information, on a general laptop of a coastal manager. In one of the conversations with dune managers, it was stated that a storm impact analysis should preferably be available within two hours. This is however a flexible limit, because more assessment details or a larger assessment area justify a longer model run time.

When storm surges are predicted by the RWsOS sytem, warnings are issued towards coastal authorities (De Kleermaeker et al., 2012; Ministerie van Infrastructuur en Milieu, 2015). The RWsOS system runs several hours and then provides a forecast of 48 hours. This 48 hour forecast is due to the forecast period of the HiRLAM model and the six hours between forecasts also originates from HiRLAM. The RWsOS steps as well as the calamity team and MorphAn storm impact application steps are depicted in Figure 4.1.

The two hour limit applies to the MorphAn sub-steps and is the time between providing input in MorphAn and being able to provide a useful result to managers. Of this two hours, not much time is required from the user, because all steps in the storm impact application of MorphAn are single click actions after which MorphAn does the work. Therefore, the two hours can mainly consist of MorphAn storm impact application runtime. The steps before running the model as well as the visualization after running the model can be completed by the user in several minutes.

Retrieving RWsOS Matroos data from the server approximately takes 5-30 seconds per transect. This can take quite some time when assessing multiple transects, because it is retrieved for each of



	0h	4h	5h	8h	10h
RWsOS	KNMI HiRLAM run BC for SWAN+DCSM ~3-4h	DCSM run BC for SWAN ~1h	SWAN run ~3h	*48-hour water level and wave forecast available in MATROOS (34 to 40 hour left)*	
Calamity team	- water level warning provided by Rijkswaterstaat - assemble calamity team - start up laptop and MorphAn - provide input parameters - select/download bathymetry			- download RWsOS water level and wave forecast data (5 min) - run the storm impact application XBeach model (max 2h)	*effect on coast can be visualized in MorphAn (32 to 38 hour left for measures from local authorities and emergency services)*

Figure 4.1: Timeline of RWsOS and calamity team. The RWsOS timeline starts every six hours, the calamity team timeline starts when necessary.

them. When using a 2D model, only RWsOS data is retrieved at the red baseline of the grid. The data is retrieved on the most seaward grid point of the model domain, for a depth of NAP -20m.

The 1D version of the storm impact application contains an XBeach model with one point in longshore y-direction (the number of grid cells in y-direction is ny=0). The runtime of such a model is approximately 1.5 minutes per transect for a 48 hour storm. This can take quite some time when assessing multiple transects, but a regular laptop with four cores is able to run four of these XBeach models parallel, which significantly reduces the total calculation time. When running more than four models at the same time, the calculation time will increase. When retrieving the RWsOS data and running the XBeach model takes 2 minutes per transect, and four cores are available, it is possible to assess 240 transects in the available two hours, with only one laptop. The Delfland water authority approximately has 270 transects, so most of them can be assessed on one laptop within the available time.

A 2D model with 5 wavebins, 50 gridcells in y-direction (ny=50) and a storm duration of 48 hours takes approximately 1.5 hours to run, ny=200 takes approximately 5 hours. An ny of 50 and a dy of 5 to 100 meter limits the size of the study area to 250 to 5000 meters.

Simple optimizations can be used, like using multiple laptops to analyze multiple 2D areas of ny=50 or multiple sets of 1D transects. Another optimization could be to use the 1D mode to make a quick assessment and a 2D run can be carried out in more complicated or risky areas indicated by the 1D analysis. Somewhat more complicated optimizations will be discussed in Chapter 8.3.

Criterion conclusion It is possible to run a 1D as well as a 2D model within the two hour limit and for a significant amount of transects or a significant area. The criterion *Speed* is therefore satisfied.

4.2 Relevance

The storm impact application can be used to assess whether dunes will overwash or breach during a storm. Even if the current storm will not cause overwash of the dunes, the storm impact application can be used to assess the erosion and other indicators. Furthermore, the function can be used to compare field measurements during the storm with the predictions from the model. All these usages provide a possibility to take necessary measures to prepare and mitigate in time.

To assess if and to motivate why the storm impact application and its indicators are relevant, they were evaluated by approximately ten coastal managers from the water authorities Scheldestromen, Fryslân, Noorderkwartier and Rijnland as well as Rijkswaterstaat. They were shown a preliminary version of the storm impact application during a presentation on 25 November 2015 where they filled in a short evaluation form. They were given notice that the product shown was only a prototype and that a GUI still needed to be developed. The prototype only worked for 1D analysis, 2D functionality was not yet implemented. The participants were asked three questions for which answers are summarized here.

Do you see potential (in general and for your organization) in a storm impact application in MorphAn and why?

All participants saw the potential of the storm impact application. The Scheldestromen and Fryslan water authority found the function more useful for a safety region (veiligheidsregio), because they are of the opinion that this is the designated party for public safety. Previous conversations with the Delfland water authority however indicated that the water authority is also asked for input during storm calamity situations. The Rijnland and Noorderkwartier water authority and Rijkswaterstaat agreed with the latter. Indicators providing information about beach accessibility, operational dune damage prediction and risks for buildings were highly valued by the Rijnland water authority. The Noorder Kwartier water authority mentioned that explanation towards citizens and clarification during storms and more understanding of and knowledge development about the effects of storms are important advantages of the storm impact application. The Scheldestromen water authority valued the fact that the storm impact application provides understanding in the public safety on the beach and in the dunes.

Is there, next to the currently provided information [list of indicators], other information that is desirable during a calamity?

The indicators that are currently implemented in the storm impact application are depicted in Table 3.1 in Chapter 3.4. Most of the participants agreed that the available indicators are sufficient. Some suggestions were outside of the direct scope of the storm impact application, like providing an evacuation decision. Such a decision can only be based on the output of the storm impact application. Making decisions should be up to the calamity team and decision makers, because they are better qualified than any application and these decisions have major consequences.

Other suggestions for instance to provide information about wind speeds and aeolian sand transport. Unfortunately, wind data is only available at the boundary (from the RWsOS MATROOS database), but this is not used as input for XBeach. Also, aeolian sand transport is not possible to model in XBeach, because it only calculates erosion of wet sand which is then transported through the water. It would be possible to couple other models or provide a wind speed relation to achieve this, but this is outside of the scope of the storm impact application.

Another suggestion was to couple the effect of a previous storm to a next storm, by using updated bathymetry data. There are two options to achieve this. One could analyze every storm since the JARKUS measurements of that year and use the output as input of the next model run, which can be quite time consuming. Another option is to use more recent bathymetry from for instance Beach Wizard or cBathy. Using Beach Wizard data is implemented in the current storm impact application. However, Beach Wizard is not operational anymore, so only historic data from 2011 can be used at the moment.

It was concluded that there were enough relevant indicators for now and that the focus should be on developing a GUI to make the storm impact application accessible for water authorities.

Do you have more suggestions for the storm impact application?

The Rijnland water authority suggested to validate the morphological calculations in the storm impact application and to show the prediction skill with examples like the storm of 1953 or the Sinterklaasstorm of 2013. Analysis of uncertainties of different bathymetry sources, RWsOS data and the XBeach model will be done in Chapter 5.1 and the effects of some of these uncertainties are evaluated in Chapter 5.2.

It was also mentioned to ask the same questions to safety regions, or to make an standalone version for them. Because MorphAn is freely available, the user only needs login credentials for the RWsOS MATROOS data that can be requested at Rijkswaterstaat. However, the output of the storm impact application should be interpreted by someone with experience in dune erosion, so a well based decision can be made. Therefore it might be better that the water authorities interpret the results and provide their conclusions and insight to the safety region.

Criterion conclusion The *Relevance* of the information provided by the storm impact application is sufficient, although building vizualization must still be implemented. There are several possible extensions, but these do not have priority.

4.3 Understanding

The result of this study is an operational prototype of a storm impact application. For this prototype to be further developed, the potential users must see the use of the storm impact application and the (prototype) of the storm impact application must provide a GUI so it will be easy to use without seeing the script. Furthermore, there must be a limited failure chance with sufficient feedback from MorphAn to the user when something goes wrong. Chapter 3 can be used as a basic manual to use the storm impact application.

It is important that all output of the storm impact application is clear for technical users and decision makers. The technical user should be provided with sufficient information to be able to trust the model to use for advise towards other people. The information that will be provided is for example all the data from RWsOS, and all the output from the XBeach model. The technical user is able to motivate why the storm impact application is trustworthy, based on this information and his knowledge. The managers, decision makers or safety region can be provided with only the necessary information. This is for example only the water level of the RWsOS database, and filtered output of the XBeach model. These people can trust the storm impact application based on the motivation of the technical user.

The storm impact application was tested by three experts from Deltares and Delfland in March 2016. The installation instructions in Appendix D were sufficient to be able to install all prerequisites. The temporary GUI was found to be somewhat unclear because of the limited overview it provides. Nevertheless, due to the feedback and errors provided by the storm impact application as well as the manual from Chapter 3, the experts succeeded to use the application and analyze transects and areas.

The *Understanding* of the results provided by the storm impact application was found to be insufficient during the testing period, but the provided feedback was processed in the latest version of the storm impact application and this report.

Criterion conclusion The criterion *Understanding* is currently insufficient because of the simple temporary GUI that is implemented. Working with the storm impact application in its current prototype version was found feasible, although a lot of improvement is possible. It is expected that implementing the GUI design from Chapter 3 will contribute to *Understanding*. The *understanding* of the information provided by the storm impact application is currently sufficient.

4.4 Robustness

Because the storm impact application depends on real-time forecast data and recent bathymetry data, it is for instance required to have an internet connection and to have access to the RWsOS database of Rijkswaterstaat. All prerequisites were mentioned in Chapter 3. The robustness of the rest of the components is described here.

Many of the currently implemented bathymetry sources originate from the Deltares OPeNDAP server. This server is publicly accessible, but it can occasionally happen that the server is not available. Because MorphAn locally provides the 1D JARKUS transects, a 1D analysis is always possible. Furthermore, it is possible to download bathymetry files from the OPeNDAP server in advance, or use the files that were used in a previous assessment. For instance, the bathymetry download part of the storm impact application can be executed every week, or at least one time at the beginning of the storm season. This way, quite recent bathymetry is always available for a storm impact analysis.

The RWsOS MATROOS database is practically always available, because it is developed as a reliable forecasting system where the possibility of component failure is considered. The RWsOS hardware is redundant and therefore automatically switches to the backup hardware in case of a hardware failure. Also, the system is able to use several alternative sources for meteorological forcing if HiRLAM would be unavailable. (De Kleermaeker et al., 2012)

The XBeach model is locally available from within the MorphAn installation. This means that it is always available and accessible.

Criterion conclusion The criterion *Robustness* is satisfied, because the components are always available or there are alternatives. Nevertheless, an internet connection is always necessary in order to at least obtain the latest RWsOS forecasts and the storm impact application can therefore not run without it.

4.5 Evolvability

The storm impact application currently works for the entire Dutch coast as well as with several bathymetry sources. This section elaborates on possible extensions to other areas, which mainly depends on input availability.

All calculations are currently done in the RD coordinate system, because it is simple to work with rectangular grids and distances in meters. Because MorphAn is able to convert coordinate systems, bathymetry with any coordinate system can be visualized and used for calculations, as long as the source coordinate system is provided to MorphAn.

