Upscaling of coastal flood assessments for reef-fronted small island developing states and investigating the adaptive capacity to coastal flooding in the context of São Tomé

by

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Preface

Over the past one and a half year, I have worked on my two master theses, of which the final result is in front of you. When I had to start my thesis and look for a topic, I talked to a lot of different people to find a topic in which I could combine both my master Hydraulic Engineering and Science Communication. After those various conversations, I met with my Deltares supervisors Kees Nederhoff and Alessio Giardino and decided to start my graduation project at Deltares. At the start, the scope was still very broad: 'Something about the different natural hazards that the Small Island Developing States (SIDS) are exposed to'.

Especially during the first phase, I struggled quite a lot to define the scope of the research. Having to define both a project for hydraulic engineering and for science communication turned out to be quite a challenge. In the end, the hydraulic engineering part of this thesis focuses on the upscaling of coastal flood assessments for reef-fronted SIDS. This part of the thesis aims to contribute to obtaining a better overview of the risks caused by coastal flooding to these islands, so that international aid can be distributed in the most efficient way. Subsequently, it is important that the resources that are allocated to these islands are used effectively. There are different ways to help these islands; the science communication part of this thesis focuses on a way that aims to increase the adaptive capacity of the SIDS.

With this project, I close off my university education. Equipped with the knowledge gained during my studies, the many friendships that have their roots in Delft and the critical attitude, but open mind that I have developed over the past years, I feel ready for the next step and I am curious for the things that the future will bring.

I hope you will enjoy reading this thesis, and that you will celebrate my graduation with me!

Martine Ellen Rottink
Delft, September 2019

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Furthermore, there are a lot of people that also helped me during my research. Thanks to Puck and Rinske, who both helped me with QGIS. Furthermore, I would also like to thank Alienor, who helped me with the initial design of the tool interface. Your insights and suggestions have made it possible for me to come up with an initial design in such a short period of time. Also a big thanks to Anna Goense and Anna Waque, who took the trouble to sit down with me and help me to improve the initial design of the tool interface. Furthermore, I would like to thank Sophie van Mechelen, for helping me with the translation of my questionnaire to Portuguese, and Ilse Nederlof, for sharing her insights related to doing social research in the context of SIDS.

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And lastly, I want to thank Martijn. You have always been there for me; to encourage me and comfort me whenever I was stressed, but maybe most importantly to put things in perspective when I really needed it:)

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Summary Hydraulic Engineering

Around the world, there are 58 Small Island Developing States (SIDS). Roughly, these SIDS can be sub-divided in three geographic divisions: the Caribbean, the Pacific, and Africa, Indian Ocean, Mediterranean and South China Sea (Kelman and West, 2009). What these SIDS generally have in common is that they are very susceptible to different natural hazards. Due to their small size, geographic isolation and generally limited financial resources, this susceptibility to natural hazards makes these island states very vulnerable. This vulnerability is expected to increase in the future under the influence of climate change (PCRAFI, 2013). In order to address the issues of these islands, adaptation measures are needed. In order to prioritize adaptation efforts and detailed risk assessments when considering these islands at a large scale (e.g. an Oceanic basin), it is important to obtain an overview of which islands are most vulnerable to different risks (Wright, 2013). Therefore, the risks due to different threats should be determined for these different islands.

An important threat for many of these islands is coastal flooding, especially for low-lying islands such as coral atolls (Department of Economic and Social Affairs of the UN Secretariat, 2014). Coastal flooding at such reef-fronted small islands is the main focus in this thesis. For small scale studies (e.g. for individual islands), it is possible to accurately model coastal flooding, using detailed bathymetry and topography data in combination with sophisticated, process-based models like XBeach. However, upscaling coastal flooding calculations to larger scales introduces some challenges.

The first challenge is the availability of topography data for these islands. For most islands, only satellite-based Digital Elevation Maps (DEMs) are available. In this thesis, 6 different satellite-based DEMs were compared to more accurate reference DEMs for 11 different islands. The results from this analysis indicated that in general, the TanDEM-X is the most accurate for terrains with mild slopes. However, the ALOS DEM is more accurate for steeper sloping areas. This is caused by a difference in horizontal resolution between the DEMs (i.e. the TanDEM-X has a horizontal resolution of 90 m and the ALOS DEM has a horizontal resolution of 30 m). Furthermore, the results indicated that the DEM error in these different satellite-based DEMs is strongly related with land cover. Large positive DEM errors were observed for forested (up to 7 m) and built-up areas (up to 2 m). Since the DEM error is strongly related to terrain cover and terrain slope, it could be concluded that the error statistics that were calculated for the different islands can be used to draw conclusions on which satellite-based DEM is the most accurate, but cannot serve as a proxy for the accuracy of these DEMs in other areas, as the terrain cover and therefore the DEM error may be totally different.

Especially the positive DEM error in built-up areas is a problem in coastal flooding assessments, since these are the main areas of interest in such assessments. In order to correct for the errors in built-up areas, a building-correction method was proposed and implemented, based on information regarding the location and type of buildings obtained from the Open Street Map (OSM) database. The results showed that this building-correction method could both increase and decrease the accuracy in built-up areas. This is caused by the fact that satellite-based DEMs are contaminated with different error sources. Apart from the errors introduced by the presence of buildings, in some areas these satellite-based DEMs can contain an overall negative bias. In case the DEM is negatively biased, this negative bias is (partly) compensated by the positive errors in built-up areas. In that case, the building-correction method locally decreases the DEM accuracy. However, it was observed that in such cases, the general shape of the DEM still improves due to the building-correction.

A second challenge that is introduced when upscaling coastal flooding assessments, is the used method for flood modelling. On such large scales, sophisticated models like XBeach are not feasible due to their high computational time. Currently, the bathtub method on water levels is often implemented in such large-scale coastal flood assessments for small islands. In this method the contribution of waves is not taken into account. However, different studies showed both high-frequency sea and swell waves and low-frequency infragravity waves to be important contributors to wave run-up and therefore to coastal flooding on reef-fronted coasts (Gourlay, 1996) (Merrifield et al., 2014). In the context of this thesis, a simple flood model was therefore developed that takes the contribution of waves into account. This model is referred to as the JBIW model; the model is a combination of the Janssen-Battjes model for short wave dissipation (Janssen and Battjes, 2007)

and the IW-method, which was originally developed for large-scale river flooding calculations (Dottori et al., 2018).

The model was tested in 1D for different idealized profiles and compared to other flood models (i.e. the bathtub method, the SFINCS model and the XBNH+ model (Roelvink et al., 2015)). Since no measured data were available, the results of the XBNH+ model runs were used as a reference. The results of these 1D tests indicated that the JBIW model is more accurate compared to the bathtub method, but comparable in terms of computational time; both models run in less than a second. For the bathtub method, a MAE in the calculated maximum water depths of 0,64 m was found (the MAE ranged from 0 till 2,59 m for all 1D runs); for the JBIW model a MAE of 0,19 m was found (the MAE ranged from 0 till 1,01 m for all 1D runs). The JBIW model is less accurate than the SFINCS model; for the SFINCS model a MAE of 0,10 m was found (with the MAE ranging from 0 till 0,71 for al 1D runs). However, the SFINCS model requires a longer computational time (i.e. a few minutes). Furthermore, the JBIW model was found to be most accurate for islands with an upslope profile (MAE of 0,13 m, ranging from 0 till 0,72 m for all runs with an upslope profile) and least accurate for islands with a bathtub profile (MAE of 0,28 m, ranging from 0 till 1,01 m for all runs with an bathtub profile). In general, based on the 1D tests it could be concluded that since the JBIW model is much more accurate than the bathtub method and comparable in terms of computational time, it would be more appropriate to use in large-scale coastal flood assessments to obtain a first estimate of coastal flooding. However, the accuracy of the model is not high enough to give accurate predictions of maximum water depths.

Subsequently, the JBIW model was implemented in a 2D case study for the island of Ebeye. In order to apply the JBIW model, which was implemented in 1D, to a 2D situation the model was applied in 1D for different cross-sections on the island. Subsequently, the water levels were interpolated between the different cross-sections and compared with the bed levels to obtain the maximum water depths on the island. Similar to the 1D tests, different XBNH+ runs were used as a reference. Furthermore, the bathtub method was applied as well. The results indicated that, similar to the 1D tests, the JBIW model is more accurate than the bathtub method. For the JBIW model, averaged over the different runs, the MAE was 0,26 m and the 90 % linear error (i.e. the value for which 90 % of the errors is lower, LE90) was 0,62 m. For the bathtub method, an MAE of 0,62 m and a LE90 of 1,71 m were found. Although the accuracy of the JBIW model is not high enough to give accurate predictions of the maximum water depths, it is possible to give a first estimate. Also, it is possible to indicate the areas on the island that are most prone to flooding.

Furthermore, the JBIW model was also applied in combination with two different building-corrected satellite-based DEMs (i.e. the TanDEM-X and the MERIT DEM) for the island of Ebeye. The calculated maximum water depths were again compared to the values calculated with the XBNH+ runs. These results indicated that the errors that are introduced by using a building-corrected satellite-based DEM are much larger than the errors introduced by the application of the simple JBIW model. For the TanDEM-X, a MAE of 0,96 m and a LE90 of 1,99 m were found. For the MERIT DEM, the errors were slightly lower: a MAE of 0,79 m and a LE90 of 1,77 m.

Lastly, the calculated water depths were combined with a building exposure map for the island and a depth-damage curve in order to calculate the economic damages to the buildings for different conditions. From the results of these calculations, it could be concluded that, at least for the island of Ebeye, the simple JBIW model can be used to obtain a first estimation of the risk in terms of economic damages; the calculated damages deviate up to 10 %. However, when applying the JBIW model in combination with the building-corrected satellite-based DEMs, the error in the calculated damages becomes very large; for the TanDEM-X the calculated damages deviate up to almost 300 % and for the MERIT DEM up to almost 100 %.

In summary, it could be concluded that the simple JBIW model that was developed in the context of this thesis can be used to obtain a first estimate of maximum water depths and an indication of which areas are most prone to flooding. However, the accuracy of the model is not large enough to obtain accurate predictions of the maximum water depths; for such exact predictions, sophisticated models like XBNH+ or SFINCS could be used. Furthermore, the results of the 2D case study for the island of Ebeye indicated that the JBIW model cannot be used in combination with publicly available satellite-based DEMs to obtain a reasonable estimate of coastal flooding; the errors that are introduced by the use of satellite-based DEMs are much higher than the errors that are introduced by the use of the JBIW model. Using these satellite-based DEMs resulted in very large deviations in the calculated risks (i.e. expressed in terms of economic damages to the buildings). These results indicate that for further studies focussing on the upscaling of coastal flood assessments for reef-fronted SIDS, obtaining higher accuracy elevation data is an important focus point.

Summary Science Communication

There are many Small Island Developing States (SIDS) around the world. What these SIDS generally have in common is the fact that they are very susceptible to different natural hazards. Due to their small size, geographic isolation and generally limited financial resources, this susceptibility to natural hazards makes these island states very vulnerable. This vulnerability is expected to increase in the future under the influence of climate change, which might for example lead to more severe coastal flood events. Over the last decades, international attention and aid for the issues that many SIDS face have increased. Much of this attention and aid is directly focused on decreasing the vulnerability of the SIDS. Although this has certainly benefitted the SIDS, such an approach does not change the dependency of these islands on external parties for their adaptation to (the risk caused by) climate change. Another approach focusses on increasing the adaptive capacity of these islands, with the eventual aim of enabling the SIDS to decrease their vulnerability themselves. The adaptive capacity of the SIDS is here defined as 'the ability or capacity of a system to cope, adapt or recover from a certain hazard or combination of hazards'.