The RWsOS data comes from DCSM and ZUNO models and is therefore available for the Dutch continental shelf or the Southern North Sea. Nevertheless, other forecast systems can be used to provide time series of water levels and wave characteristics. If they provide the same output format as RWsOS, not much work is needed. If the output format is different, it is relatively easy to extend the storm impact application to this new input source by writing an extra conversion script.

With 2D bathymetry data, currently an irregular rectangular grid is constructed for the XBeach model. It includes extended areas to enable waves to travel to the area of interest without disturbance. In MorphAn, it is also possible to define curved grids for curved coastlines. Furthermore, it is possible to evaluate data from multiple bathymetry sources, which enables to combine JARKUS with vaklodingen and various topographic data sources.

MorphAn contains all the Dutch JARKUS transect data, boundary conditions and more specific Dutch data. The ambition of Deltares is to also deploy MorphAn abroad. In that case it is not desirable anymore to enclose all this kind of specific data sets, but online databases like the OpenEarth repository should be used from which the needed data is imported. This database contains data in a standardized format which is also used in MorphAn. This would also provide a chance to always have access to the latest data sets. Older MorphAn versions would automatically retrieve the most recent data of the relevant coastal section, for instance the water level and wave boundary conditions, grid topography data, or the JARKUS transect measurements.

Besides the possibility to implement the storm impact application in other countries, evolvability also implies for instance implementation of possible new developments, processes and possibilities for visualizations. Chapter 3 already provides GUI features that are not implemented yet, and Chapter 8.5 provides recommendations for further development of the storm impact application in MorphAn.

Criterion conclusion The application area of the storm impact application can expand abroad as well as provides the possibility for new functionalities to be added. Furthermore, the application has potential to become operationally implemented. Therefore, the criterion *Evolvability* is satisfied.

Chapter 5

Accuracy and performance of the storm impact application results

This chapter evaluates the quality of the results of the storm impact application, by evaluating two of the evaluation criteria.

5.1 Accuracy

The storm impact application is designed to give an indication of the effects of a storm on the coastal area. Nevertheless, there will always be uncertainties in the results. With an approaching storm, it is important to give a sufficiently fast and reasonable result, not to provide an exact value. However, for the storm impact application to become operational, it is important to provide insight in the uncertainties of the bathymetry and RWsOS input data and the XBeach model. These uncertainties are derived from literature. Furthermore, a sensitivity analysis of the RWsOS uncertainties will be carried out in Chapter 5.2. The sensitivity analysis provides a confidence interval, based on which coastal managers can decide whether a prediction is sufficiently certain to base decisions on.

5.1.1 Uncertainties of the bathymetry data

Because of the different uncertainties belonging to the several different bathymetry sources, there will be an effect on the erosion volume. In case of storm calamities, it is better to make an overestimation of the erosion volume than to underestimate it.

JARKUS transect and grid bathymetry

The JARKUS transect data is collected once a year in the spring, so the bathymetry has changed when the storm season starts and certainly after some storms. According to Van Dongeren et al. (2008) and Cohen et al. (2009), the bathymetry strongly varies trough the year. This was validated by comparing Beach Wizard measurements throughout the year with JARKUS measurements. The transect volume on a certain elevation was compared. The selected transect part consisted of the distance between the dune foot and the mean low water line and a same distance below the mean low water line. There was strong correlation during the spring, which means that Beach Wizard performed well in estimating the bathymetry from cameras. However, these studies show that the winter profiles contain significantly less volume than the spring profiles. Working with JARKUS data therefore causes an overprediction of the available dune volume prior to a winter storm, which causes an overprediction of the dune safety.

There are two main methods for collecting JARKUS dry measurements. One is with a LIDAR plane, and the other is with a GPS device on a vehicle or a stick. According to De Graaf et al. (2003), LIDAR (laser altimetrie) measurement errors have an standard deviation of 10 to 15 cm and the GPS measurements have an uncertainty of 5 to 10 cm. These uncertainties slightly increase because these are point measurements that are interpolated to a transect of points with a distance of 10 meter offshore and 5 meter near the shore, on the beach and in the dunes.

The grid data are interpolated between the JARKUS transects that have an interval of 125 to 250 meters. This interpolation model error results in a vertical uncertainty of 10 to 60 cm (De Graaf et al., 2003). Furthermore, the grid resolution of 20 meters causes a lot of the JARKUS transect precision to be lost. The uncertainty could be decreased if the collected LIDAR data is provided directly as a JARKUS grid.

Real-time bathymetry

The accuracy of Beach Wizard data is described by Van Dongeren and Cohen (2006) and has an average vertical RMS error of 0.6 meter. This error varies both over time and over the distance from the shore and is higher in bar troughs as well as at the shoreline and lower at the bar tops. Nevertheless, the error of 0.6 meter gives a good indication of the error over the entire domain. Furthermore, as already mentioned in Chapter 2.2, the Beach Wizard data does provide a better estimation of the winter profile in comparison to JARKUS data (Cohen et al., 2009).

The cBathy data is not implemented in MorphAn during this study, because it does not contain beach and dune data. However, it could still provide a valuable data source if combined with other bathymetry data. cBathy has an RMSE of 0.36m (Sembiring, 2015), which is more accurate than Beach Wizard.

5.1.2 Uncertainties of the RWsOS water level and wave data

Water level from DCSMv6

Harley et al. (2015) show an Italian case study with a newly developed early warning system. A hindcast with a recent extreme event showed that the serious underestimation of the predicted hazard levels were mainly due to a significant underestimation of the extreme water levels. Although this is a low-lying location where a higher water level has a lot of influence, this risk occurs everywhere where the combination of storm surges and waves approach the dune crest and are on the verge of overtopping.

According to Zijl et al. (2013), the Root Mean Square Error (RMSE) of the DCSMv6 storm surge water levels for a single storm along the Dutch coast are 15 cm. Because this RMSE is of a single storm, it is not the best indication of the uncertainty of the DCSMv6 water levels. More recently, a study was conducted to decrease this uncertainty. The RMSE for a lead time of six hours at Hoek van Holland was decreased from 7.2 to 3.5 cm for normal conditions and from 29 to 9 cm for storm conditions (Zijl et al., 2015). This is only for one location and for a short lead time, longer lead times result in different RMSE values. The RMSE along the entire Dutch coast has not been studied since this improvement to the DCSMv6 model, so the RMSE of 15cm from Zijl et al. (2013) will be used in the sensitivity analysis.

Wave height and period from SWAN

The operational SWAN models from RWsOS that are used to derive wave characteristics were validated by Gautier and Caires (2015). Because the SWAN model is mainly used for port operations and shipping, the focus was not only on the prediction skills for H_{m0} and $T_m^{-1.0}$. Waves of lower frequencies between 0.03Hz and 0.10Hz (H_{E10}) were also assessed, which correspond to wave heights of 0.5 to 1.5 meters. The H_{E10} wave heights are not used in the JONSWAP spectrum in XBeach, so they are not taken into account here. This study was supplemented by additional research, which resulted in the final settings for the operational SWAN model (Gautier, 2015). The settings were optimized based on six locations with both calm conditions and four storms with significant wave heights up to 8 meter. The current settings of the operational SWAN model result in a relative bias of +4% (+0.08m) and a scatter index of 16% for H_{m0}. This causes overprediction of the wave heights and thus a conservative estimation of the dune erosion. $T_m^{-1.0}$ has a relative bias of -12% (-0.75 seconds) and a scatter index of 9%, which results in an underprediction of the wave period and thus an underestimation of the dune erosion.

Wave angle from SWAN

No studies were found that provided the accuracy of the prediction of the wave direction of the SWAN model. There are specific studies about for instance wave propagation in the Wadden Sea, but these are not general enough to provide uncertainty values. Therefore, tests will be carried out with plus and minus 15°and 30°.

5.1.3 Uncertainties due to the XBeach model

Harley et al. (2015) shows that it is important to use an XBeach model that is calibrated for the study area. The storm impact application uses the XBeach default settings that are derives based on a series of tests for the Holland coasts Deltares (2015c). This implies that the XBeach model is sufficiently calibrated to be operational in the storm impact application and these settings will therefore not be elaborated on. These 'WTI settings' are however depicted in the XBeach input file (Appendix C).

Changing the values for θ_{min}, θ_{max}, $d\theta$ and the resulting number of wave bins influences the runtime of the XBeach model. The values for θ_{min} and θ_{max} of 50 °capture most of the waves towards the shore and the wavebin size $d\theta$ is not higher than recommended. Also, the morphological factor (morfac=10) is valid for situations where there is no overwash or breach. These settings are such that it can be assumed that the predictions of the XBeach model are realistic and the model runtime is not too large. Therefore, there will be no sensitivity analysis carried out with different values for XBeach parameters.

Criterion conclusion The uncertainties in the bathymetry data were derived from literature and is 10cm for JARKUS transects, 60cm for JARUKUS grids and 36cm for cBathy. The uncertainties of the RWsOS input data were derived from literature. They consists of standard deviations, RMSE values and scatter index values. The wave direction was estimated because there was no literature available. The values that will be used in the sensitivity analysis are depicted in Table E.1. The XBeach uncertainties are not assessed because the calibration settings are expected to provide trustworthy results.

5.2 Performance: sensitivity analysis for the water level and wave uncertainties

The effect of the water level and wave uncertainties are assessed separately. The sensitivity of the erosion volume to these different uncertainties is compared to a base case. The comparison parameter is the total net volume change in the area of interest of the model domain, on grid cells where the initial bed level was higher then NAP +3m. This level approximately corresponds to the dune foot, and thus indicates the total net erosion from the sea defense.

The base case (Case 0) consist of an initial bed level near the city of Egmond, which is depicted in Figure 5.1. The water levels and wave characteristics that are used as boundary conditions for the base case are depicted in Figure 5.3. The maximum water level ranges to NAP +2.55 meter, the wave heights range from 1.57 to 5.20 meter, the wave period ranges from 4.96 to 8.87 seconds and the wave direction ranges from 250°to 317°with respect to the north. Gautier (2015) provided bias values of +4% for the wave height and -12% for the wave period, which were incorporated in all cases (except the base case) by dividing the wave heights and wave periods by 1.04 and 0.88

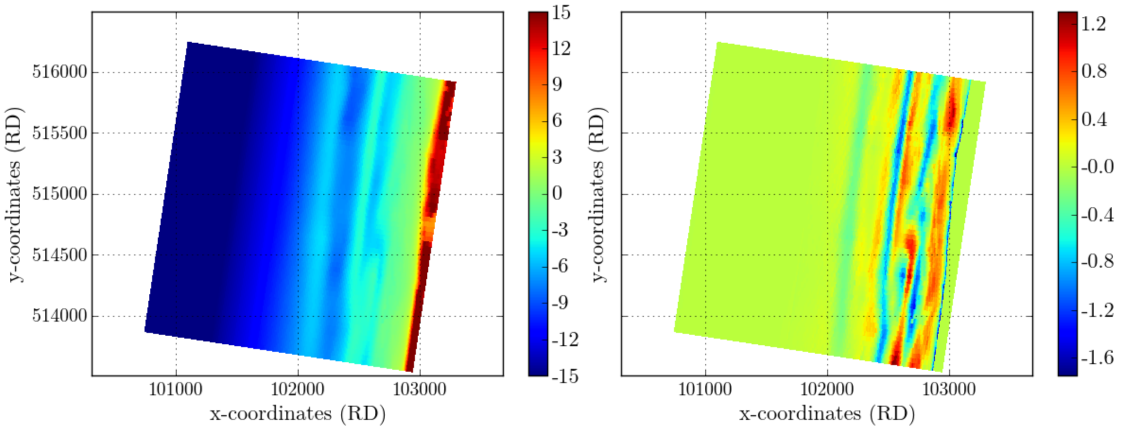


Figure 5.1: The left image shows the bathymetry of the area of interest of the model domain (the extended grid is omitted), the right image shows the bed level change for the base case.

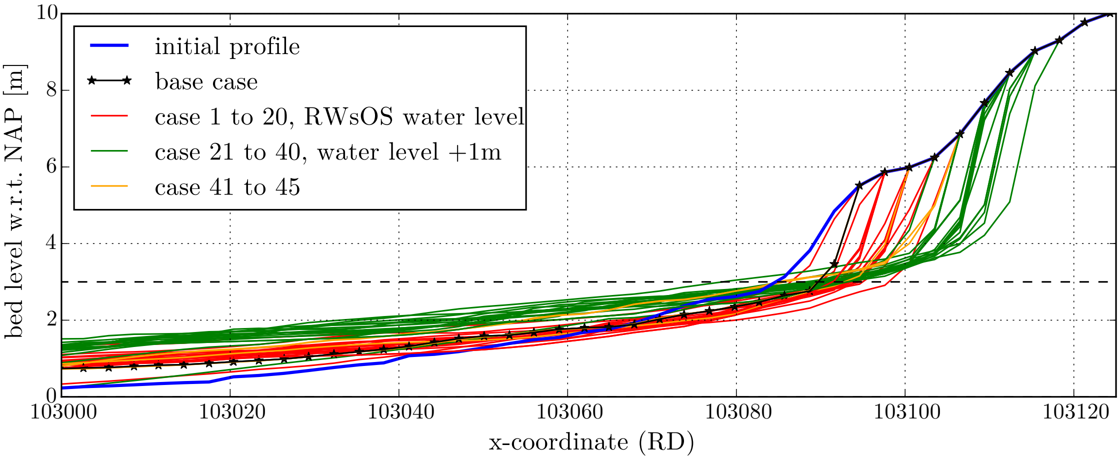


Figure 5.2: Initial (blue) and eventual (black, red, green, orange) bed levels for the different cases, and two reference lines on NAP and NAP +3m (dotted black).

respectively. In the cases other than the base case, the water level, wave height, wave period and wave direction were both decreased and increased with the values from Chapter 5.1.2. Furthermore, this analysis is repeated for a water level that is 1 meter higher (or a bathymetry that is 1 meter lower), to assess if the erosion volume sensitivity is stable. A side view of the initial and the eventual profile for all the cases is depicted in Figure 5.2. The relative sensitivities are depicted in Figure 5.4. An overview of all cases and their results are depicted in Table E.1, of which the right column corresponds to the values in Figure 5.4.

The sensitivity analysis results in Figure 5.4 show that a higher water level as well as a larger wave height and wave period result in more net erosion of the dune, which is expected. The analysis shows that the predicted erosion volume is quite sensitive to the RMSE of the waterlevel from Zijl et al. (2013). The erosion volume is less sensitive for the wave height scatter index, but very sensitive to the wave period scatter index from Gautier (2015). Furthermore, cases 41 to 45 in Appendix E show that the wave period bias of -12% from SWAN can have significant effects on the erosion volumes, while the wave height bias of +4% does not.

A positive change in the wave angle leads to less erosion in Figure 5.4. However, a decrease of the wave angle does not lead to more erosion. This can be explained by looking at the time series of the wave direction in Figure 5.3, where the wave direction varies from 250°to 317°. The dominant wave direction is around 310°with respect to the north, especially when looking at the period with high water levels. These waves are already very oblique with respect to the coastline that has a rotation of 8.4°with respect to the north (Figure 5.1). If the wave direction increases with 15°or 30°, the waves are even more oblique. This probably causes that they are not all captured by the extended model grid as well as a part of the waves not reaching the coastline and leaving the domain

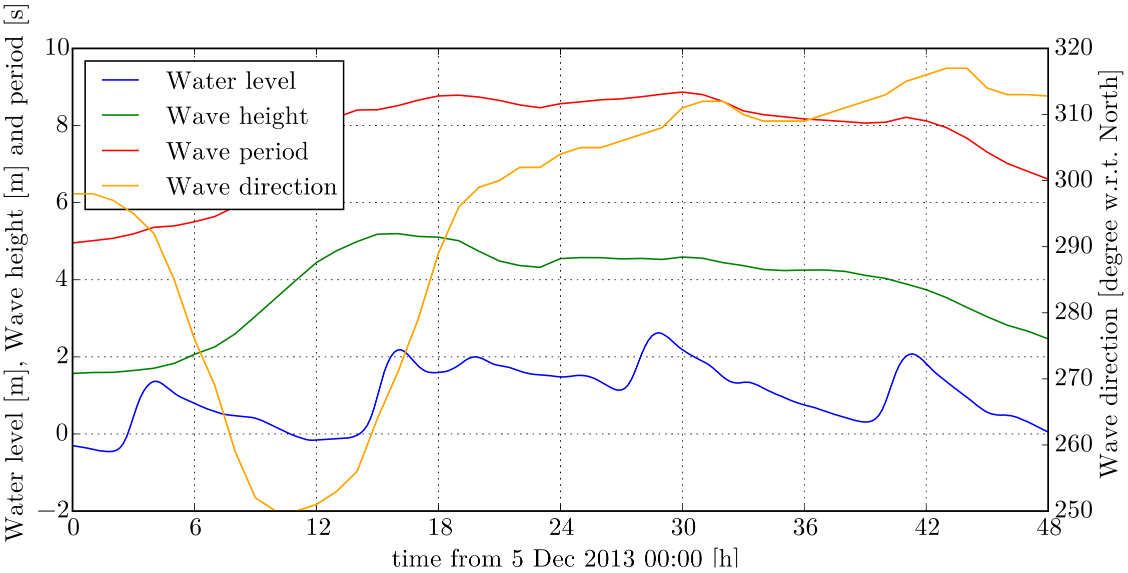


Figure 5.3: The water level, wave height (H_{m0}), wave period (T_p) and wave direction (T_{h0}) for the Sinterklaasstorm of 5 December 2013. The wave period (T_p) depicted here is 110% of the RWsOS wave period ($T_m^{-1.0}$).

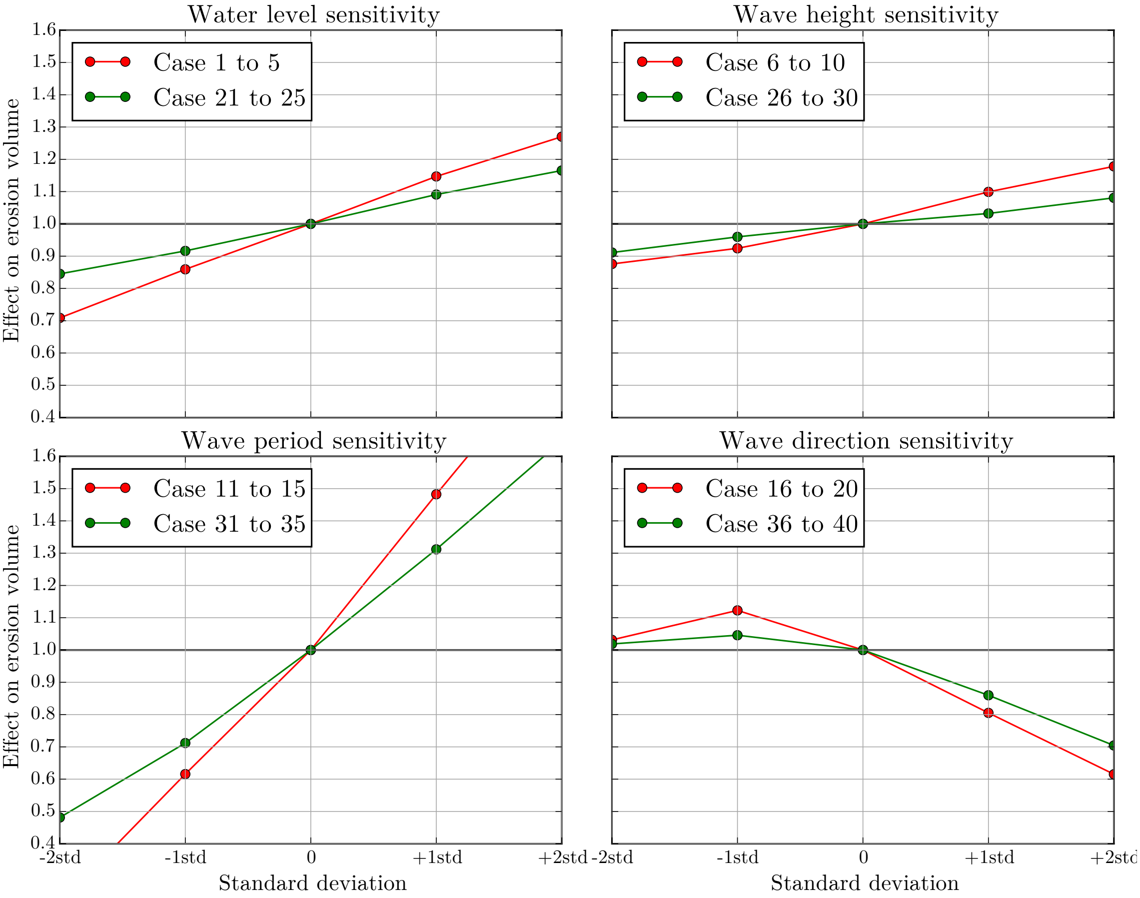


Figure 5.4: Sensitivity results of case 1 to 40. The cases numbers correspond to the numbers Table E.1. The cases with the RWsOS water level (case 1 to 20) are depicted in red and the cases with +1m water level (case 21 to 40) are depicted in green, corresponding with the colors from Figure 5.2.