In the hydraulic engineering part of this thesis, a simple flood model was developed that can be used to obtain a first estimate of coastal flooding. In contrast to many models used in hydraulic engineering practice, this model has the potential to be implemented in a tool that could be used by people without an engineering background. Such a tool could therefore add to the adaptive capacity to coastal flood events of the SIDS.

In the context of this thesis, it was investigated how a tool based on the simple flood model could be used to increase the adaptive capacity to coastal flood events. This was done specifically for the island of São Tomé, which is one of the SIDS and was the case study for this study.

In order to do this, different steps were taken. First, a theoretical framework was developed to provide practical guidance in the analysis of the (barriers to) adaptive capacity for a certain system. This framework is based on a system-based approach and assumes that the systems that are relevant in relation to coastal flooding (and other natural hazards) can be represented by a network of actors, that have different functions in the context of a specific hazard (e.g. coastal flooding) and that are linked to each other via various interactions. Each of these actors draws on a resource base, which entails both physical and non-physical resources. The interplay between a system's actors, interactions and resources determine a system's adaptive capacity. By assessing which barriers the different actors experience in relation to the resources that they need in order to carry out their functions, the interactions that they have with other actors and the actors/functions that are missing in the system, the barriers to adaptive capacity related to a specific risk in a certain system can be identified.

This theoretical framework was applied to the context of São Tomé. During a field trip to the island, different interviews were conducted with actors that are relevant in the context of coastal flooding. Furthermore, during the field trip different coastal communities were visited and the people living in these communities were asked to fill in a questionnaire. The information that was obtained from the interviews and questionnaires was used in combination with the newly developed theoretical framework. This resulted in an overview of the barriers to the adaptive capacity to coastal flooding that are present in the system of São Tomé.

Not all the barriers to adaptive capacity that were identified can be addressed by a tool based on the simple flood model. The overview of barriers to adaptive capacity was analysed in order to identify the barriers to adaptive capacity that could be addressed by such a tool. From this analysis, it could be concluded that there are 3 actors that could be (direct) users of the tool in the context of São Tomé: the national meteorological institute (INM), CONPREC (a government organ that is responsible for the preparation and response to disasters) and the observatoire (a government department that is responsible for the gathering and storing of information related to climate change effects). For each of these potential users, a user story was developed that focuses on what they need from the tool (i.e. in order to overcome the barrier to adaptive capacity that they experience) and why.

These user stories were used to design an interface for the tool based on the simple flood model. This design is depicted in Figure 17.1 till 17.6.

In summary, it could be concluded that a tool based on the simple flood model can indeed be used to increase the adaptive capacity to coastal flooding in the context of São Tomé, by adressing different barriers to adaptive capacity that are experienced by different potential users of the tool. Identifying these barriers provided a good starting point for the formulation of user stories for the tool and eventually for the development of an initial tool interface design.

The theoretical framework that was developed in order to analyse the (barriers to) adaptive capacity of a certain system is expected to be applicable in a much wider context than only for the case study of São Tomé. Different opportunities for further development of this framework are suggested. Regarding the theoretical framework itself, it could be interesting to develop a categorization of the different elements that make up the theoretical framework (i.e. the actors, interactions and resources). Furthermore, it would be interesting to try to link the current theoretical framework to the functions carried out by the system to which the framework is applied, in order to try to develop a (qualitative) measure for adaptive capacity that could be used to compare different systems with each other. Regarding the use of the theoretical framework in practice, it would be interesting the explore the possibility of operationalizing the framework by developing a tool or game based on the framework. Such a tool/game could be used in practical projects in order to obtain insight in the system under consideration and involve different relevant stakeholders in the process.

Also regarding the tool based on the simple flood model, different opportunities for further research were suggested, both related to the development of the technical model and to the development of the interface. An important next step in the development of the interface is the validation with local users. In this validation, special attention should be paid to the people living in the different coastal communities and the observatoire.

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Introduction to this report

A loud knock on the door woke me up. Everything was dark and it took me some moments to realize what was happening. When my eyes were adjusted to the dark, I quickly got out of bed and went outside. The other men were already busy towing away the boats from the beach. I could feel the wind in my face; it was already quite strong. This would be a rough storm. I ran towards the waterline and started helping my neighbor with one of the boats. The water had already reached the back of the boat and it wouldn't be long before the sea would take it if we didn't do something. Together we pulled the boat over the beach, all the way behind the first row of houses. Then we went back again to help the others. Fortunately, we were able to secure all the boats before the storm fully hit. Then, everybody went back inside to wait out the storm. When the worst seemed to be over, the first people started to appear from their houses. After a first inspection, it turned out the damage was not too bad. At least no boats got lost this time. The houses that stand closest to the beach got partly flooded, but fortunately the owners had decided to wait out the storm in the houses of their relatives, so nobody got hurt.

- Aderito, Praia Abade (Principe) [1]

Praia Abade is a small coastal community at the island of Principe, which is part of the small island country São Tomé and Principe. Many coastal communities on these islands, like Praia Abade, suffer from the consequences of storms that occur every year during the rain season and that lead to flooding, damaged houses and loss of boats and lifestock. São Tomé and Principe is one of the 57 Small Island Developing States (SIDS). Many of these SIDS are under threat from a range of different natural hazards, among which coastal flooding. Other important natural hazard to these islands are for example earthquakes, volcano eruptions, droughts, and tropical cyclones. In combination with their small size, geographic isolation and generally limited financial resources, the susceptibility to these different natural hazards cause many of these SIDS to be very vulnerable. This vulnerability is expected to increase in the future under the influence of climate change.

Since the 1994 Declaration of Barbados and the Barbados Programme of Action, which was the first initiative for international cooperation between SIDS to raise awareness of the issues that they face, international concern for these countries has increased (Campling, 2006). Many developed countries and international institutions like the World Bank allocate part of their resources to studies and projects aimed at assisting SIDS in their adaptation to climate change. Although this increasing international concern and aid has certainly benefitted the SIDS, it is important to realize that the amount of resources from developed countries and international organizations that are available to the SIDS is still limited, especially considering the large amount of islands that are at risk and the fact that the risks will increase in the future. Therefore, it is important to allocate the available resources in the most efficient way and subsequently spend these resources as effectively as possible. The eventual aim is to decrease the vulnerability of the SIDS as much as possible.

Combined thesis

The vulnerability of the SIDS and the eventual aim to decrease their vulnerability as much as possible forms the wider context of this thesis. Within this thesis, two different master directions were combined: the master Hydraulic Engineering at the faculty of Civil Engineering and the master Science Communication at the faculty of Applied Sciences, both at the Technical University of Delft. Starting from these two master directions, the research that is described in this report focuses on two different sub-goals within the wider aim of decreasing the vulnerability of SIDS. This will be further elaborated below.

As described above, in order to decrease the vulnerability of the SIDS as much as possible considering the limited amount of resources that are available, first the available resources should be allocated in the most efficient way and subsequently, the resources should be spend as effectively as possible. In order to allocate

[1] Aderito is a fictional person. This story is based on conversations held during a field trip to São Tomé. The people in the community of Praia Abade have set up a storm warning system. During the storm season, every night one of the community members stands watch. In case of a storm, this person wakes up the rest of the community and everybody helps to secure the boats and the livestock. This system works pretty well, but they are often surprised by the first storm of the season.

the available resources as efficiently as possible, an important prerequisite is an overview of the risks to different natural hazards for all SIDS. Such an overview can be used as a basis for decisions regarding the allocation of resources. This is the main focus of the hydraulic engineering part of this thesis. The starting point for this part is the upscaling of coastal flood assessments for reef-fronted SIDS. The final goal here, to which this part of the thesis aims to contribute, is to be able to quantify the risks to coastal flooding for all SIDS.

Secondly, the resources should be spend in the most effective way. In this context, 'most effective' can be defined as 'leading to the largest decrease in vulnerability of the SIDS'. In order to decrease the vulnerability of SIDS, two different approaches can be distinguished. The first approach is here defined as the direct approach. This approach is characterised by external parties that use the allocated resources to design measures to decrease the vulnerability of the SIDS directly. Using the example of Praia Abade from the start of this introduction, this could for example be a project in which a dyke is designed and build by external parties to protect this community against coastal flooding. This dyke will indeed decrease the vulnerability of the coastal community of Praia Abade, because during the next high water event, the community is better protected against coastal flooding. However, a disadvantage of this approach is that despite the allocation of resources to the coastal community of Praia Abade, they remain to a large extent dependent on international assistance for their adaptation, because the social system of this community has not changed.

The other approach, in contrast, is here defined as the indirect approach. This approach is characterised by external parties that use the allocated resources to increase the capacity of the SIDS to adapt in order to decrease their vulnerability themselves, instead of focusing on decreasing the vulnerability of the SIDS directly. An important concept here is the concept of 'adaptive capacity', which can be defined as 'the capacity of social systems to manage risks so that impacts are avoided or reduced' (Barnett and Waters, 2016). Again using the example of the coastal community of Praia Abade, this could for example be a project in which a program is set up to teach the people in this community how to build their houses on poles. It is important to note that both the external and internal approach require external parties to help the SIDS in their adaptation. The difference between the two approaches is their direct aim; the indirect approach aims to change the capacity of the social system at the SIDS to decrease their vulnerability themselves, while the direct approach aims to change the vulnerability of the SIDS directly. The advantage of the indirect approach is that it can decrease the dependency on international assistance for the SIDS. Both approaches are visualized in Figure 1. The blue colour in these figures indicates the direct focus of the two approaches; the direct approach focuses on the vulnerability of the system directly, while the indirect approach focuses on the system. Furthermore, the arrows indicate who influences the vulnerabiliy; in the direct approach, the vulnerability is influenced by the external parties while in the indirect approach, the vulnerability is influenced by the system itself.

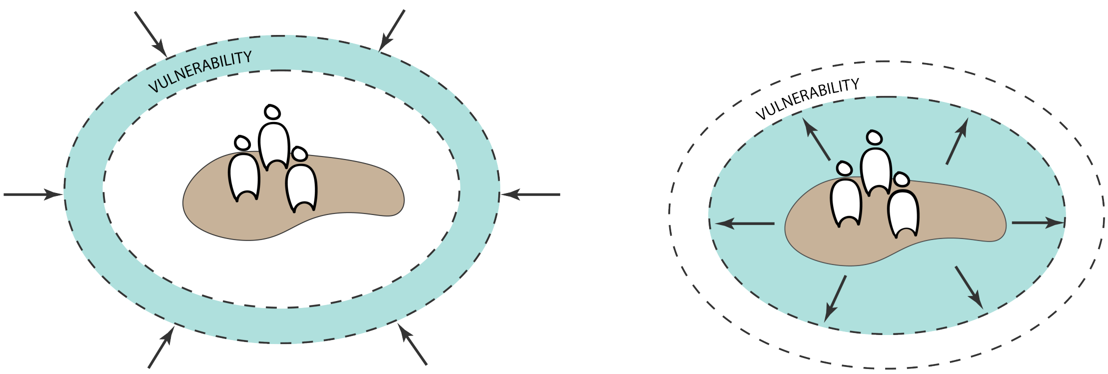


Figure 1: Direct and indirect approach

So, the indirect approach can lead to a decreasing dependency of the SIDS on international assistance, while this is not the case for the direct approach. Therefore, in an ideal world it would be a good strategy to focus solely on the indirect approach; the final aim would be to increase the adaptive capacity of the SIDS to such a level that they are able to deal with their vulnerability on their own. However, in practice, there is a practical limit to the extent to which it is possible to increase the adaptive capacity of the SIDS (at least on a small to medium long time scale). As described in the beginning of this chapter, limited financial resources are for example an important constraint for many SIDS. Furthermore, many SIDS do not have the expertise, skills or experience that are required for certain studies or the implementation of certain measures. At least on the short to medium long time scale, such factors can be important constraints to the application of the indirect approach for SIDS. Therefore, in practice both approaches are needed. These approaches can also be applied simultaneously in one project. An example would be a project where external parties use the allocated resources to design and construct a dyke for the community of Praia Abade and set up a program to teach the people in this community how to maintain the dyke.