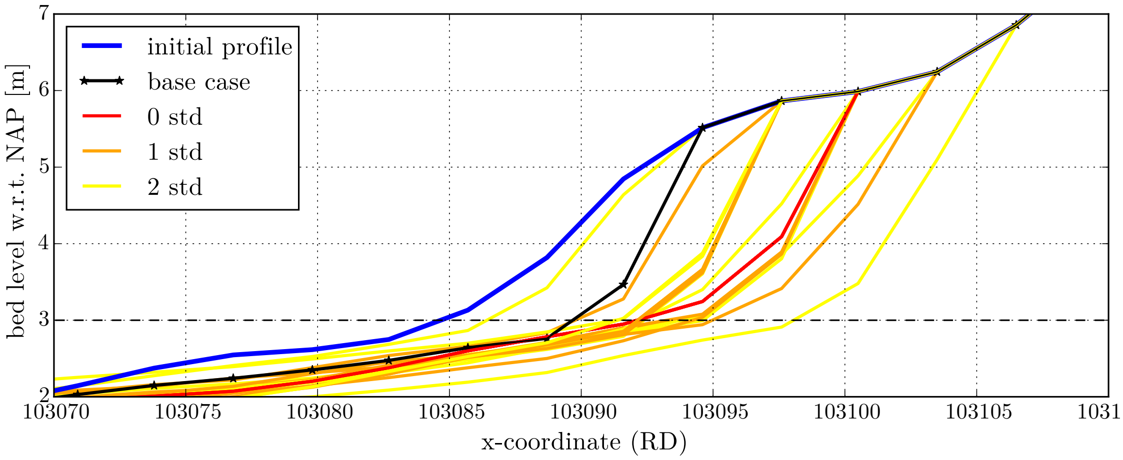


Figure 5.5: Initial (blue) and eventual (red, orange, yellow) bed levels for cases 1 to 20, grouped by their standard deviations (std) from the sensitivity analysis.

through the other side boundary. Less waves reaching the coastline cause less erosion. When the wave direction decreases to 295°or 280°, the waves become less oblique. The sensitivity result shows that this does not significantly influences the erosion volume. The sensitivity for the wave direction is significant where the waves are expected to not reach the coastline and insignificant where they do reach the coastline.

Finally, all cases show the same sensitivity trends when the water level increases with 1 meter (the green lines in Figure 5.4), but the sensitivity does decrease everywhere. This means that there is no general conclusion possible about the relative amount of increase of the erosion volume, when the water level and wave characteristics change. Furthermore, it also shows that the sensitivity partly depends on the bathymetry of the area.

5.2.1 Performance conclusion

It is dangerous to derive generic conclusions from these sensitivity results. It seems that the erosion volume is the most sensitive for a change in the wave period, but this is probably largely due to the large uncertainty of the wave period (a bias of -12% and a scatter index of 9%). Furthermore, RMSE values of the water level are compared to scatter index values for the wave height and wave period as well as with a assumed deviation of the wave direction which is not based on literature. Differences in the statistical parameters of the different RWsOS time series make generic conclusions about the most important RWsOS uncertainty impossible.

Criterion conclusion However, the sensitivity analysis is still useful. In operational practice and in terms of erosion volumes, it important to provide a confidence interval of for instance the dune retreat. Figure 5.5 shows the results of the different standard deviations of case 1 to 20. In the figure it is visible that even with two standard deviations, the confidence interval is 15 meters wide. Even when looking at cases 21 to 40 with a water level increase of 1m (which could also represent a serious global overestimation of the bed level), the confidence interval is also approximately 15 meters, and 25 meters with respect to the base case (Figure 5.2). This is expected to be small enough for operational practice, but it must be noted again that these values do depend on the bathymetry.

Chapter 6

Discussion

6.1 Speed

It is possible to acquire the results of the storm impact application within two hours. 1D transect analyses are always fast enough, even when assessing multiple transects at once. The limit is approximately 240 transects in two hours, on a single computer. Although it is possible to assess a sufficient amount of transects on a single computer in two hours, 25% of the runtime consists of RWsOS data retrieval. The amount of transects that can be analyzed can be larger if the retrieval time reduces, which contributes to operational use of the storm impact application.

With 2D model domains, the results are available within two hours if the number of cells in longshore direction is up to fifty, corresponding to a study area of roughly 250 to 5000 meters in longshore direction. The shadow zones are kept out of the area of interest by extending the model grid in both longshore directions. This extended grid is as coarse as possible, because the grid size increases towards the boundary of the grid. Nevertheless, this method results in more grid cells and therefore increases the computational time of the 2D model.

6.2 Relevance

A survey with water authorities and Rijkswaterstaat showed that the potential users saw the relevance of the storm impact application. Also, the information provided by the storm impact application is indeed considered sufficient. This survey was taken in an early stage, but information provided by the storm impact application has not changed since.

The 2D functionality was not yet implemented at the time of the survey, and its relevance was therefore not discussed. The 2D mode takes more time to run and currently does not provide much more information than the 1D mode because the plan view visualization is not implemented yet. Nevertheless, the 2D mode was received with great enthusiasm from the Delfland water authority. Oblique waves that enter the 1D model domain are converted into waves that travel perpendicular towards the coast with the Snell's law estimation. With this estimation, longshore transport is ignored and only cross shore transport remains. As already mentioned in Chapter 1.4, oblique waves can cause 30-50% more erosion because of this longshore transport (Den Heijer, 2013). One of the benefit of the 2D mode is the expected higher accuracy, because there is no Snell's law approximation used for wave refraction and all processes can evolve in a 2D domain.

Furthermore, the 2D mode provides the potential for an overview of all output in plan view, although this can also partly be acquired in a plan view of transects. The main benefit of the 2D mode is the possibility to assess (parts of) strongly curved coastlines like islands heads and coasts with non-uniform bathymetry.

6.3 Understanding

A GUI is provided in order to make it possible to use the storm impact application without using the scripts. This GUI provides input possibilities and gives feedback to the user if an error occurs. Because the GUI is not yet fully implemented as it is designed in Chapter 3, there is a lot of improvement possible that would increase the understanding of the storm impact application. For this reason, the storm impact application is currently less user-friendly as it should be. Nevertheless, users are able to work with the application in its current prototype version.

The understanding of the information provided by the storm impact application is sufficient. The information can be visualized in several different levels of detail. The technical user is able to see all details and can provide simplified and clear information in order to inform others with only the necessary information.

6.4 Robustness

There are certain prerequisites for the storm impact application to work, like a MorphAn installation, RWsOS credentials and an internet connection. If all prerequisites are available, the storm impact application is very robust. There are several bathymetry sources available, of which one is part of the MorphAn installation. Furthermore, the RWsOS system is redundant and therefore expected to be always available. Also, the XBeach model is part of the storm impact application installation and therefore always available. However, the storm impact application is highly dependent on an internet connection. Without it, it is impossible to acquire real-time RWsOS data and therefore use the storm impact application.

6.5 Evolvability

The storm impact application works for the entire Dutch coast. However, strongly curved coastlines of for instance island heads can currently not be assessed in a single 2D model. This is because there would be water at the 'landward boundary', which does not match the landward boundary condition water level of NAP -5m.

The storm impact application is operational with several bathymetry sources and for the entire Dutch coast. Other bathymetry sources can be built in and other water and wave forecast data could be used if it is in a comparable format, which also makes it possible to apply the storm impact application in other countries with sandy coasts.

The evolvability of the storm impact application prototype towards a widely used operational application now depends on the potential users. The Delfland water authority will use the prototype for demonstrations, but GUI improvements would contribute to acceptance among users. According to Delfland, understanding and demonstrations of the prototype will result in people working with the prototype and demand for further development will emerge naturally. This would in its turn contribute to further development of the storm impact application.

6.6 Accuracy

The used wave period in the storm impact application (T_p) is 110% of the RWsOS wave period ($\mathrm{T}_m^{-1.0}$). This conversion is valid for not too shallow water and single peaked wave spectra (Van der Meer, 2002). The data is retrieved for deep water, but it cannot be guaranteed that there are only single peaked wave spectra during storms.

The bias values for the wave height (+4%) and for the wave period (-12%) are not yet incorporated in the storm impact application, because they are expected to decrease in the future and are partly corrected by Rijkswaterstaat. Nevertheless, the bias values cause inaccuracies in the RWsOS input data and therefore affect the results of the storm impact application.

The RWsOS data is retrieved on a fictional NAP -20m coordinate, determined by extending the bathymetry data to NAP -20m with a constant slope of 1:50. This slope is higher than in reality, which minimizes the amount of grid cells. This approximation is fine for the XBeach result, but it causes the RWsOS data to be retrieved on a location that is not NAP -20m in reality, so this data might deviate from reality.

6.7 Performance

Even with the extended model grid that causes most of the waves to not cast a shadow zone in the area of interest, very oblique waves may still not reach the coastline of this area. This would be waves that travel with a direction near or more than 50°from a line perpendicular to the coastline. This might explain the decreasing erosion volume in the wave direction sensitivity analysis in Figure 5.4.

The current XBeach implementation makes the storm impact application not suitable to assess a dune breach and the flooding of the hinterland or the amount of overwash or overtopping. This is due to the morphological factor of 10 and the surf beat mode. A lower morphological factor and the non-hydrostatic mode are needed to calculate these processes. Nevertheless, the surf beat mode can be used to assess whether overwash or overtopping occurs and if the grid size smaller than the scale of a potential breach, it can also be used to assess whether a dune will breach.

The sensitivity analysis implies that the component uncertainties that were assessed, where one or two times the standard deviation. This implies a normal distribution, which is probably true because they are uncertainties of natural occurring phenomena. However, the used uncertainty values were based on standard deviations as well as scatter index and RMSE values, which might not be comparable to each other directly. Therefore, the sensitivity analysis results cannot be used to derive generic conclusions about which of the RWsOS uncertainties has the most influence on the erosion volume. Furthermore, the uncertainties of the bathymetry is not assessed in the sensitivity analysis. In order to provide a complete indication of the performance of the storm impact application, a more thorough sensitivity analysis must be performed. This contributes to usage of the storm impact application in operational practice.

Chapter 7

Conclusions

7.1 RQ 1: What are necessary storm impact application components to acquire relevant storm impact information?

The effects of a storm are for instance dune erosion or breaching, damage of property, high current velocities near the shore and overtopping of dunes or structures. In order to provide insight in these effects, the relevant storm impact information for an approaching storm is the following:

- Bed levels change (erosion) during the storm
- Flow velocities
- Water level ranges over the entire cross-shore domain
- Wave heights over the entire cross-shore domain
- Water run-up on the shore
- Affected buildings

This information can be used to provide insight in the effect of a storm on the coast, as well as on buildings that are located there. In order to acquire this relevant storm impact information, three components are necessary in a storm impact application:

- Recent bathymetry data for the study area
- Real-time water level and wave data on the offshore boundary of the study area
- A hydrodynamic and morphological model that is suitable for nearshore predictions

For 2D analysis, there are several suitable bathymetry sources like JARKUS grids, Beach Wizard and cBathy. For 1D analysis, JARKUS transects are the most logical data source. The real-time water level and wave data from the operational RWsOS system are used, because this data is already available and provided by operational models that are constantly improved. Furthermore, using available data instead of generating it with a new model saves computational time. The DCSMv6 and SWAN models in RWsOS provide time series of water levels as well as wave heights, periods and directions. XBeach is the model that provides the hydrodynamic and morphological predictions of the approaching storm. It is used in surf beat mode, in which many processes that are relevant for storms are incorporated, but in which the model runtime is still sufficiently fast. XBeach is widely used, validated and continuously developed further for better performance.

7.2 RQ 2: How can the storm impact information be provided using a storm impact application in MorphAn?

Each of the components of the storm impact application already exists. Storm impact information is only provided if the components are combined in a way that they are easy to use. For this reason, the three components are combined in MorphAn, a program that is already used by water authorities and Rijkswaterstaat for dune assessment and other coastal related analyses.

The components are coupled in MorphAn with Python scripting, to make it possible to use a wide range of Delta Shell and MorphAn functions. A GUI is designed and partly implemented, thus a user can use the storm impact application without using the actual scripts. It has proven possible to couple forecast water data and recent bathymetry to an XBeach model and get an indication of the expected effects on the coasts. These effects can be combined with building data and can be used for decision making about for instance evacuation.