In order to apply the indirect approach successfully, a thorough understanding of the adaptive capacity of a specified social system and the most important barriers to the adaptive capacity for that system is needed. This can subsequently be used as a basis to understand how certain projects could benefit the system and to help shape these projects. Also, more in general it can be used to make decisions regarding the best ways to increase the adaptive capacity for that system (related to a certain risk or combination of risks). This is the focus of the science communication part of this thesis. In this part, the aim is to develop a practical framework for the assessment of the (barriers to) adaptive capacity for a specified social system. Subsequently, this framework is applied in the context of a case study for the island of São Tomé to analyse how this island could benefit from a tool based on the simple flood model that was developed in the hydraulic engineering part of the thesis.

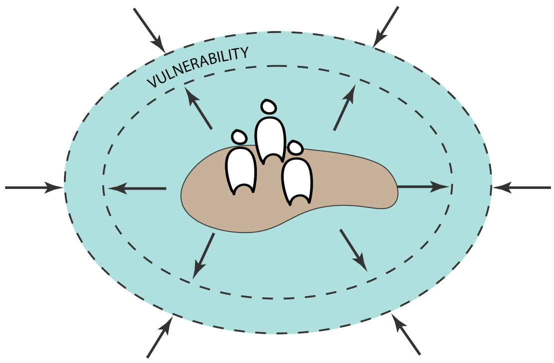


Figure 2: Combination of the direct and indirect approach

Structure of the report

In the first part of this report the hydraulic engineering part of this thesis is described. This part includes chapters 1 to 10. The science communication part is described in the second part, which covers chapters 11 to 20. Although these parts are linked to each other, they can both be read seperately. In the third and last part of this report a reflection is given. Here, the connection between the two parts is evaluated. Furthermore, the importance of the combination of hydraulic engineering and science communication in a wider context is discussed.


4 BITS

1

Introduction

1.1. Background

Around the world, there are 58 Small island Developing States (SIDS). Roughly, these SIDS can be subdivided in three groups: the Caribbean SIDS, the Pacific SIDS and lastly SIDS in Africa, Indian Ocean, Mediterranean and South China Sea (Kelman and West, 2009). What these SIDS generally have in common is that they are very susceptible to different natural hazards, like (among others) earthquakes, volcano eruptions, droughts, tropical cyclones, swell wave events and tsunamis. These hazards lead to different onshore threats such as inundation, coastal erosion, ground shaking and high wind velocities, which can lead to large damages. Due to their small size, geographic isolation and generally limited financial resources, this susceptibility to natural hazards makes these island states very vulnerable (Department of Economic and Social Affairs of the UN Secretariat, 2014). The vulnerabilty of these islands is expected to increase in the future under the influence of climate change (e.g. due to increasing water levels (Vitousek et al., 2017)). In order to address the issues of these islands, adaptation measures are needed. However, in order to prioritize adaptation efforts and detailed risk assessments when considering these islands at a large scale (e.g. an oceanic basin), it is important to obtain an overview of which islands are most vulnerable to different risks (Wright, 2013). Therefore, the risks due to different threats should be determined for these different islands.

An important onshore threat for many of these islands is coastal flooding, especially for low-lying islands such as coral atolls (Department of Economic and Social Affairs of the UN Secretariat, 2014). This thesis will focus on the determination of coastal flooding for reef-fronted SIDS.

1.2. Challenges in upscaling coastal flood modelling

The process of modelling coastal flooding can be depicted in a model train, see Figure 1.1. The first step is to determine the offshore conditions. The offshore water levels and wave characteristics can be derived from gauge stations (if available) or from global wave and tide models. Next, these offshore conditons need to be translated from deep towards shallow water. These nearshore conditions can subsequently be used as input for flood modelling.

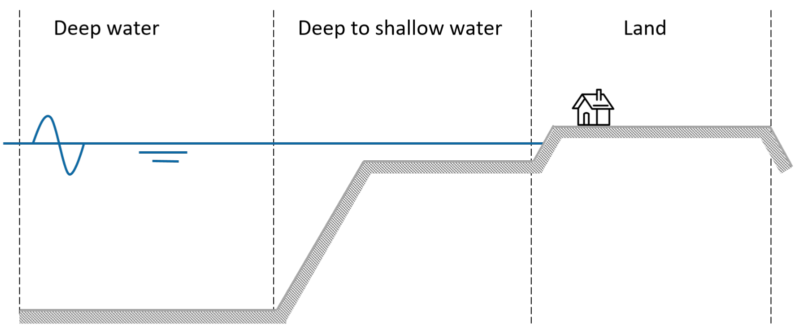


Figure 1.1: Model train for coastal flood modelling

For small scale studies (e.g. for individual islands), it is possible to accurately model coastal flooding. For such small scale studies, the bathymetry and topography of the study site can be measured on-site and used as input for sophisticated process-based models like XBeach, which solve the (non-hydrostatic) shallow water equations and can be used to model both the transformation of water levels and wave characteristics from offshore to nearshore and the flooding of the island. The second and third step in the model train as described above are then solved by the same model. For a few individual islands in the Pacific Ocean, these data were gathered and detailed coastal flooding calculations are available (Storlazzi et al., 2018)(Giardino et al., 2018). However, two main challenges are introduced when upscaling the coastal flood modelling.

The first challenge is the scarce bathymetry and topography data that is available for these islands. All flood modelling approaches require topographic data, but for most reef-fronted SIDS only satellite-based DEMs are available. There are different global satellite-based DEMs that cover these islands, but they generally have a course horizontal resolution and a low vertical accuracy. Especially for the smaller islands, the coarse horizontal resolution of these satellite-based DEMs can be a problem, because it means that only a rough indication, based on a few elevation tiles, of the topography of these islands is available. This has a large influence on the uncertainty in coastal flood risk assessments based on these elevation data (van de Sande et al., 2012) and imposes a challenge when it comes to inundation modelling.

Secondly, the sophisticated process-based models (like XBeach) that are used in small scale studies are not appropriate for usage on such large scales. This has different reasons. First, the advantage of a sophisticated, process-based model like XBeach is cancelled out when it is applied to the low-resolution, low-accuracy topographic data that is available for these islands. Secondly, these complex models come with high computational costs. In terms of computational time, it is not preferable to use these sophisticated models to model coastal flooding on large scales. A modelling approach requiring less computational time is preferred.

In order to deal with this second challenge, less sophisticated models are used. In current large scale coastal flood risk assessments, often a static (or 'bathtub') approach for the determination of inundation extent and depth is applied. In this approach the projected flood water level is compared with the elevation to determine which areas are flooded (van de Sande et al., 2012) (Hinkel et al., 2014). The projected flood water level in this approach incorporates offshore water levels, tide and storm surge, but does not take the contribution of waves into account. However, for reef-fronted shorelines both high-frequency sea and swell waves and low-frequency infragravity waves are important contributors to the wave run-up and therefore to coastal flooding events (Gourlay, 1996) (Hoeke et al., 2013). This contribution of waves to runup and coastal flooding is expected to increase in the future due to sea level rise (Merrifield et al., 2014). Coastal flood risk for reef-fronted SIDS is therefore expected to be higher when taking wave-driven flooding into account compared to the situation in which wave-driven flooding is not taken into account.

1.3. Research objectives

As was described in the previous section, in order to obtain an estimate of coastal flooding and the associated risks for reef-fronted SIDS, a methodology is needed that is low in terms of computational demand and that takes the contribution of waves to coastal flooding into account explicitly. Futhermore, it must be investigated whether this method can be used in combination with publicly available satellite-based DEMs to obtain a reasonable estimate of the coastal flooding for the different reef-fronted SIDS.

The first objective of this thesis is therefore to find a methodology that is low in terms of computational demand to model coastal flooding for reef-fronted SIDS. In contrast to common practice in large scale coastal flood assessments (van de Sande et al., 2012), in this methodology waves should be taken into account explicitly, since this will change the islands ability to cope with sea level rise (Storlazzi et al., 2018) (Giardino et al., 2018).

The second objective of this thesis is to analyse the accuracy of the different publicly available satellite-based DEMs and to investigate the different error sources in these DEMs. There have been many studies that investigate the accuracy of different satellite-based DEMs for different areas in the world (van de Sande et al., 2012) (Bayik et al., 2018) (Rodríguez et al., 2006) (Rodriguez et al., 2005) (Wessel et al., 2018b). However, these studies do not focus on small islands specifically. In this study, the accuracy of the different satellite-based DEMs will be investigated specifically for the low-lying coastal zones of islands. Furthermore, it will be tried to increase the accuracy of these satellite-based DEMs.

Lastly, it must be determined whether these satellite-based DEMs can be used in combination with the methodology for large-scale coastal flood risk assessments in order to obtain a reasonable estimate of coastal flooding for reef-fronted SIDS.

1.4. Research questions

The question that this research aims to answer is therefore:

'What is a suitable methodology for upscaling the calculation of coastal flooding for reef-fronted small islands and can this methodology be used in combination with publicly available satellite-based DEMs to obtain a reasonable estimate of coastal flooding?'

In order to answer this question, the following sub questions need to be addressed:

1. Which publicly available satellite-based DEM is the most accurate to use in large-scale coastal flood assessments for SIDS and what is the accuracy of this DEM?
2. Can the accuracy of these publicly available satellite-based DEMs be improved by applying a building correction?
3. What methodology is suitable for large-scale calculations of coastal flooding for reef-fronted small islands when taking into account the level of accuracy and the computational time?
4. What is the accuracy of coastal flood calculations using this methodology in combination with a publicly available satellite-based DEM?

1.5. Reading guide

In the next chapter, Chapter 2, more information regarding the different publicly available satellite-based DEMs will be given. In this chapter, the different error sources that are present in satellite-based DEMs are described. Furthermore, the different publicly available satellite-based DEMs are shortly described and an overview of the errors present in these satellite-based DEMs, as reported in other studies, will be given.

In Chapter 3, the accuracy of the different publicly available satellite-based DEMs, as listed in Chapter 2, will be analysed. Both the methodology that was applied for this analysis and the results will be described and discussed. Based on these results, the first sub-question can be answered.

From the analysis that is described in Chapter 3, it could be concluded that DEM errors are related to the presence of buildings. Since builded areas are the main interest in coastal flood assessments, In Chapter 4, a method to improve the accuracy of satellite-based DEMs in builded areas is proposed. This method was implemented for different areas. Both the methodology and the results will be described in this chapter. Based on these results, the second sub-question can be answered.

Next, in Chapter 5, the simple flood model that was developed as part of this thesis is described. This simple flood model was tested for different 1D simplified profiles and compared to different flood models. The setup of these 1D tests and the results are described in Chapter 6. These results were used to formulate an answer to the third sub-question.

Lastly, in Chapter 7, the simple flood model as described in Chapter 5 is applied in a 2D case study for the island of Ebeye (i.e. an island in the Republic of the Marshall islands). The simple flood model is applied both in combination with accurate, locally measured elevation data and in combination with two different building-corrected satellite-based DEM. Lastly, the calculated waterdepths in both cases were used to calculate the economic damages to the buildings that are present on the island. Both the methodology and the results are described in this chapter. Based on these results, the fourth and last sub-question can be answered.

In Chapter 8, the results of this study are discussed. Subsequently in Chapter 9, the answers to the different sub questions and the main research question are summarized. Lastly, in Chapter 10, some recommendations for further research are given.