7.3 RQ 3: What is the quality of the storm impact application?

The quality of the storm impact application was assessed with the five criteria *Speed, Relevance, Understanding, Robustness* and *Evolvability.* These criteria were already separately discussed in Chapter 6. The criteria were all satisfied, although there is much improvement potential for the GUI. Improving the GUI contributes to the usage in practice, which is expected to contribute to further development and implementation of the storm impact application in operational practice.

7.4 RQ 4: What is the accuracy and performance of the storm impact application results?

The sensitivity analysis (*Performance*) compares erosion volumes of different uncertainties (*Accuracy*) of the RWsOS water levels, wave heights, wave period and wave directions. It is not possible to derive generic conclusions about which of the RWsOS uncertainties has the most influence on the erosion volume, and should therefore be improved if the storm impact application is used in operational practice. However, it can be concluded that the confidence interval size for dune retreat is approximately 15 meters. Decision makers can decide for each individual storm if the confidence interval of 15 meters is accurate enough.

7.5 Research objective

The research objective of this study was:

"Provide coastal managers with relevant, accurate and timely storm impact information for the coast, by developing, implementing and evaluating a prototype of a robust and operational storm impact application in MorphAn, based on real-time water level and wave forecast data as well as recent bathymetry."

The storm impact application can indeed be used to provide relevant, accurate and timely storm impact information for the coast. A prototype of a storm impact application was developed, implemented in MorphAn and evaluated. This application uses real-time water level and wave forecast data as well as recent bathymetry.

The storm impact application developed in this study is only useful if it will be used in practice. The evaluation of the seven criteria that were defined in this study provide a promising outlook for the application, although many improvements are possible for the GUI.

Chapter 8

Recommendations

8.1 Bathymetry

Structurally collect real-time bathymetry data Real-time bathymetry data like Beach Wizard, cBathy or radar data can provide a trustworthy bathymetry source to use in the storm impact application. However, it is necessary that such a data source system is maintained for the source to be constantly (in time) available and along the entire Dutch coast or on interest locations like coastal cities as well as risk locations like weak spots in the coastline (in space). Installing such a system requires less effort than collecting for instance JARKUS transect measurements, because it only consists of a set of cameras on a high building or pole, or a radar unit. Although measuring JARKUS transect data is more accurate, real-time bathymetry provides a better winter profile estimation than the JARKUS transects collected during the spring (Cohen et al., 2009). Once such real-time data collection system is installed on several locations, bathymetry can be provided on request or with a constant interval. This data can be automatically downloaded with the storm impact application.

Increase flexibility and accuracy by combining data sources If it will become possible to retrieve one bathymetry grid from combined data sources in MorphAn, cBathy may provide a good alternative for or supplement to the real-time Beach Wizard data. Furthermore, Vaklodingen, as well as lidar and AHN data may be a suitable data source to expand the available dataset in seaward and landward direction respectively. Combining data enables the usage of the most complete and most recent data sources. This contributes to more realistic results of the storm impact application.

Make assessment of strongly curved coastlines easier The storm impact application currently only works with bathymetry sources that have land at the landward boundary, due to the landward tidal boundary condition of NAP -5m. This means that entire island heads cannot be assessed with a single 2D model in the storm impact application. There are several possibilities to improve this. First of all, parts of the island head can be assessed separately, as long as there is land at the landward boundary of the grid. Another option is to develop a new grid that follows the curve of the coastline. Finally, a levee can be added to the part of the landward boundary that is actually land, which should be combined with real tidal signals for the 'landward' corners of the grid to replace the NAP -5m water level.

8.2 RWsOS

Increase the RWsOS retrieval speed Retrieving the RWsOS data takes up to 30 seconds and can cost a significant amount of time when assessing multiple transects. If the assessed transects are close to each other, the retrieved data does probably not differ much and it would be possible to decrease the needed time by retrieving RWsOS data of only one or some of the transects and use these for all transects. Another option is to use data from fixed points. Rijkswaterstaat is working on providing RWsOS data on fixed locations along the coast, with a spacing of several kilometers. These data is already retrieved from the models and therefore only has to be transfered to the storm impact application, which saves a significant amount of time. Currently, it is unclear if these data represents location with a bed level of NAP -20m. Another disadvantage is that all these data must first be retrieved from the models before it becomes available, so retrieving it directly as currently implemented in the storm impact application makes it possible to get the data directly when the DCSMv6 and SWAN models are finished.

Increase the RWsOS retrieval period Currently, the RWsOS forecast length is 48 hours. This is due to the forecast length of the HiRLAM model from KNMI. Increasing the HiRLAM forecast period provides a longer RWsOS forecast length, but with less certainty. This longer forecast length provides more time for actions of local authorities and emergency services.

Compensate for wave height and period biases The wave period is underestimated by the SWAN model and the wave height is overestimated. For some locations where measurements are available (buoys), these biases are corrected by Rijkswaterstaat. However, these corrections are not implemented in the entire model field, from which the RWsOS data used in the storm impact application is retrieved. Therefore, it is recommended to change the wave height and wave period values in the operational storm impact application with -4% and +12% respectively, these changes were already implemented in the sensitivity analysis. Furthermore, it is recommended to further decrease the inaccuracy of the different models and the bathymetry data in order to provide decrease the uncertainty of the storm impact application results.

Improve RWsOS retrieval coordinate A quite steep seaward slope of 1:50 is added to the bathymetry in order to provide a model boundary of NAP -20 meter. This slope is steeper than in reality and the real NAP -20m location lays further offshore. However, this location is used to retrieve the RWsOS data, which means that this data actually belongs to a location with more shallow water. This could be improved by first estimating a retrieval coordinate by using a real or more realistic slope and using this data for the seaward boundary of the model.

Improve tide processes in the model by retrieving RWsOS boundary conditions at two corners Currently, two boundary conditions are used in the XBeach model of the storm impact application. The RWsOS boundary conditions (water level and wave characteristic data) are retrieved on the most seaward coordinate of the user defined baseline (x_{ori}, y_{ori}). This boundary conditions is applied along the entire seaward boundary, while the landward boundary has a tide of NAP -5m, in order to represent a dry hinterland. XBeach also provides the option to provide four boundary conditions, one for each corner of the model domain. The boundary conditions are then interpolated along the border of the model domain. With this method, tide-induced longitudinal flow can be taken into account in the XBeach model at the seaward boundary. Although the effect on the sediment transport is not assessed in this study, it would provide a more realistic model set-up and is expected to predict this transport better. Furthermore, implementing boundary conditions on each corder omits the artificial landward boundary condition of NAP -5m. This artificial boundary condition will cause problems if the landward boundary does not entirely consist of land, for instance on strongly curved islands heads.

8.3 XBeach model

1D versus 2D modeling Oblique waves that enter the 1D model domain are converted into waves that travel perpendicular towards the coast with the Snell's law estimation, where longshore transport is ignored. Nevertheless, the 1D version of XBeach is calibrated to provide an accurate estimation along longshore perfectly uniform coasts. Non-uniform coastlines, with skewed troughs and bar systems, curved coastlines or an area like the Sand Engine, cannot be represented accurately by a 1D model. It is recommended to at least use the 2D model in these situations.

Increase 1D and 2D XBeach speed with computation power When assessing all transects of for instance the entire Dutch coasts or multiple small 2D XBeach models (ny=50), it is possible to use several laptops to still stay within the two hour limit for the calculation time. Calculations for the entire coast will most probable be carried out at the different coastal water authorities and are thus already divided over multiple computers. Furthermore, it is possible to increase the speed of a larger 2D XBeach model by using multiple cores of a single laptop. The model domain is then sliced in for instance four parts of several 'transects' and the parts are computed on a separate core while results are exchanged when necessary. Another option is to perform the calculations on external computational facilities, by sending the model and input to for instance the Amazon computing facility and retrieve the results when the analysis is finished. Because all the XBeach files of a single model are created in one folder, it is easy to collect these files and the XBeach model and send them to such a computational facility.

Increase 2D XBeach speed by replacing grid extensions with cyclic boundary conditions Currently, shadow zones that are the result of oblique waves are kept out of the area of interest by extending the grid in both longshore directions. This is somewhat more computationally expensive than only using the area of interest in the model domain. An alternative is to implement cyclic boundary conditions. This means that oblique waves that exit one boundary enter the other boundary. In order to keep the XBeach model stable with these cyclic boundary conditions, it is necessary to have the same bathymetry on both sides of the model domain. Futhermore, there must be some 'transects' with the same bathymetry at the sides of the model domain. This means that an interpolation function is needed that calculates the bathymetry of the side of the model domain, which can be devious to automate. It would result in somewhat less computational time, because it is expected that less grid extra cells are needed compared to the extended grid method.

Increase 2D XBeach speed by first retrieving RWsOS data and avoid remaining shadow zones Currently, the grid is extended in both longshore directions with a default angle of 50°in order to prevent shadow zones in the area of interest for most of the waves. However, it is still possible that some of the waves cast a shadow zone in the area of interest, if they are approaching at near or more than 50°with respect to a line perpendicular to the shore. These waves probably refract and end up in the area of interest after all, althoug the wave direction sensitivity result from Figure 5.4 does indicate wave energy loss for very oblique waves. Furthermore, storms that consist of waves from mainly cross shore directions still have wave bins up to 50°with respect to a line perpendicular to the shore which makes the calculation time larger than necessary. An optimization could be made by first retrieving the RWsOS data and use this to determine the necessary θ_{min} and θ_{max} values, as well as the angle with which the model grid is extended. Another useful improvement would be do visualize these shadow zones in MorphAn and enable the user to alter the values for θ_{min}, θ_{max} and the grid extension angle.

Increase 2D XBeach speed by enabling insight in preliminary results The output file of the XBeach model can already be used when the model is still running. It is possible to view the results of the XBeach model for the part of the storm duration that is already modeled. This would provide the user with an insight in the first hours of the storm before the complete model has finished.

Implement the possibility to use the non-hydrostatic XBeach model in case of possible overwash The current *XBeach surf beat* implementation is sufficient to accurately predict most hydrodynamic and morphological processes for storm conditions on sandy beaches. However, the current XBeach implementation makes the storm impact application unsuitable for overwash or overtopping amounts of dunes or modeling the effects of a dune breach. For overwash, the non-hydrostatic mode of XBeach is needed. For a dune breach to be simulated, the longshore grid size must be sufficiently small for the breach to occur. For both overwash and the effects of a dune breach, the morphological factor must be decreased to avoid overprediction of erosion. Implementing a non-hydrostatic XBeach model also requires smaller grid cells in cross shore direction and a smaller timestep, which increases the computational time significantly. Non-hydrostatic mode could also be used to model non sandy beaches as well as calm weather conditions, as depicted in Figure 2.6.

Allow more waves to enter the 2D model domain Currently, θ_{min} and θ_{max} for a 2D model are -50°and +50°respectively, with respect to a line perpendicular to the coastline. This is in order to keep the model runtime limited. Therefore, a certain amount of wave energy from very oblique waves cannot enter the model domain, which results in less wave energy and therefore less erosion at the coastline. XBeach provides warnings about the percentage of wave energy that was lost. In order to ensure prediction of realistic erosion volumes even when there are strongly oblique waves, the values for θ_{min} and θ_{max} should be increased. The θ_{min} and θ_{max} values for the 1D model are already -90°and +90°respectively, because they do not influence the 1D model runtime due to the single wave bin.

Implement some buildings as hard structures to assess the effect on the dune erosion The GUI design already incorporates buildings in plan views and side views. Visualizing buildings that will collapse with a storm is enough, for instance for beach pavillions. However, buildings like bunkers, hotels, sea dikes or boulevards are hard structures which will hopefully remain stable under storm conditions. These buildings will however affect the sediment transport around them (Raaben, 2015) and should therefore be implemented as non-erodible structures in XBeach.

8.4 Sensitivity of the model results

Assess the erosion volume sensitivity for bathymetry sources The erosion volume sensitivity was only assessed for water level and wave data uncertainties. By also assessing the sensitivity of a water level increase of 1m (case 21 to 40 of the sensitivity analysis), an indication was given about the change in sensitivity when the bed level decreased with 1m over the entire domain. However, in order to provide a complete overview of the sensitivity and a generic confidence interval for the dune retreat, the sensitivity for different bathymetry sources and their uncertainties should also be assessed. For instance, local uncertainties in rip channels, in troughs or on bars might have a large influence. It is also useful to compare the erosion volumes two identical and consecutive storms, where the output bed level of the first storm is the input bed level of the second. The JARKUS spring profile will be partly changed into a winter profile after the first storm, which makes the bed level response to the second (winter) storm more realistic.

Provide insight in the validity duration of the storm impact application results When a storm impact assessment is finished and output is provided, there is a new water level and wave characteristic forecast available within several hours, because they are published every six hours. The sensitivity analysis provides insight in the erosion volume sensitivity for the water level and wave characteristic accuracy, but it does not provide a threshold for the amount of change these forecasts can undergo before the storm impact result becomes invalid. It would be an improvement for operational practice if the observed changes in the water level and wave forecasts can be coupled to an increasing uncertainty value of the storm impact application result and to a threshold after which the storm impact application must be run again in order to provide new valid results.

Increase grain size sensitivity and implement this as variable input An important difference with the DUROS+ model that is currently used for dune assessment is the variability of the grain diameter along the Dutch coastline. Because XBeach is not sensitive to the grain diameter in contrast to DUROS+ (Brandenburg, 2010), it is not yet necessary to implement this variable into the XBeach model and thus the default of 200 µm is used. Currently, the grain diameter sensitivity is being improved by the XBeach developers, because sediment transport does depend on the grain diameter according to lab tests (Van Rijn, 1984). If this improvement is finished, a variable grain diameter can be implemented into the storm impact application to improve the model predictions. It should be noted that there are only slight variations of only tens of µm along the Dutch coast, which might not have a significant effect on the model predictions. Furthermore, this grain diameter also varies in cross shore direction and thus some caution is needed when using the already available values for the Dutch coast.

8.5 MorphAn and scripting

Further development of the storm impact application Chapter 3 provides the design of the storm impact application of which the starred ($\star$) items are not implemented yet, but should be implemented for a better user experience:

- project tree which provides all input and output in one overview, for which implementation in C# is probably necessary.
- shapefile with building data to be visualized in both plan views as side views, for 1D as well as 2D models.
- JARKUS transect selector which already exists in MorphAn, but is not yet coupled to the storm impact application.
- 1D analysis with 2D bathymetry, for which optional settings for $d\theta$, snells as well as a disabled exteded grid are necessary.
- map view output for 1D and 2D models, where clicking in the map would provide the RWsOS data and the storm impact application result of the transects or 2D model sideview on that location.

Improve scripting documentation It requires a lot of effort and personal assistance or input to implement advanced new functions in MorphAn via Python scripting, because there is a very wide range of possiblities with often no or limited documentation available. In order to make it easier to implement new functions in MorphAn, it is necessary to extend the documentation.

Bibliography

Baart, F., Van der Kaaij, T., Van Ormondt, M., Van Dongeren, A., Van Koningsveld, M., and Roelvink, J. A. (2009). Real-time forecasting of morphological storm impacts: a case study in the Netherlands. *Journal of Coastal Research*, (SI 56 (Proceedings of the 10th International Coastal Symposium)):1617–1621.

Baart, F., Van Ormondt, M., Van Thiel de Vries, J., and Van Koningsveld, M. (2015). Morphological impact of a storm can be predicted three days ahead. *Computers & Geosciences*, (December 2015).

Booij, N., Ris, R. C., and Holthuijsen, L. H. (1999). A third-generation wave model for coastal regions. 1. Model description and validation. *Journal of Geophysical Research*, 104(C4):7649–7666.

Brandenburg, P. (2010). Master Thesis: Scale dependency of dune erosion models, Performance assessment of the DUROS and XBeach model for various experiment scales.

Cohen, A., Van Dongeren, A., and Plant, N. (2009). Beach Wizard: application of a nearshore bathymetric data-assimilation model for Dutch coastal management. In *ICCE (International Conference of Coastal Engineering)*.

De Graaf, H. J. C., Oude Elberink, S. J., Bollweg, A. E., Brügelmann, R., and Richardson, L. R. A. (2003). Inwinning droge JARKUS profielen langs Nederlandse kust. Technical report, Rijkswaterstaat.

De Kleermaeker, S., Verlaan, M., and Kroos, J. (2012). A New Coastal Flood Forecasting System for the Netherlands. In *Proceedings of the presentations made during Hydro12*, pages 135–140, Rotterdam, The Netherlands. Hydrographic Society Benelux.

Deltares (2015a). MorphAn 1.2.3 User Manual. Technical report, Deltares.

Deltares (2015b). Practical application of XBeach non-hydrostatic model, where, why and how. Memo for TKI XBeach JIP by R. McCall.

Deltares (2015c). XBeach 1D - Probabilistic model: ADIS, settings, Model uncertainty and Graphical User Interface. Technical report, Deltares, Delft.

Deltares and Royal HaskoningDHV (2011). Rapport Duinwaterkeringen 2011: Hoofdrapport. Technical report, Deltares, Royal HaskoningDHV, Nijmegen.

Den Heijer, C. (2013). *The role of bathymetry, wave obliquity and coastal curvature in dune erosion prediction*. PhD thesis, TU Delft, Delft.

ENW (2007). Technisch Rapport Duinafslag (TRDA2006). Technical report, Expertise Netwerk Waterveiligheid (ENW).

Friedman, J., Stive, M., Reniers, A., Luijendijk, A., Hoekstra, R., Swinkels, C., and Radermacher, M. (2014). Development of an X-band Radar Depth Inversion Model at the Sand Motor.

Gautier, C. (2015). Deltares Memo: proposal for SWAN-North Sea settings release 2015.

Gautier, C. and Caires, S. (2015). Operational wave forecasts in the southern north sea. *36th IAHR World Congress 28th June - 3 July*, (1):2–5.

Haerens, P., Ciavola, P., Ferreira, Ó., van Dongeren, A., van Koningsveld, M., and Bolle, A. (2012). Online Operational Early Warning System Prototypes to Forecast Coastal Storm Impacts (CEWS). In Lynett, P. and Smith, J. M., editors, *Proceedings of 33rd Conference on Coastal Engineering 2012*, pages 1142–1149, Santander, Spain. International Conference on Coastal Engineering.

Harley, M. D., Valentini, A., Armaroli, C., Perini, L., Calabrese, L., and Ciavola, P. (2015). Can an early warning system help minimize the impacts of coastal storms? A case study of the 2012 Halloween storm, Northern Italy. *Natural Hazards and Earth System Sciences Discussions*, 3(5):3409–3448.

Hasselmann, K., Barnett, T. P., Bouws, E., Carlson, H., Cartwright, D. E., Enke, K., Ewing, J. A., Gienapp, H., Hasselmann, D. E., Kruseman, P., Meerburg, A., Muller, P., Olbers, D. J., Richter, K., Sell, W., and Walden, H. (1973). Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). *Ergnzungsheft zur Deutschen Hydrographischen Zeitschrift Reihe*, A(8):p.95.

Lodder, Q. and van Geer, P. F. C. (2012). MorphAn: A new software tool to assess sandy coasts. In *NCK-days 2012: Crossing borders in coastal research*, pages 161–164.

Ministerie van Infrastructuur en Milieu (2009). Waterwet (BWBR0025458, 29 January 2009).

Ministerie van Infrastructuur en Milieu (2015). Landelijk draaiboek hoogwater en overstromingen: Informatie-uitwisseling, afstemming over maatregelen en afstemming over pers- en publiekscommunicatie Datum.

MX Systems (2007). HIS-KUST PILOT2007: Technisch Ontwerp PILOT2007 HIS-KUST. Technical report, MX-Systems, Rijswijk.

Raaben, T. (2015). *Including the effect of Non-Water-retaining Objects in the probabilistic modelling of dune safety.* PhD thesis, University of Twente.

Roelvink, D., Van Dongeren, A., McCall, R., Hoonhout, B., Van Rooijen, A., van Geer, P., De Vet, L., Nederhoff, K., and Quataert, E. (2015). XBeach Technical Reference : Kingsday Release. Technical report, Deltares, Delft.

Sembiring, L., Van Dongeren, A., Winter, G., Van Ormondt, M., Briere, C., and Roelvink, D. (2014). Nearshore bathymetry from video and the application to rip current predictions for the Dutch Coast. *Journal of Coastal Research*, 70(APRIL):354–359.

Sembiring, L. E. (2015). *Rip Current Prediction System for Swimmer Safety: Towards operational forecasting using a process based model and nearshore bathymetry from video.* PhD thesis, Delft University of Technology, UNESCO-IHE Institute for Water Education, Delft.

TAW (1984). Leidraad duinafslag 1984. Technical report, Technische Adviescommissie voor de Waterkeringen (TAW), Den Haag.

Uunk, L., Wijnberg, K., and Morelissen, R. (2010). Automated mapping of the intertidal beach bathymetry from video images. *Coastal Engineering*, 57:461–469.

Van Aalst, J. W. (2016). Waterschappen Nederland 2016. www.imergis.nl.

Van der Meer, J. (2002). Technical report wave run-up and wave overtopping at dikes. Technical report, TAW (Technical Advisory Committee on Flood Defence), Delft.

Van Dongeren, A., Bolle, A., Vousdoukas, M., Plomaritis, T., Eftimove, P., Williams, J., Armaroli, C., Idier, D., Van Geer, P., Van Thield de Vries, J., Haerens, P., Taborda, R., Benavente, J., Trifonova, E., Ciavola, P., Balouin, Y., and Roelvink, D. (2009). Micore: Dune erosion and overwash model validation with data from nine European field sites. In *Proceedings of Coastal Dynamics 2009: Impacts of Human Activities on Dynamic Coastal Processes*, Tokyo, Japan.

Van Dongeren, A., Ciavola, P., Viavattene, C., De Kleermaeker, S., Martinez, G., Ferreira, O., Costa, C., and McCall, R. (2014). RISC-KIT: Resilience-Increasing Strategies for Coasts - toolKIT. *Journal of Coastal Research*, (66):366–371.