2

Literature review satellite-based DEMs

There are many different sources of topographic data, which can be rougly divided in 3 groups: satellite-based data, air-based data (e.g. LiDAR) and ground-based data (e.g. GPS field observations). For many small islands, only satellite-based data from global datasets are available. The other two data sources, air-based and ground-based, are more accurate, but also more expensive to obtain.

The different error sources of satellite-based DEMs are discussed in section 2.1. Subsequently, the different publicly available global DEMs and an overview of their errors found in different studies are described in section 2.2.

2.1. Errors in satellite-based DEMs

Satellite-based DEMs are inevitably contaminated by errors. In literature, DEM errors are categorized in different ways. In this section, the categorizations by (Fisher and Tate, 2006) and (Lemmens, 1999) are described.

(Fisher and Tate, 2006) categorizes DEM errors in three groups, based on the type of error: gross errors or blunders, systematic errors, and random errors. Gross errors or blunders can be the result of user error or equipment failure. The areas in a DEM that are subject to gross errors are identified and removed prior to release of the DEM. Systematic errors in DEMs are for example a bias in the elevation values or the parallel striping artefacts that are present in some DEMs. Lastly, random errors in DEMs usually have a short spatial scale and can have many different causes. Especially systematic and random errors are more difficult to remove from satellite-based DEMs. A schematic example of systematic and random errors is depicted in figure 2.1.

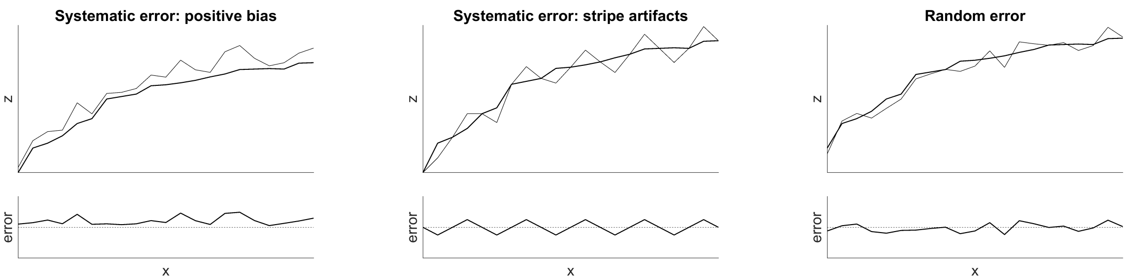


Figure 2.1: Schematic examples of different error types. Adjusted from (Fisher and Tate, 2006)

The categorization by (Fisher and Tate, 2006) focuses on the type of error in satellite-based DEMs. In contrast, (Gong et al., 2000) focuses on the different sources of errors in satellite-based DEMs. He distinguishes between errors introduced by instrumental errors, errors related to the (horizontal) resolution of the considered DEM and errors introduced by the terrain characteristics of the covered area.

Instrumental errors arises from inaccuracies and errors in the measurement equipment and method. There are different measuring techniques that can be used to derive satellite-based elevation data. The two main techniques on which the different publicly available satellite-based DEMs are based are SAR interferometry and radar stereogrammetry. A short explanation of these two techniques can be found in Appendix A.

The error introduced by terrain characteristics are caused by the characteristics of the earth surface. This is elaborated by (Lemmens, 1999). (Lemmens, 1999) explains that the main terrain characteristics that are relevant for DEM error are: micro-relief, coverage, reflectivity, and slope.

The micro-relief refers to the fluctuations in elevation within a certain region. All publicly available satellite-based DEMs are organized into individual rasterized cells. The elevation value of such a cell is assumed to be the average elevation within that cell and is based on different measurements that were taken in that cell (the amount of measurements per cell differs spatially). Since these measurements were taken 'blindly', the measurements may not lead to an accurate average elevation value for the area within that cell. This can be understood when comparing ground-based DEMs to satellite-based DEMs. When a DEM is constructed based on land-based measurements (e.g. with GPS measurements), the surveyor taking the point measurements has to choose locations of which the height is close to the average terrain height within the vicinity of the point. However, satellite-based data are obtained through automatic sampling; the terrain is captured blindly. The larger the micro-relief within the cell, the larger the error may be.

Another terrain characteristic that influences the error in satellite-based DEMs, is the land cover. In areas that are densily populated (i.e. contain a lot of buildings) or vegetated, the satellites may measure the tops of buildings or the canopies of trees instead of the bare earth level. Therefore, satellite-based DEMs are often Digital Surface Models (DSM), representing the earth surface with objects on it (e.g. buildings, vegetation) instead of Digital Terrain Models (DTM). Whether a DEM represents the bare earth depends to a large extent on the coverage of the terrain (Lemmens, 1999). Since for the application of (coastal) flood modelling the bare earth elevation is needed, this can pose a problem in e.g. urban and forested areas.

Also, the amount of signal reflection of the terrain surface (i.e. reflectivity) is linked to the DEM error. Water bodies are for example difficult to capture both in SAR interferometry and in image matching (i.e. stereo grammetry).

Lastly, the DEM error is related to the slope of the terrain. In different studies that investigate this relation, it was found that higher terrain slopes yield higher DEM errors (Gorokhovich and Voustianiouk, 2006) (Bolstad and Stowe, 1994). For higher terrain slopes, it is more difficult to measure elevation accurately.

Finally, errors related to the horizontal resolution of satellite-based DEMs are induced by the geometry of the terrain in relation to the horizontal resolution of the satellite-based DEMs. The different publicly available satellite-based DEMs all have a horizontal resolution of either 30 or 90 m. For areas with a large micro-relief, topographic features on a scale smaller than this DEM resolution cannot be captured accurately.

2.2. Satellite-based DEMs

There are different publicly available, satellite-based DEMs. These different satellite-based DEMs are based on satellite data acquired in different periods and with different measuring techniques. Therefore, the accuracy of the different satellite-based DEMs differ from each other. In this section, the SRTM, SRTM void filled, MERIT, ALOS, ASTER and TanDEM-X DEMs will be shortly descibed. For each DEM, a short description of the measuring process is given. Also, an overview of the DEM errors of each DEM as found in different studies is given. At the end of this chapter, an overview of the different publicly available satellite-based DEMs is listed in Table 2.1.

2.2.1. SRTM and SRTM void filled

The SRTM DEM is the result of an 11-day flight of the Shuttle Radar Topography Mission in 2000, which was a collaboration between NASA and the National Imagery and Mapping Agency (NIMA) of the U.S. Department of Defense. The DEM was produced with the SAR interferometry technique (see Appendix A for an explanation of this technique). The two SAR images needed for the construction of a topography map (as explained in section A.1.1), were obtained simultaneously (i.e. single-pas interferometry) in order to avoid inaccuracies due to temporal decorrelation (Farr et al., 2007).

The linear error 90 (LE90) (i.e. the absolute value for which 90% of the errors is smaller) as published in the SRTM data specification is ±16 m. Many studies performed a local error analysis of the SRTM DEM by comparing the SRTM DEM to local higher accuracy elevation data (e.g. GPS or LiDAR datasets) (Hassan, 2018) (Zhao et al., 2011) (Kolecka and Kozak, 2014). They report different values for the errors of the SRTM DEM and mention that the error statistics are dependent on terrain features like slope and forest cover. Overall it can be stated that the errors are significantly higher in mountainous areas. The reason for this was explained in section 2.1. (Kolecka and Kozak, 2014) for example, reported a mean error (ME) of 9.03 m and a root mean square error (RMSE) of 38.47 m for the SRTM DEM in the Polish Tatra Mountains. According to this study, only 74% of the SRTM elevation values had an absolute vertical error below 16 m. Also (Zhao et al., 2011) reported a RMSE of 24.64 m for the SRTM DEM in the Loess Plateau in China. This plateau comprises ridges, hills and mountains with large reliefs and steep slopes. At the North China Plain however, which is mostly low and flat, a RMSE of 2.22 m was found for the SRTM DEM.

The accuracy of the SRTM DEM is assessed on a global scale by (Rodriguez et al., 2005). In this technical report, the accuracy of the SRTM DEM is assessed by comparison to different higher-accuracy datasets, among which is a global dataset of GPS measurements. The error statistics are calculated for each continent separately. The results show that the error statistics are quite constant over the different continents, except for New Zealand which has a much larger RMSE and 90% absolute error. In the report this is attributed to the fact that the ground control points for New Zealand are all located in mountainous terrain. However, the relation between different land covers and SRTM vertical elevation error is not further investigated in the report. The ME of the SRTM DEM is reported to range from -0.7 m (for Eurasia) till +1.8 m (for Australia). The 90% absolute linear error ranges from 6 m (for Africa and Australia) till 10 m (for New Zealand). However, in the report it is stated that the ground control points that are used to calculate the error statistics are all derived from kinematic GPS points (i.e. a GPS device mounted to a car), which are therefore limited to roads. Very rugged terrains are underrepresented in the higher-accuracy dataset; therefore the error statistics as calculated in the report may be too optimistic. (Hawker et al., 2019) investigated the error in the SRTM, MERIT and TanDEM-X 90 m for 32 different floodplains in the world. The different satellite-based DEMs were compared to high resolution LiDAR DEMs that were available for these floodplains. He found and a RMSE and ME for the SRTM of 4.03 m and 2.16 m respectively.

2.2.2. MERIT DEM

The MERIT DEM is a global DSM developed by (Yamazaki et al., 2017). It is an error-corrected version of a baseline DEM consisting of the SRTM3 DEM and the ALOS DEM. The SRTM3 DEM is used below N60° and the AW3D DEM is used above N60°. The SRTM3 DEM is an early version of the SRTM DEM, which is described above. This DEM has a horizontal resolution of 3 arcseconds (90 m), instead of 30 m like the later version. The AW3D DEM is described in more detail in section 2.2.4. The unobserved areas in both DEMs were filled with datapoints from the Viewfinder Panoramas DEM. This DEM has a resolution of 3 arcseconds globally (local resolution can be higher) and is composed of different datasets such as digitized paper topography maps, the Canadian Geobase DEM and the U.S. National Elevation Data. Since it is composed of different data sources, the quality is not consistent globally.

According to (Yamazaki et al., 2017), the vertical height errors of spaceborne DEMs can be classified into four major categories: speckle noise, stripe noise, absolute bias and tree height bias. Speckle noise is a random error with low spatial correlation lengths, which is mainly caused by variability of the surface reflectance over flat terrains. Stripe noise is a regular height undulation with longer spatial correlation lenghts (up to 100 km). It is caused by an error in the knowlegde of the altitude and roll adjustments made by the satellites while measuring the earth's surface (Rodríguez et al., 2006). Absolute bias is the mean shift of average elevation over a larger area. As is explained in A.1.1, it is difficult to determine the absolute elevations through radar interferometry and stereo viewing of optical images; it is usually easier to assess relative height differences. The absolute bias in spaceborne DEMs can be decreased by the use of high-quality ground measurements. In areas where these ground control points (GCPs) are absent or scarce, absolute height errors tend to be larger. Both for radar interferometry and stereo viewing of optical images, it is not possible to 'see' below the forest canopies. Spaceborne DEMs based on these methods can therefore have large three height biases in densily forested areas.

The error removal algorithm designed to create the MERIT DEM starts with removal of the stripe noise, using a two-dimensional Fourrier transform filter. Unrealistic regular terrain undulations were removed using this filter. Subsequently, absolute elevation bias was corrected by using the calculated differences between the DEM and the ICESat elevations. The ICESat measurements are a global database with high accuracy elevation points. Next, the tree height bias was estimated based on global tree density and tree height maps and used to correct the DEM for tree height biases. Lastly, the speckle noise was removed by applying an adaptive smoothing algorithm after (Gallant, 2011). This algorithm is based on the statistical separation of speckle noise and topography signals. The amount of smoothing is adjusted to the ratio between the two; the algorithm applies stronger smoothing if the noise is large compared to the topography signal and less smoothing if the noise is low compared to the topography signal.