Van Dongeren, A. and Cohen, A. (2006). Beach Wizard: A data model assimilation method for nearshore bathymetry and coastal state indicator estimation (Z4293). Technical report, WL Delft Hydraulics, Delft.

Van Dongeren, A., Plant, N., Cohen, A., Roelvink, D., Haller, M. C., and Catalán, P. (2008). Beach Wizard: Nearshore bathymetry estimation through assimilation of model computations and remote observations. *Coastal Engineering*, 55(12):1016–1027.

Van Rijn, L. C. (1984). Sediment transport, part I: bed load transport. *Journal of hydraulic engineering*, 110(10):1431–1456.

Veenstra, J. (2015). Calamity analysis and response with MorphAn: Literature review.

Vousdoukas, M. V., Almeida, L. P., Ferreira, Ó., Taborda, R., and Silva, A. N. (2010). Coastal morphological monitoring using an automated video system at Praia de Faro (South Portugal). In *Jornadas de Engenharia Hidrográfica*, number 1, Lisbon.

Wiegman, N., Perluka, R., Oude Elberink, S., and Vogelzang, J. (2005). Vaklodingen: de inwintechnieken en hun combinaties. Vergelijking tussen verschillende inwintechnieken en de combinaties ervan. Technical report, Rijkswaterstaat.

Zijl, F., Sumihar, J., and Verlaan, M. (2015). Application of data assimilation for improved operational water level forecasting on the northwest European shelf and North Sea. *Ocean Dynamics*, 65(12):1699–1716.

Zijl, F., Verlaan, M., and Gerritsen, H. (2013). Improved water-level forecasting for the Northwest European Shelf and North Sea through direct modelling of tide, surge and non-linear interaction. *Ocean Dynamics*, 63(7):823–847.

Appendix A

Water authorities and regulations

A.1 Coastal water authorities in the Netherlands

The 23 water authorities are depicted in Figure A.1. Five of them are coastal water authorities with dune coasts, who join together as a coastal workgroup (Themagroep Kust) to share experiences. Starting in the north, the Fryslân water authority (2) contains the Frisian coast and the Wadden islands Vlieland, Terschelling, Ameland and Schiermonnikoog, although Rijkswaterstaat manages the dunes of the first three of these islands. The water authority Hollands Noorderkwartier (10) is located further southward. The coastline of this water authority consists of the Wadden island Texel a large part of the straight North-Holland dune coast. The South-Holland dune coast is managed by the water authorities Rijnland (11) and Delfland (12). South of Delfland, the Hollandse Delta water authority (15) is located, but it does not contain any dunes and is therefore no member of the coastal workgroup. The most southern water authority is Scheldestromen (16), which contains the Zeeland coast.

Figure A.1: Water authorities of the Netherlands (Van Aalst, 2016)

A.2 Dune safety regulations

Since 1996, regulations for these assessments were provided every five years by new versions of the VTV[1] and the HR[2], most recently in 2006. Currently, the assessment period has been increased to 12 years and water defenses that do not pass the assessment are included in the high water protection program. Together with the provided computational software, the VTV2006 and HR2006 form the WTI[3] for assessing flood defenses. The VTV describes the processes, procedures and definitions that are relevant for dunes. For the details of the technical failure assessment calculations, it refers to technical reports, in which the technical assessment calculations for dunes are explained.

The first technical report was LD1984[4] (TAW, 1984), which describes the dune safety model DUROS. It was supplemented by TRDA2006[5] (ENW, 2007), focusing mainly on new insights regarding dune erosion and presenting the updated DUROS+ model. The last large-scale national dune assessment in which all primary defenses were assessed was in 2006. New developments in assessment regulations have been going on and will be included in the WTI of 2017. In 2011, RD2011[6] was published, which focused on new insights regarding dune erosion (Deltares and Royal HaskoningDHV, 2011). An additional assessment was executed for a selection of the primary water defenses without RD2011, because all critical dune safety issues were already resolved. Currently, there is not one single complete guide for dune erosion and safety assessment. TRDA2006 is still the prescribed official technical report, but RD2011 supplements a complete dune assessment guide for coastal managers with a lot of new information about for instance hybrid water defenses and Non Water retaining Objects (NWO). Furthermore, RD2011 prescribes dune assessment with DUROS+ with the software package MorphAn.

---

[1] VTV: Voorschrift Toetsen op Veiligheid, safety assessment regulations.

[2] HR: Hydraulische Randvoorwaarden, hydraulic boundary conditions.

[3] WTI: Wettelijk ToetsInstrumentarium, legal assessment instruments.

[4] LD1984: Leidraad Duinafslag 1984, the dune erosion guidebook from 1984.

[5] TRDA2006: Technisch Rapport Duinafslag 2006, the official technical dune erosion report from 2006.

[6] RD2011: Rapport Duinafslag 2011, a report on dune protection which did not receive the status of an official technical report.

Appendix B

MorphAn functions and possibilities

The computer program MorphAn (Lodder and van Geer, 2012; Deltares, 2015a) provides a clear and quite simple environment where models can be executed to assess different characteristics of the coast. It contains the official Dutch hydraulic boundary conditions (HR2006) that are provided bij Rijkswaterstaat for the dune safety assessments. Besides that, it also contains transects of the entire Dutch coast in the standard installation.

MorphAn is developed to support dune and coastline assessment and is mainly used by two groups of users. The first group are managers from coastal water authorities who mainly use MorphAn to assess the safety of the dunes that are exposed to normative storm surges with DUROS+, after which a boundary profile (grensprofiel) must remain. This dune safety model calculates erosion volumes, a sand balance and other DUROS+ indicators, then determines and visualizes boundary profiles and finally summarizes the results of each transect in time including questionable points and nourishments. Besides the national safety assessment, this group of users also uses MorphAn to assess dune safety for determining an administrative boundary or to evaluate whether designs for nourishments and dune protections are sufficient.

The second group consists of coastline managers from Rijkswaterstaat who use it to keep track of the development of the coastline with respect to the reference coastline (Basiskustlijn, BKL) and to extrapolate trends and design and plan nourishment along the coast. They use the coastal development model where a combination of nourishment data and measured JARKUS transects are used to predict a trend in coastline change. This trend is extrapolated into the future and can be visualized per single transect or all at once in plan view. This second group also uses MorphAn to assess volume developments in several layers of the coastal foundation. The volume development model is then used to calculate sand volume changes based on JARKUS transects.

Many of the assessments described above are based on JARKUS transect data, which can be filtered, visualized, created, edited, compared and analyzed with MorphAn. Besides this, the program can be used to manage and adjust imported data and visualize GIS data like maps, grids and shapefiles. Furthermore, it provides the possibility to visualize data of for example a water authorities. MorphAn is also equipped with the possibility to do transect analysis with a 1D XBeach model. This function makes a process based analysis of each transect possible, so more detailed analyses can be carried out in comparison to the DUROS+ model. Additionally, MorphAn provides the possibility to use Python scripting to access a wide range of advanced functions to expand the standard functions.

MorphAn is mainly used for assessments based on 1D JARKUS transect, but it is possible to perform calculations on grid data. MorphAn only uses quite simple 1D models, because it is fast and sufficient for simple and alongshore relative uniform coastlines, where transects are a good estimate of the entire coastal area. Also, transect data is collected yearly and therefore the time resolution is quite high.

MorphAn itself is written in the programming language C# (pronounced as "C sharp") and is a plugin of the DeltaShell. New Morphan functions can be developed with this language, but this is only necessary if scripting in Python does not suffice and will not be elaborated on. The scripting function can be used to quickly develop new functions with the programming language Python. It gives access to the DeltaShell software library, which also makes it possible to use any functions and general software routines that were developed for other DeltaShell software packages.

Appendix C

XBeach input files

A brief description of the XBeach input files are listed in Table C.1, the actual contents of the input files for a 2D XBeach model are in the listings below. The slight differences for files for a 1D model are depicted with some comments in the files. Two other text files that can be used in the storm impact application are depicted in this Appendix.

Table C.1: XBeach input files

File	Brief content description
params.txt	parameters that are different from the XBeach defaults
x.grd	x-coordinates of all grid points
y.grd	y-coordinates of all grid points
bed.dep	z-values (bathymetry) of all grid points
tide.txt	timeseries of the water level on the boundary
waves.lst	timeseries of the wave conditions on the boundary
xboutput.nc	output file of the model run (not listed). It contains for instance the output variables defined in params.txt

Listing C.1: params.txt

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                                     %%%
%%%                                                                          %%%
%%% created with: python scripting in DeltaShell                             %%%
%%% function: writeparamstxt                                                 %%%
%%%                                                                          %%%
%%% params in this file are different from the default XBeach params         %%%
%%% the other (default) XBeach params are in XBlog.txt after startrun        %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Grid parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

gridform   = xbeach
xfile      = x.grd
yfile      = y.grd
vardx      = 1
nx         = 272
ny         = 86         % ny = 0 for a 1D model
depfile    = bed.dep
posdwn     = -1
thetamin   = -50        % thetamin = -90 for a 1D model
thetamax   = 50         % thetamax = 90 for a 1D model
snells     = 0          % snells = 1 for a 1D model
dtheta     = 20         % dtheta = 180 for a 1D model

%%% WTI PARAMETERS (Deltares2015_XBeachDefaults) %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```

fw         = 0.000
bedfriccoef = 0.001
bedfriction = cf
gammax     = 2.364
beta       = 0.138
wetslp     = 0.260
alpha      = 1.262
facSk      = 0.375
facAs      = 0.123
gamma      = 0.541

%%% Model time %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tstop      = 172800
CFL        = 0.900

%%% Morphology parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

morfac     = 10

%%% Tide boundary conditions %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tideloc    = 2
zs0file    = tide.txt

%%% Wave boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

instat     = jons_table
bcfile     = waves.lst
thetanaut  = 1

%%% Output variables %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tint         = 1800
tstart       = 0
outputformat = netcdf

nglobalvar = 4
zb
H
u
v

nmeanvar = 5
H
zs
u
v
hh
```

Listing C.2: x.grd

```
<x 1,1> <x 2,1> <x 3,1> .. <x nx,1> <x nx+1,1>      % only this line for a 1D model
<x 1,2> <x 2,2> <x 3,2> .. <x nx,2> <x nx+1,2>
<x 1,3> <x 2,3> <x 3,3> .. <x nx,3> <x nx+1,3>
...
<x 1,ny> <x 2,ny> <x 3,ny> .. <x nx,ny> <x nx+1,ny>
<x 1,ny+1> <x 2,ny+1> <x 3,ny+1> .. <x nx,ny+1> <x nx+1,ny+1>
```

Listing C.3: y.grd

```
<y 1,1> <y 2,1> <y 3,1> .. <y nx,1> <y nx+1,1>      % only this line for a 1D model
<y 1,2> <y 2,2> <y 3,2> .. <y nx,2> <y nx+1,2>
<y 1,3> <y 2,3> <y 3,3> .. <y nx,3> <y nx+1,3>
...
<y 1,ny> <y 2,ny> <y 3,ny> .. <y nx,ny> <y nx+1,ny>
<y 1,ny+1> <y 2,ny+1> <y 3,ny+1> .. <y nx,ny+1> <y nx+1,ny+1>
```

Listing C.4: bed.dep