The accuracy improvement of the MERIT DEM was assessed by comparing the differences between the original DEM and the ICESat elevation points and the MERIT DEM and the ICESat elevation points. The ICESat points that were used for this accuracy assessment were not included in the correction of the absolute height bias. This assessment showed that on a global level, the amount of land pixels which were mapped with a height accuracy of 2 m or lower increased from 39% in the original DEM to 56% in the MERIT DEM. Also, the 90% linear error was reduced from $\pm$14 m to $\pm$12 m. Furthermore, it was found that the improvement was largest in flat forested areas and that errors remained highest in mountainous areas. This is attributed to the large subpixel topography variability resulting from the steep slopes in these areas (see section 2.1) (Yamazaki et al., 2017). An accuracy assessment of the MERIT DEM was carried out by (Hawker et al., 2019) for different floodplains in the world. In this assessment, the RMSE and ME of the MERIT DEM were calculated to be 2.32 m and 1.09 m respectively.

2.2.3. ASTER DEM

The ASTER DEM was produced from the data acquired with an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board the Terra satellite between 2000 and 2009. The Terra satellite was operated by NASA and has collected about 1.5 million stereo images. These images were used to produce a global DEM; this was a joint initiative of NASA and the Ministry of economy, Trade and Industry (METI) of Japan. The ASTER GDEM has a horizontal resolution of 1 arc second (30 m around the equator) and covers land surfaces between 83° N and 83° S latitudes (ASTER GDEM Validation Team: METI/ERSDAC NASA/LPDAAC USGS/EROS, 2009).

The vertical accuracy of the ASTER GDEM was assessed as part of the ASTER GDEM project. The validation was carried out against two large datasets of GCPs based on GPS-measurements: one in the US and one in Japan. The accuracy assessment in the US showed a mean error over all ground points of -0.20 m and an accuracy at the 95% confidence interval of 17 m. The RMSE was found to be 8.68 m. Furthermore, it was established that the ASTER GDEM was sensitive to tree canopy height; the mean error over forested areas is +8 m. The accuracy assessment in Japan showed similar results: a mean error of -0.70 m over bare areas and +7.4 m over forested areas (Tachikawa et al., 2011).

Different studies have assessed the vertical accuracy of the ASTER GDEM and compared it to other freely available global DEMs. (Santillan and Makinano-Santillan, 2016) analysed the vertical accuracy for the north-eastern part of Mindanao in the Philippines. The analysis was based on a comparison with a dataset of GCPs based on GPS-measurements. In this analysis, a RMSE of 11.98 m was found, with a higher RMSE of 14.88 m for densely vegetated areas. This study showed that the ASTER GDEM was less accurate than the ALOS and SRTM DEM in this area. Other studies report similar values for the RMSE of the ASTER DEM. (Chaieb et al., 2016) reports a RMSE of 10.13 m over the Kasserine region in central west Tunisia and (Amans et al., 2013) reports a RMSE of 12.72 m in the Ondo state in Nigeria. These studies are again based on a comparison with a dataset of GCPs based on GPS-measurements.

2.2.4. ALOS DEM

The ALOS World 3D 30 m mesh DEM (AW3D) was produced using the data acquired by the Panchromatic Remote Sensing Instrument for Stereo Mapping (PRISM) operated on the Advanced Earth Observing Satellite (ALOS), operated by the Japan Aerospace Exploration agency (JAXA) between 2006 and 2011. The global DEM is based on approximately 3 million stereo images. These images have a horizontal resolution of 2.5 m, but the DEMs produced from these images have a resolution of 5 m (the commercial version) and 30 m (the free version). The DEMs were produced using an averaging kernel (Bayik et al., 2018).

The target accuracy of the 5 m horizontal resolution DEM was a RMSE of less than 5 m. The RMSE of this DEM was calculated to be 4.10 m. This was based on the comparison of the 5 m ALOS World 3D DEM and a large database of GCPs based on GPS measurements. These GCPs were mainly located in Japan, but also in some other countries. The 30 m horizontal resolution version of the ALOS World 3D DEM was also targeted to have a vertical RMSE of 5 m (Tadono et al., 2015).

In (Santillan and Makinano-Santillan, 2016), the vertical accuracy of the 30 m horizontal resolution AW3D was analysed for the northeastern part of Mindanao in the Philippines. The vertical accuracy was analysed by comparing GCPs to the AW3D DEM. The ME and RMSE of the AW3D DEM were calculated to be 4.36 m and 5.68 m respectively. The standard deviation of the AW3D DEM (which is about equal to the unbiased RMSE) was calculated to be 3.66 m and it was reported that the majority of the AW3D DEM errors are within the 0-10 m range for this area. In this study, the SRTM and ASTER DEMs were also analysed; it was concluded that the AW3D DEM was the most accurate for this area. Lastly, the DEM elevation error was linked to different landcover types. The RMSE of the AW3D DEM was found to be 4.29 m in built-up areas and 6.75 m in areas with dense vegetation (Santillan and Makinano-Santillan, 2016). In (Bayik et al., 2018), the RMSE of the AW3D DEM is reported to be 1.78 m. This value was calculated based on the comparison of the AW3D DEM with the longitudinal profiles of 36 runways all over the world. Since runways are very uniform, flat horizontal surfaces, the surface is relatively easy to map (compared to for example a forest on a mountain slope). In (Becek et al., 2016), it is mentioned that the comparison of satellite-based DEMs with the elevation of runways, also called the runway method, is used to determine the instrumental error in the concerned satellite-based DEM. This is based on the assumption that the total error in satellite-based DEMs is subdivided in an instrumental error, an error related to the terrain characteristics and an error related to the resolution. On runways, the last two errors are assumed negligible. The calculated error therefore corresponds to the instrumental error in the satellite-based DEM. This could explain the significantly lower RMSE found in this study compared to (Santillan and Makinano-Santillan, 2016). It should be noted that, since the ALOS World DEM is based on radargrammetry, it is a digital surface model (DSM), representing the canopy top and building roofs' elevations. When compared to bare ground data, larger errors are therefore expected in densily vegetated and built-up areas (Bayik et al., 2018). In the remainder of this report, the ALOS World 3D 30 m mesh DEM will be referred to as the ALOS DEM.

2.2.5. TanDEM-X 90 m DEM

The TanDEM-X 90 m DEM is the result of the TanDEM-X mission, which was financed and implemented as a public-private partnership between DLR and Airbus Defence & Space. Currently, it is the most recent publicly available satellite-based DEM. The publicly available version has a horizontal resolution of 3 arcseconds (90 m around the equator). The DEMs are based on SAR interferometry, just like the SRTM and SRTM void filled DEMs. The SAR images were obtained from a single-pass, bistatic SAR interferometer with adjustable baseline between 2010 and 2014. Bistatic refers to the fact that the SAR images were obtained from two different satellites at the same time (i.e. the German radar satellite TanDEM-X and the TerraSAR-X satellite), flying in close formation. This is different from the other global DEMs based on SAR interferometry, where only one satellite is used. In order to reach the target accuracies, all land masses were covered at least twice in the same looking direction (i.e. angle between satellites and measured areas), with different baseline lenghts (i.e. length between the two satellites). Mountainous areas required additional image acquisitions in order to allow filling the gaps caused by oblique radar viewing geometry (see section 2.1) (Wessel et al., 2018a).

Based on the measured data from this mission, different DEMs were generated with horizontal resolutions of 0.4 (~ 12 m), 1 (~ 30 m) and 3 (~ 90 m) arcsecond(s). Currently, only the version with a horizontal resolution of 3 arcseconds, the TanDEM-X 90 m, is publicly available free of charge. The other versions are only commercially available (Wessel et al., 2018a).

The target accuracy of the TanDEM-X mission was to produce a DEM with an absolute, linear 90% error of 10 m. Currently only one global accuracy assessment of the TanDEM-X DEM has been carried out by (Wessel et al., 2018b). In this study, the accuracy of the TanDEM-X DEM (with a horizontal resolution of 0.4 arcseconds) was assessed using two different GPS point reference data sets, which are distributed across all continents. The absolute vertical accuracy was assessed by comparing the TanDEM-X DEM with ~ 3 million globally distributed GPS points, which were obtained as part of the TanDEM-X mission. The sensitivity of the height error to landcover was assessed by comparing the TanDEM-X DEM to ~ 23,000 GPS points (provided by the US National Geodetic Survey) scattered across different land cover types, as listed in the US National Land Cover Data Base. The results of this study showed a global absolute vertical mean error smaller than ± 0.20 m, a RMSE smaller than 1.4 m and an absolute 90% linear height error below 2 m. This is much lower than the target accuracy of the mission. However, in the study it is mentioned that the GPS points are often located in exposed and better accessible sites; steep slopes and high altitude points are underrepresented. This could decrease the calculated errors. On the other side, points in developed areas, where errors in satellite-based DEMs are often higher, were highly overrepresented. Furthermore, it was shown that the height error is sensitive to land cover, with higher RMSEs for developed areas and forests. Lastly, it is stated that although the TanDEM-X shows very good accuracy on a global scale, on smaller scales a local validation of the vertical accuracy should be carried out to understand the potential and limitations of the TanDEM-X DEM for a specific area (Wessel et al., 2018a). (Hawker et al., 2019) carried out an assessment of the TanDEM-X 90 m for 32 different floodplains around the world. In this study, the TanDEM-X 90 m is compared to diferent high-resolution LiDAR DEMs. The RMSE and ME of the TanDEM-X 90 m were calculated to be 3.16 m and 1.06 m respectively.

In the remainder of this report, the publicly available TanDEM-X 90 m will be referred to as the TanDEM-X.

Table 2.1: Overview of the different publicly available satellite-based DEMs

	horizontal resolution	**acquisition method & observation epoch**	**accuracy**
ALOS	1 arc second (~ 30 m)	Radargrammetry, from data obtained by the ALOS satellite (2006-2011)	(Santillan and Makinano-Santillan, 2016): RMSE = 5.68 m; ME = 4.36 m (Bayik et al., 2018): RMSE = 1.78 m (on runways)
ASTER	1 arc second (~ 30 m)	Radargrammetry, from data obtained by the terra satellite (2000-2008)	(Tachikawa et al., 2011): RMSE = 8.68 m (Santillan and Makinano-Santillan, 2016): RMSE = 11.98 m; ME = 8.37 m (Chaieb et al., 2016): RMSE = 10.13 m (Amans et al., 2013): RMSE = 12.72 m
MERIT	3 arc seconds (~ 90 m)	Based on SRTM, ALOS and VFR DEM, error corrected	(Yamazaki et al., 2017): LE90 = 12 m (Hawker et al., 2019): RMSE = 2.32 m; ME = 1.09 m
SRTM	1 arc second (~ 30 m)	SAR interferometry, from data obtained during the Shuttle Radar Topograpy Mission (2000)	(Kolecka and Kozak, 2014): RMSE = 38.47 m; ME = 9.03 m (Tatra mountains) (Zhao et al., 2011): RMSE = 24.64 m (Loess plateau) RMSE = 2.22 m (north China valley) (Hawker et al., 2019): RMSE = 4.03 m; ME = 2.16 m
SRTM void filled	3 arc second (~ 90 m)	Based on SRTM (2000)	
TanDEM-X	3 arc seconds (~ 90 m)	SAR interferometry, from data obtained by the TerraSar-X and TanDEM-X satellites (2010-2015)	(Hawker et al., 2019): RMSE = 3.16 m; ME = 1.06 m

3

Error quantification in satellite-based DEMs

In this chapter, the different satellite-based global DEMs are validated compared to more accurate reference DEMs, for 11 different islands. The main goal is to quantify the error in the different publicly available satellite-based DEMs, in order to see which publicly available satellite-based DEM is most accurate. Furthermore the aim is to investigate the dependence of the DEM error on different terrain characteristics, focussing specifically on vegetated and builded areas. The validation was carried out for 11 islands, which are described in Section 3.1. For each of these islands, a more accurate reference DEM is available; these DEMs are described in Section 3.1. The method that was applied to carry out the comparison is subsequently described in Section 3.2. In Section 3.3, the results of the comparison are described and discussed. Lastly, in Section 3.4, some concluding remarks are given.

3.1. Datasets

In this section, the different datasets that were used in the comparison are discussed. In Section 3.1.1, the different islands for which the comparison was carried out are shortly described. In Section 3.1.2, the reference DEMs that are available for these different islands are described. Lastly, in Section 3.1.3, the different satellite-based DEMs and their most important characteristics are shortly listed. For a more elaborate description of these datasets, the reader is referred to Section 2.2.

3.1.1. Islands

The comparison between different satellite-based and reference DEMs is carried out for 11 islands in total, which can be subdivided in 3 groups. The first group consists of the islands of Ebeye, Roi Namur, and Majuro. These are all coral atolls that are part of the Marshall Islands in the Pacific Ocean. Ebeye and Roi Namur are both part of Kwajalein atoll, and Majuro is part of Majuro atoll. These islands are small, low-lying and relatively flat.

The second group of islands consists of the islands of Tutuila, Aunu'u and Ofu-Olosega, which are all part of American Samoa. Ofu and Olosega used to be 2 separate islands, but the two islands were connected by the construction of a road in 1970 and are since regarded as one island. These islands are all volcanic islands and are therefore more mountainous than the coral atolls, with steeper slopes and higher elevations relative to MSL.

The third group consists of the 5 Wadden islands in the Netherlands: Texel, Vlieland, Terschelling, Ameland, and Schiermonnikoog. These islands were included in the comparison because reliable reference data is available for these islands and the topography of these islands is comparable to that of the coral atolls in the first group. Just like the coral atolls, the Wadden islands are low-lying relative to MSL and relatively flat.

3.1.2. Reference DEMs: ground truth

The reference DEMs that are available for the different islands are all DTMs, which means that these DEMs represent the earth surface without any objects on it. The reference DEM for the island of Ebeye is obtained from local measurements using a GPS device (Trimble CenterPoint RTX) (Giardino et al. (2018)). These GPS measurements were defined in the WGS84 horizontal reference system and vertically referenced with respect to the WGS84 ellipsoid. The level of local MSL relative to the WGS84 ellipsoid was calculated from several measurements of the water level with the same GPS device at different moments in time. Using these measurements in combination with tidal information for Ebeye, a DEM relative to local MSL was constructed. No information on the accuracy of the DEM is given. However, since the DEM was created from GPS measurements, which is a more accurate method for DEM construction than SAR interferometry and radargrammetry, the accuracy of the DEM is assumed good enough to serve as a reference for the island of Ebeye.

The reference DEM for Roi Namur is obtained from the USGS and is based on GPS surveys carried out by the USGS in November 2013 and April 2014. The reference DEM is defined in the WGS84 horizontal reference system and is vertically referenced with respect to the WGS84 ellipsoid. More information on how this DEM was created can be found in (Storlazzi et al., 2018). No information on the accuracy of the DEM is given. Again, since the DEM was created from LiDAR data and GPS measurements, the accuracy of the DEM is assumed good enough to serve as a reference for the island of Roi Namur.

The reference DEM for Majuro is obtained from the topobathymetric DEM (TBDEM) for Majuro. This DEM is produced by the USGS as part of the CoNED project, which focuses on creating cross-shore topobathymetric DEMs in select regions around the US coast and Pacific islands and atolls. The reference DEM for Majuro is constructed based on GNSS (Global Navigation Satellite System) measurements obtained during a field survey in September 2016. The measurements are defined in the WGS84 horizontal reference system and are vertically referenced with respect to the WGS84 ellipsoid. As part of the CoNED project, a local reference model based on local water level measurements was developed for Majuro Atoll to determine the levels of local MSL with respect to the WGS84 ellipsoid. This model was used to create a DEM for Majuro referenced with respect to local MSL. The accuracy of the DEM was assessed by the use of GCPs that were also measured as part of the project. The RMSE of the topography of the TBDEM was calculated to be 0.197 m. The accuracy of the bathymetry part is much lower (1-1.5 m RMSE), but the bathymetric part is not used in this analysis (Palaseanu-Lovejoy et al. (2018)).

The reference DEMs for the islands of Tutuila, Aunu'u and Ofu-Olosega are obtained from LiDAR data from the USGS. The LiDAR data were acquired in June and July 2012. This DEM is defined in the NAD83 horizontal reference system and vertically referenced with respect to the NAVD83 level. The RMSE of the LiDAR-based DEMs for the different islands was calculated from a comparison with several GCPs, which were measured as part of the project as well. The RMSE of the LiDAR DEMs varies somewhat per island, but is around 7 cm for all islands (Office for Coastal Management, 2019).

The reference DEMs for the Wadden islands are obtained from the 'Actueel Hoogtebestand Nederland' (AHN), which is based on LiDAR data. The LiDAR data are filtered to remove buildings and vegetation from the DEM. This DEM is horizontally defined in RD-coordinates (Rijks Driehoek) and vertically referenced with respect to Normaal Amsterdams Peil (NAP). These DEMs are very accurate; the errors are assumed to be lower than 5 cm (Algemeen Hoogtebestand Nederland (AHN), 2018).

3.1.3. Satellite-based global DEMs

For all islands, the measured DEMs are compared to the 6 different satellite-based DEMs that were described in the previous chapter: SRTM DEM, SRTM void filled DEM, MERIT DEM, ASTER DEM, ALOS DEM and TanDEM-X. More information on these different satellite-based DEMs can be found in Chapter 2.

3.2. Method

In this section the method that is applied in order to compare the different satellite-based and reference DEMs with each other is described.

3.2.1. Horizontal reference system

In order to compare the different DEMs with each other, the different DEMs are converted to the same horizontal reference system. All DEMs are converted to the WGS84 horizontal reference system. The reference DEMs for the Wadden islands are therefore converted from the RD coordinate system to WGS84 in QGIS. The reference DEMs for Tutuila, Aunu'u and Ofu-Olosega are converted using VDatum, an online tool developed by the National oceanic and atmospheric administration (NOAA) of the US. The reference DEMs for Ebeye, Roi Namur and Majuro and the different satellite-based global DEMs are already referenced in the WGS84 coordinate system.

3.2.2. Vertical reference level and grid resolution

Subsequently, in order to compare the different satellite-based DEMs, the different DEMs (both the satellite-based and reference DEMs) must be referenced with respect to the same vertical datum level. Most publicly available satellite-based DEMs are vertically referenced with respect to a geoid computed from the the Earth Gravitational Model from 1996 (EGM96). However, since a geoid computed from the EGM2008 model is a better representation of the earth's gravity field (Rao et al., 2012), the different DEMS for the different islands are all converted to a geoid computed from EGM08. A description of the conversion for the different datasets can be found in Appendix B.1.

Lastly, the different DEMs had to be converted to the same grid resolution. For all islands, the reference elevation dataset has the finest horizontal grid resolution. In order not to loose any information from the reference datasets, the different satellite-based DEMs are converted to the grid of the reference elevation data. There are different interpolation methods that could be used, for example nearest neighbour, bilinear, cubic or cubicspline interpolation. From these different methods, the nearest neighbour interpolation method is the most conservative, where the elevations of the satellite-based data are preserved. The elevation values of the pixels in the satellite-based DEMs are based on multiple measurements in the area of the pixel. These different measured elevation values are averaged and this averaged value is assigned to the pixel. These pixel values can therefore be interpretated as the mean elevation of the pixel area. By applying the nearest neighbour method, these mean elevation values of the pixels are preserved. However, applying this method will result in a trapped elevation map, which is not a realistic representation of terrain. Also, using this interpolation method will result in larger errors for terrains with larger subpixel topography variability (i.e. larger errors for the more mountainous islands compared to the coral atolls and Wadden islands). Other interpolation methods (e.g. bilinear, cubic or cubicspline) lead to a more realistic representation of terrain, but do not necessarily preserve the mean elevation values in the original pixels.

The differences in error statistics were small when comparing bilinear and cubicspline interpolation. The errors were larger for the nearest neighbour interpolation method, especially for the more mountainous islands. Eventually the cubicspline interpolation was chosen and applied to all satellite-based DEMs.

3.2.3. Island points

When looking at the different satellite-based DEMs, it was observed that some global satellite-based DEMs contained points located on the island with negative elevation values, while the elevation values in the reference data points were all positive on the island. The negative values located on the island were assumed to be caused by noise and were therefore included in the analysis. The negative values located at the border of the islands were excluded from the analysis, assuming these points were not located on the island.

3.2.4. Vertical accuracy assessment

For each island, the vertical accuracy of the different satellite-based DEMs was assessed for points that are identified as land in both the satellite-based DEM and the reference DEM. Since the points identified as land are not the same for the different satellite-based DEMs (i.e. the island area is different for the different satellite-based DEMs), the vertical accuracies of the different satellite-based DEMs for a particular island are based on different sets of points, depending on the considered satellite-based DEM.

The DEM error at each point is calculated by subtracting the reference DEM elevation from the corresponding satellite-based DEM value. For a particular satellite-based DEM, a positive error thus indicates that the elevations in the satellite-based DEM are too high and a negative error indicates that they are too low.

The vertical accuracy of the different satellite-based DEMs is assessed by calculating different error statistics; the bias or mean error (see equation 3.1), the mean absolute error (MAE) (see equation 3.2), the unbiased mean absolute error (UMAE) (see equation 3.3), the root mean square error (RMSE) (see equation 3.4), the unbiased root mean square error (URMSE) (see equation 3.5), the minimum and maximum error and the 90% absolute error (LE90).

$$Bias = \frac{\sum_{i=1}^{N}(Z_{DEM} - Z_{true})}{N} \tag{3.1}$$

$$MAE = \frac{\sum_{i=1}^{N}(|Z_{DEM} - Z_{true}|)}{N} \tag{3.2}$$

$$UMAE = \frac{\sum_{i=1}^{N}(|Z_{DEM} - Z_{true}| - Bias)}{N} \tag{3.3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Z_{DEM} - Z_{true})^2}{N}} \tag{3.4}$$

$$URMSE = \sqrt{\frac{\sum_{i=1}^{N}((Z_{DEM} - Z_{true}) - Bias)^2}{N}} \tag{3.5}$$

The errors in the different satellite-based DEMs are further analysed based on the histograms of the DEM error for the different satellite-based DEMs. In many studies on error modelling of satellite-based DEMs, the errors are assumed to be normally distributed and zero mean (Fisher, 1998). However, according to (Fisher and Tate, 2006), several studies showed that these assumptions are not always valid. In order to check these assumptions for the different islands, the mean errors (equation 3.1) of the different satellite-based DEMs were calculated and histograms of the DEM error constructed.

Lastly, the spatial variation of the DEM error is considered. Difference plots for the different satellite-based DEMs were constructed for all islands to show the spatial variation in DEM elevation error. These difference maps were compared with satellite images of the different islands. In this way, the link between DEM elevation error and landcover type was analysed qualitatively. Many studies have examined the relation between DEM elevation error and landcover type quantitatively by using land cover maps. However, these maps are unavailable for most (smaller) islands in the Pacific Ocean.