```
<z 1,1> <z 2,1> <z 3,1> .. <z nx,1> <z nx+1,1>      % only this line for a 1D model
<z 1,2> <z 2,2> <z 3,2> .. <z nx,2> <z nx+1,2>
<z 1,3> <z 2,3> <z 3,3> .. <z nx,3> <z nx+1,3>
...
<z 1,ny> <z 2,ny> <z 3,ny> .. <z nx,ny> <z nx+1,ny>
<z 1,ny+1> <z 2,ny+1> <z 3,ny+1> .. <z nx,ny+1> <z nx+1,ny+1>
```

Listing C.5: tide.txt

```
<time 1 (tstart)>    <offshore water level> <landward water level>
<time 2 (tstart + Δt)>  <zs 1,2> <-5m>
<time 3 (tstart + 2*Δt)>  <zs 1,3> <-5m>
...
<time tlen-1 (tstop - Δt)>  <zs 1,tlen-1> <-5m>
<time tlen (tstop)>  <zs 1,tlen1> <-5m>
```

Listing C.6: waves.lst

```
<Hm0 1> <Tp 1> <mainang 1> <gammajsp> <s> <duration> <dbtc>
<Hm0 2> <Tp 2> <mainang 2> <3.30> <10.00> <3600> <1.00>
<Hm0 3> <Tp 3> <mainang 3> <3.30> <10.00> <3600> <1.00>
...
<Hm0 tlen-1> <Tp tlen-1> <mainang tlen-1> <3.30> <10.00> <3600> <1.00>
<Hm0 tlen1> <Tp tlen1> <mainang tlen1> <3.30> <10.00> <3600> <1.00>
```

Listing C.7: matrooscredentials.txt

```
<username>
<password>
```

Listing C.8: strandtenten.txt, with example values for Delfland

```
#RSPland and RSPsea are distances from RSP (measurable with the morphan JARKUS ...
    overview with areal maps)
#raai   RSPland RSPsea
9770    -60 -75
9795    -50 -80
9807    -50 -80
9830    -50 -80
9847    -50 -80
9853    -50 -80
9875    -45 -75
9897    -10 -30
9903    0   -30
9925    10  -25
9947    5   -25
9950    5   -25
9953    5   -25
9975    5   -30
9997    20  -15
10003   20  -15
10025   45  -45
11850   945 925
```

Appendix D

Installation guide

This Appendix provides the installation instructions for the prerequisites in Chapter 3.1. It elaborates on how to get the (installation) files, how to install and where to apply for credentials. Currently, installation of the storm impact application is quite devious, because the storm impact application is not yet fully implemented in MorphAn. If the storm impact application will become part of the MorphAn installation, only the first two steps are necessary.

Acquire a suitable laptop MorphAn does not require a computational cluster or high end laptop. However, analysis will be faster on more powerful computers. MorphAn is currently only available for Windows computers, for 32-bit as well as 64-bit installations.

Install MorphAn The installation file for MorphAn 1.4 or higher can be found on the MorphAn website (http://oss.deltares.nl/web/morphan/download) from April 2016. The *.msi file can be downloaded and installed. If the user has no administrator rights, click advanced options to install it in the *User* folder instead of the *Program Files* folder. Select the options *Scripting* and *XBeach* during installation.

Acquire a newer XBeach version The required XBeach Kingsday release is not yet incorporated in the MorphAn release. It can be downloaded from http://oss.deltares.nl/web/xbeach/source-code-and-exe. In the folder of the newest release (currently *2015-10-22 XBeach v1.22.4867 Kingsday*), download the 32-bit or 64-bit version (depending on your computer) of the XBeach *.zip file with NetCDF. Find the MorphAn shortcut in the start menu, open the properties window via the context menu and navigate to the MorphAn installation directory with the *Open file location* button. Navigate one folder up and then to */plugins/DeltaShell.Plugins.XBeach.Common/XBeach*. Delete the old XBeach files from this folder and unpack the new XBeach files from the *zip file and place them in the XBeach folder.

Download Tortoise SVN Sign up for an account on http://oss.deltares.nl/, sign in when prompted during the following steps. Download and install the Tortoise SVN repository browser from https://tortoisesvn.net/downloads.html. Create the folder *D:/StormImpactApplication/MorphAn_OET_scripts* in the Windows explorer. Go to the context menu of this new folder and select the *Repo-browser* in the Tortoise SVN sub-menu. If you do not have a D-drive, put it on the C-drive.

Acquire the MorphAn storm impact application scripts Navigate to https://svn.oss.deltares.nl/repos/openearthtools/trunk/python/applications/ using the repository browser URL window and press OK. Go to the context menu of the *MorphAn* folder in the repository browser and *Checkout* to the new local *MorphAn_OET_scripts* folder. Opening and running *StormImpactApplicationScript.py* from the *StormImpactApplication* folder starts the storm impact application. Switching between 1D and 2D can be achieved by changing line 1 of the script. If you did not had a D-drive, change the *”C:¨* on line 2 to *”C:¨*. When pressing *Cancel* in the input screen that pops up, default test values are used. Chapter 3 can be used as a guideline to use the storm impact application. A description of the buttons that appear when running the storm impact application, can be found in Chapter 3.5.

Acquire RWsOS credentials Credentials are required in order be able to use the RWsOS data from http://matroos.rws.nl/direct/. These can be requested via Marc Philippart of RWS-WVL (marc.philippart@rws.nl), operational manager of RWsOS. These credentials can be provided in the storm impact application input screen, or in a *D:/StormImpactApplication/matrooscredentials.txt* file (Appendix C). Alternatively, the Deltares research version of matroos can be used while logged on on the Deltares network via http://matroos.detares.nl/direct/, for which no credentials are required, but less data is available. If you do not have a D-drive, put it on the C-drive.

Install Python (optional) Download and install Python 2.7 (Anaconda) from https://www.continuum.io/downloads. This is only required if one also wants to be able to use the JARKUS transect files from the OPeNDAP server next to the ones from the local MorphAn installation.

Appendix E

Sensitivity analysis case overview

Table E.1 depicts an overview of all the sensitivity analysis cases. Case 0 is the base case, which shows the default parameter values. All given values of the other cases in the table deviate from these default values. There are eight groups of five cases, which are also depicted in Figure 5.4. The middle cases of the groups are often equal (for instance case 3, 8, 13 and 18 as well as case 23, 28, 33 and 38). Furthermore, case 41 to 45 do not form a similar kind of group, but are only assessed in order to show the relative effect of the wave height bias and the wave period bias from (Gautier, 2015) separately.

The volume change (d vol) is the net volume change of grid cells with an initial bed level above NAP +3 meter, per meter of coast line. The two right columns show the volume change value relative to the base case (rel1), or relative to the case with bias (rel2).

Table E.1: Overview and results of the sensitivity analysis model runs.

Case	**Water level [m]**		**H_{m0} [m]**		**$T_m^{-1.0}$ [s]**		**th_0 [°]**	**d vol**	**rel1**	**rel2**
	incr	**stdev**	**bias**	**stdev**	**bias**	**stdev**	**stdev**	**[m^3/m]**	**[-]**	**[-]**
0	+0	+0.00	/1.00	*1.00	/1.00	*1.00	+0	-24.75	1.00	1.00
1		-0.30	/1.04		/0.88			-32.21	1.30	0.71
2		-0.15	/1.04		/0.88			-39.05	1.58	0.86
3		+0.00	/1.04		/0.88			-45.45	1.84	1.00
4		+0.15	/1.04		/0.88			-52.13	2.11	1.15
5		+0.30	/1.04		/0.88			-57.72	2.33	1.27
6			/1.04	*0.68	/0.88			-39.81	1.61	0.88
7			/1.04	*0.84	/0.88			-42.01	1.70	0.92
8			/1.04	*1.00	/0.88			-45.45	1.84	1.00
9			/1.04	*1.16	/0.88			-49.95	2.02	1.10
10			/1.04	*1.32	/0.88			-53.55	2.16	1.18
11			/1.04		/0.88	*0.72		-9.86	0.40	0.22
12			/1.04		/0.88	*0.91		-27.97	1.13	0.62
13			/1.04		/0.88	*1.00		-45.43	1.84	1.00
14			/1.04		/0.88	*1.09		-67.34	2.72	1.48
15			/1.04		/0.88	*1.18		-88.66	3.58	1.95
16			/1.04		/0.88		-30	-46.85	1.89	1.03
17			/1.04		/0.88		-15	-51.00	2.06	1.12
18			/1.04		/0.88		+0	-45.43	1.84	1.00
19			/1.04		/0.88		+15	-36.58	1.48	0.81
20			/1.04		/0.88		+30	-27.95	1.13	0.62

Table E.1: (continued)

Case	**Water level [m]**		**H_{m0} [m]**		**$T_m^{-1.0}$ [s]**		**th$_0$ [°]**	**d vol**	**rel1**	**rel2**
	incr	**stdev**	**bias**	**stdev**	**bias**	**stdev**	**stdev**	**[m^3/m]**	**[-]**	**[-]**
0	+0	+0.00	/1.00	*1.00	/1.00	*1.00	+0	-24.75	1.00	1.00
21	+1	-0.30	/1.04		/0.88			-78.11	3.16	0.85
22	+1	-0.15	/1.04		/0.88			-84.68	3.42	0.92
23	+1	+0.0	/1.04		/0.88			-92.43	3.73	1.00
24	+1	+0.15	/1.04		/0.88			-100.83	4.07	1.09
25	+1	+0.30	/1.04		/0.88			-107.70	4.35	1.17
26	+1		/1.04	*0.68	/0.88			-84.23	3.40	0.91
27	+1		/1.04	*0.84	/0.88			-88.71	3.58	0.96
28	+1		/1.04	*1.00	/0.88			-92.43	3.73	1.00
29	+1		/1.04	*1.16	/0.88			-95.41	3.86	1.03
30	+1		/1.04	*1.32	/0.88			-99.88	4.04	1.08
31	+1		/1.04		/0.88	*0.72		-44.48	1.80	0.48
32	+1		/1.04		/0.88	*0.91		-65.79	2.66	0.71
33	+1		/1.04		/0.88	*1.00		-92.43	3.73	1.00
34	+1		/1.04		/0.88	*1.09		-121.25	4.90	1.31
35	+1		/1.04		/0.88	*1.18		-152.30	6.15	1.65
36	+1		/1.04		/0.88		-30	-94.16	3.80	1.02
37	+1		/1.04		/0.88		-15	-96.65	3.91	1.05
38	+1		/1.04		/0.88		+0	-92.41	3.73	1.00
39	+1		/1.04		/0.88		+15	-79.46	3.21	0.86
40	+1		/1.04		/0.88		+30	-65.09	2.63	0.70
41			/1.04		/1.00			-24.50	0.99	
42			/1.00		/0.88			-46.77	1.89	
43	+1		/1.00		/1.00			-60.37		1.00
44	+1		/1.04		/1.00			-60.20		1.00
45	+1		/1.00		/0.88			-92.85		1.54

The result of Case 41 to 45 in Table E.1 show that the underestimation of the wave period (case 41 and 44) from the SWAN model can have significant effects on the erosion volume and the overestimation of the wave height (case 42 and 45) has negligible effects.

UNIVERSITY OF TWENTE.

Deltares
Enabling Delta Life

Hoogheemraadschap van
Delfland