3.3. Results

In this section, the results of the comparison between different satellite-based and reference DEMs will be discussed for the 3 different island groups seperately. For each island group, first the error statistics are discussed. Subsequently, the distribution of the error is analysed based on the histograms of the DEM error. Finally, the spatial variation of the DEM error is considered and linked to different landcover types based on a comparison with satellite images. Since the results for the different islands in an island group were comparable in some cases, not all results are included in this chapter. For a complete overview of the results of the comparison for all islands the reader is referred to Appendix B.

3.3.1. Coral atolls

For Ebeye (Table 3.1) and Roi Namur (Table 3.2) the error statistics for the different satellite-based DEMs compared to the reference DEMs were calculated. The results for the island of Majuro were comparable to the results for Roi Namur and are therefore not included in this chapter. From Table 3.1 and 3.2, it can be seen that all satellite-based DEMs have a positive bias, except the TanDEM-X. The ASTER DEM has a large positive bias (in the range between 5 and 8 m), a large MAE and RMSE and is the least accurate for all coral atolls. From the other satellite-based DEMs, the TanDEM-X is the most accurate. The TanDEM-X has the lowest bias, MAE, RMSE and LE90 for all three coral atolls. For Ebeye, the TanDEM-X has a negative bias (-0,27 m), but for Roi Namur and Majuro it is positively biased (0,11 and 0,83 m respectively).

Table 3.1: Error statistics for the island of Ebeye

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	1,74	2,13	1,35	2,45	1,73	-3,49	6,74	3,69
ASTER	5,42	5,45	2,00	5,97	2,50	-2,35	13,23	8,54
MERIT	0,76	1,64	1,45	1,93	1,77	-4,34	4,83	3,07
SRTM	1,20	1,56	1,11	1,85	1,41	-3,10	5,25	2,94
SRTMvf	1,12	1,60	1,19	1,87	1,50	-3,44	4,60	2,90
TanDEM-X	-0,27	0,92	0,94	1,23	1,20	-4,07	3,62	2,22

Table 3.2: Error statistics for the island of Roi Namur

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	2,05	2,36	1,39	2,85	1,99	-4,45	8,68	4,50
ASTER	7,13	7,30	2,50	7,88	3,35	-3,32	17,49	11,07
MERIT	1,54	1,92	1,42	2,34	1,76	-3,76	5,96	3,99
SRTM	1,75	2,25	1,72	2,78	2,16	-4,80	8,31	4,66
SRTMvf	1,62	1,98	1,48	2,44	1,82	-3,89	6,09	4,18
TanDEM-X	0,11	1,64	1,65	2,02	2,02	-9,80	6,73	3,34

The statistics in Table 3.1 and 3.2 list averaged error statistics, but do not provide information on the spatial distribution of the error in the different satellite-based DEMs. In order to study the spatial distribution of the error, difference plots were constructed for the different satellite-based DEMs. Such a difference plot for the ALOS DEM is depicted in Figure 3.1 for the island of Ebeye. An overview of the difference plots for all satellite-based DEMs can be found in Appendix B. These difference plots show the distribution of the DEM error. The DEM error is calculated by subtracting the local elevation from the reference DEM from the value in the satellite-based DEM. A positive value thus indicates that the elevation in the satellite-based DEM is too high.

The difference plot for the ALOS DEM in Figure 3.1 indicates a positive error in the ALOS DEM almost everywhere on the island. Only in the northern tip of the island, the elevation in the ALOS DEM is too low. This might be explained by comparing the difference plot to a satellite image of the island, see Figure 3.1. As can be seen from this satellite image, the island of Ebeye is almost entirely build. Only in the northern tip of the island, there are no buildings. This suggests that there is a relation between (positive) DEM error and the presence of buildings, as was found in literature (see Chapter 2).

This can be seen even more clearly for the island of Roi Namur. In Figure 3.2, the difference plot for the ALOS DEM for the island of Roi Namur is depicted. When this difference plot is compared to the difference plot for the island of Ebeye in Figure 3.1, it can be seen that the spatial variation of the DEM error is much larger for the island of Roi Namur. This can be explained by comparing the difference plot for Roi Namur with a satellite image of the island (see Figure 3.3).

In contrast to the island of Ebeye, the land cover for the island of Roi Namur is more heterogenous. At the island of Roi Namur not many buildings are present, but especially the east side of the island is densely vegetated with trees. When looking at the difference plots for the different global DEMs, a clear relation between the presence of these trees and positive DEM errors can be observed. In Figure 3.3 the contourlines of the areas with a DEM error larger than 4 m are plotted on top of a satellite image of the island. It can be clearly seen that these areas coincide with densely vegetated areas and also with some built areas. It should be noted that some green parts of the satellite image are not within the error contourline. Closer inspection of the satellite image showed that these parts are covered with low vegetation (grass and bushes) and not with trees; the DEM error is therefore expected to be much lower in these areas. Lastly, it can be seen from the satellite image of the island in Figure 3.2 that there is a runway present at the island of Roi Namur. In Section 2.2.4, it was mentioned that runways are very uniform, flat horizontal surfaces. The error that is calculated on these surfaces is assumed to be equal to the instrumental error in the satellite-based DEM concerned. From Figure

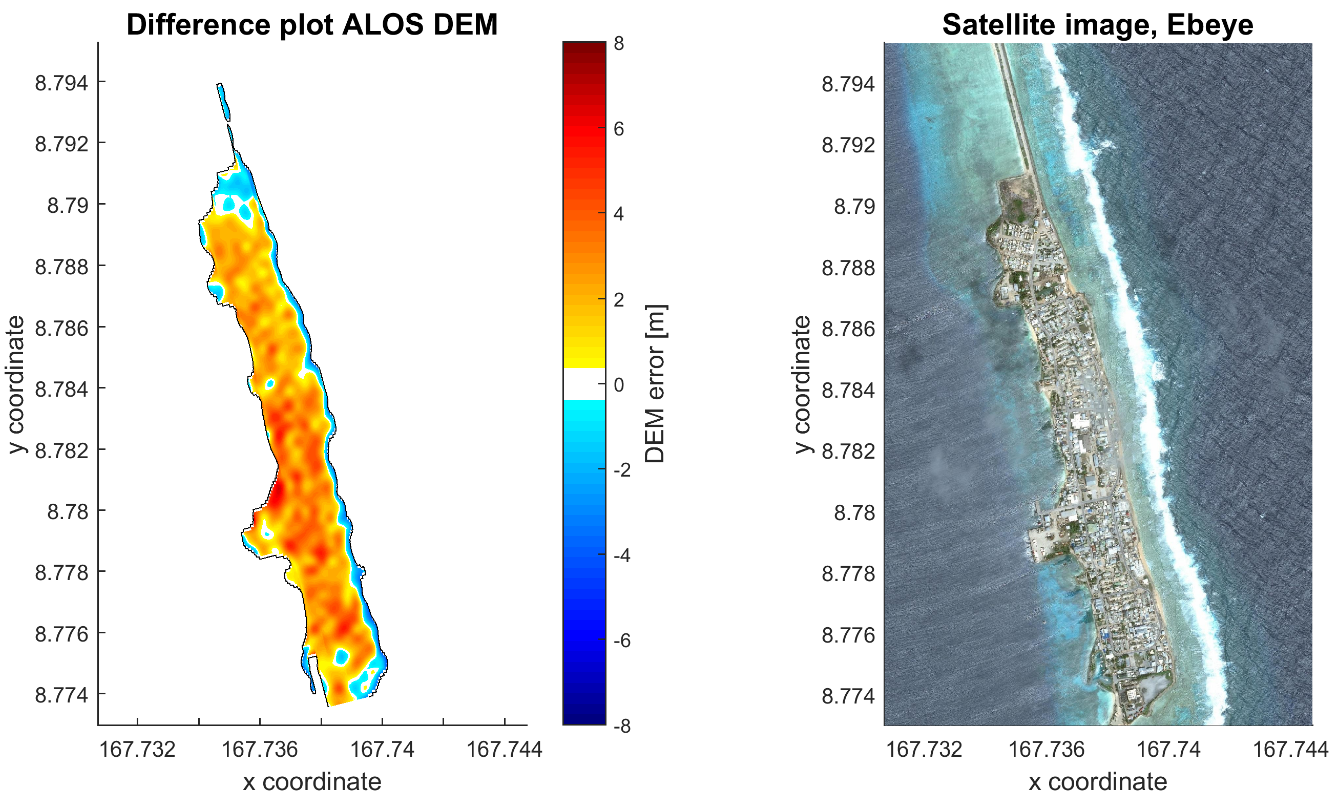


Figure 3.1: Difference plot ALOS DEM, for the island of Ebeye. The left figure is a difference plot for the island for the ALOS DEM. The DEM error is calculated by subtracting the elevation from the reference DEM from the elevation from the ALOS DEM ($z_{ALOS} - z_{reference}$). The right figure is a satellite image of the island.

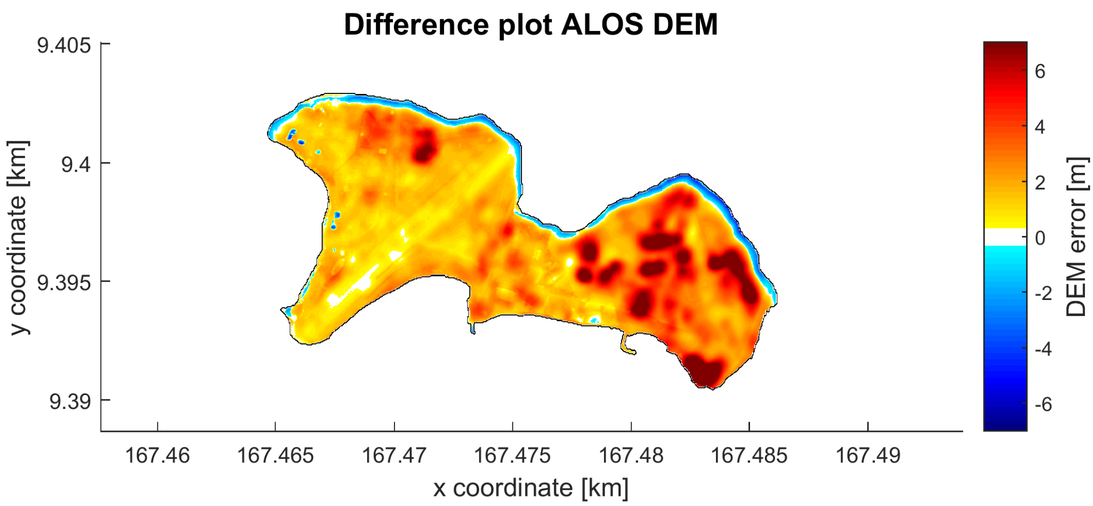


Figure 3.2: Difference plot ALOS DEM, for the island of Roi Namur. The DEM error is calculated by subtracting the elevation from the reference DEM from the elevation from the ALOS DEM ($z_{ALOS} - z_{reference}$).

3.2, it can be seen that the ALOS DEM error on this runway is slightly positive; this indicates that for the island of Roi Namur the ALOS DEM has a positive bias due to an instrumental error.

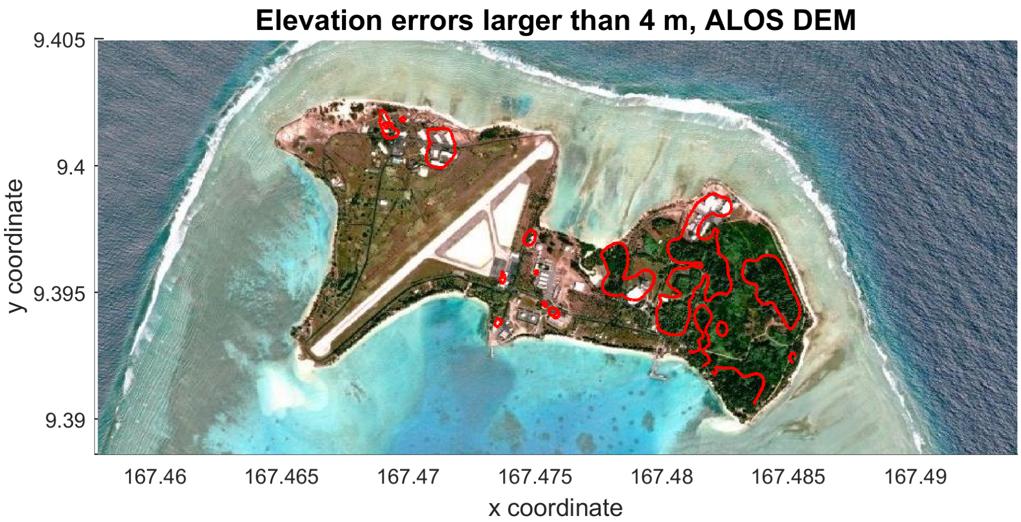


Figure 3.3: A satellite image of the island of Roi Namur. The red contour lines indicate areas with positive DEM errors larger than 4 m.

When comparing the difference plots of the ALOS DEM for the islands of Ebeye and Roi Namur, which have the same color scale, it can be observed qualitatively that the DEM errors caused by buildings are lower than the errors caused by trees. The errors caused by buildings are generally in the order of 1 to 2 m, with occasionally a bit larger errors. The errors caused by the vegetation on Roi Namur are up to 7 m.

In the ALOS DEM difference plots for both Ebeye and Roi Namur, it is striking that in both cases one side of the island is too low in the ALOS DEM, compared to the reference DEMs. For Ebeye, this is the eastern side of the island and for Roi Namur the northern side. This is probably caused by a combination of the cubicspline interpolation of the different satellite-based DEMs on the grid of the reference data and an error related to the horizontal resolution of the ALOS DEM. In Section 3.2.1, it was explained that the different satellite-based DEMs are interpolated on the grid of the different reference DEMs using cubicspline interpolation. In the different satellite-based DEMs, only the elevation on the island is given; all surrounding water tiles are not included in the database. In order to be able to carry out the interpolation, all these surrounding tiles were assigned a zero-value. Therefore, the elevation values at the border of the islands may be a bit too low.

Furthermore, this underestimation may be caused by the horizontal resolution of the ALOS DEM in relation to the micro-relief in the topography of the island. In Figure 3.4, a cross-section of the reference DEM for the island of Roi Namur is depicted. In this figure, it can be seen that the island has a ridge following the coastline at the northern part of the island. This was observed at multiple coral atolls and is called the oceanward ridge (Woodroffe, 2008). This oceanward ridge has a spatial scale that is small compared to the horizontal resolution of the different satellite-based DEMs; therefore, this ridge is not captured accurately in the different DEMs. The same is true for the island of Ebeye, where the oceanward ridge is located at the eastern side of the island.

3.3.2. Volcanic islands

Similar to the coral atolls, the error statistics for the volcanic islands were calculated for each island seperately. A complete overview of the error statistics can be found in Appendix B. In contrast to the coral atolls, these volcanic islands can have elevations up to a few hundred meters. Especially the island of Tutuila is very mountainous with steep sloping terrain. Areas with steeper slopes are generally captured less accurately in satellite-based DEMs (steeper terrains are more difficult to measure, see also Section 2.1). Also, the error caused by the coarse horizontal resolution of the different satellite-based DEMs is larger for areas with steeper slopes; the micro-relief of these areas is not captured accurately in the satellite-based DEMS. Different literature studies showed the DEM errors to be larger in more mountainous terrains for different satellite-based DEMs (Kolecka and Kozak, 2014) (Zhao et al., 2011) (Yamazaki et al., 2017). This was also found in the com-

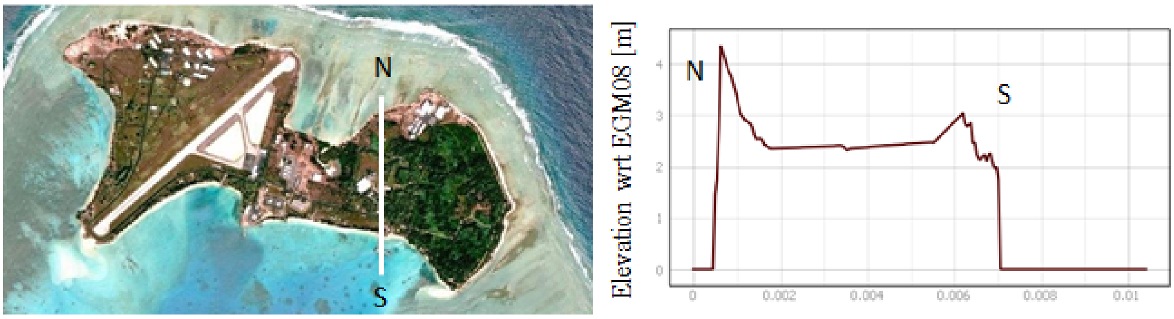


Figure 3.4: Satellite image and cross-section, Roi Namur

parison of the different satellite-based DEMs to the reference DEMs for the different volcanic islands. The errors were significantly larger than the errors found for the coral atolls (for the island of Tutuila a RMSE of over 25 m was found). Since the areas with larger elevations (and generally steeper slopes) are not relevant in coastal flood risk assessments, these areas were excluded from the analysis. Only the areas with an elevation less then 10 m with respect to the EGM08 level were included in the analysis.

The results for Tutuila and Ofu-Olosega were comparable and deviated from the results for Aunuu. Therefore, the error statistics for both the island of Tutuila and Aunuu are included in Table 3.3 and 3.4.

Table 3.3: Error statistics for the island of Tutuila

	Bias [m]	**MAE [m]**	**UMAE [m]**	**RMSE [m]**	**URMSE [m]**	**min [m]**	**max [m]**	**LE90 [m]**
ALOS	3,15	3,80	3,16	5,25	4,21	-10,97	21,02	8,52
ASTER	13,32	13,46	6,32	15,88	8,66	-11,19	51,56	24,32
MERIT	6,24	6,52	5,29	9,17	6,72	-10,91	31,99	16,36
SRTM	4,19	4,53	3,51	6,38	4,81	-10,86	25,26	10,70
SRTMvf	5,98	6,24	5,01	8,79	6,44	-10,75	31,16	15,65
TanDEM-X	4,87	5,67	5,59	9,04	7,62	-10,87	46,52	15,02

Table 3.4: Error statistics for the island of Aunuu

	Bias [m]	**MAE [m]**	**UMAE [m]**	**RMSE [m]**	**URMSE [m]**	**min [m]**	**max [m]**	**LE90 [m]**
ALOS	3,19	3,73	3,20	4,89	3,71	-8,05	14,56	8,27
ASTER	12,98	13,11	9,64	19,05	13,95	-10,80	70,41	30,97
MERIT	2,63	3,02	2,71	4,40	3,53	-5,69	15,22	8,12
SRTM	2,06	2,57	2,21	3,53	2,87	-4,74	13,23	5,90
SRTMvf	2,58	2,99	2,65	4,32	3,46	-5,26	14,98	7,90
TanDEM-X	1,74	2,92	2,89	4,30	3,94	-10,44	25,50	7,07

From these tables, it can be seen that the errors are generally higher for the island of Tutuila (and for the island of Ofu-Olosega) than for the island of Aunuu. The only exception is the ALOS DEM, for which the errors are comparable. Again, it can be seen that the ASTER DEM has the highest bias, MAE and RMSE and is the least accurate. For the islands of Tutuila (and Ofu-Olosega), the ALOS DEM is the most accurate, while for the island of Aunuu the TanDEM-X is the most accurate satellite-based DEM.

For all mountainous islands, the errors are larger than for the coral atolls and Wadden islands (see next section). This difference in DEM error can be explained by the difference in terrain slope. The Wadden islands and coral atolls are mostly flat, while the vulcanic islands have much larger terrain slopes. For the island of Tutuila, and for the islands of Aunu'u and Ofu-Olosega as well, the larger terrain slopes seem to be associated with a larger positive bias in the different satellite-based DEMs. The difference in error between Tutuila and Ofu-Olosega on the one hand and Aunuu on the other hand may also be explained by a difference in terrain slopes. The low-lying part of the island of Aunuu is quite flat, while the low-lying parts of Tutuila and Ofu-Olosega are more sloped.

The influence of the error introduced by the coarse horizontal resolution of satellite-based DEMs can also be seen from the comparison of the different global DEMs for the islands of Tutuila and Ofu-Olosega. In Table 3.3, it can be seen that the DEM errors in the ALOS and SRTM DEM are smaller compared to the MERIT, SRTM void filled and TanDEM-X DEMs. This can be explained by a difference in horizontal resolution; ALOS and SRTM have a horizontal resolution of 30 m and the MERIT, SRTM void filled and TanDEM-X of 90 m. For the island of Aunuu, this distinction is not observed: the TanDEM-X is here even more accurate than the ALOS DEM. This also indicates that the low-lying part of the island of Aunuu is quite flat.

Table 3.3 and 3.4 list averaged error statistics, but do not provide information on the spatial distribution of the error in the different satellite-based DEMs. In order to acquire more information on the distribution of the error, the DEM errors for the different satellite-based DEMs were plotted in a histogram. A complete overview of these histograms can be found in Appendix B, the histograms for the ALOS DEM and TanDEM-X are depicted in Figure 3.5 and 3.6. The red line represents the normal distribution. Also, similar to the coral atolls, difference plots were constructed for the different satellite-based DEMs. In Figure 3.7 and 3.8, the difference plots for the MERIT DEM and SRTM vf DEM for the island of Aunuu are depicted.

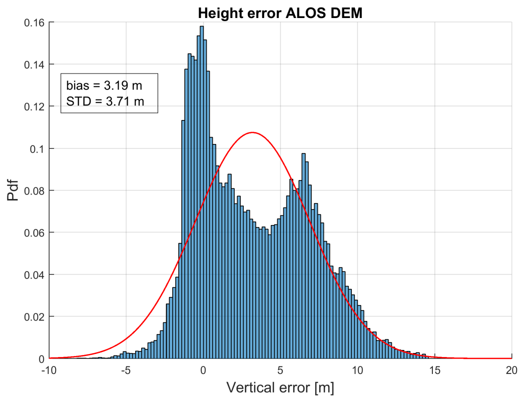


Figure 3.5: Histogram DEM error ALOS DEM, Aunuu

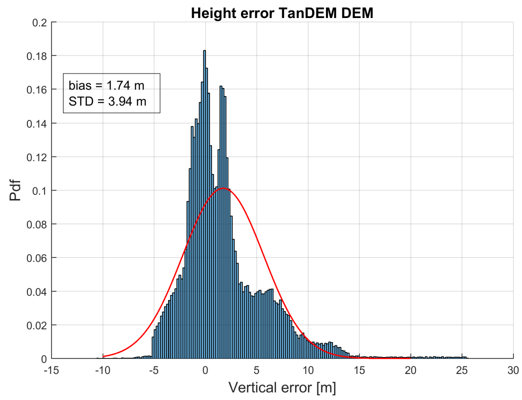


Figure 3.6: Histogram DEM error TanDEM-X, Aunuu

From figure 3.5 and 3.6, it can be clearly seen that the errors of both DEMs deviate substantially from the normal distribution. In both histograms, a peak can be observed around a DEM error of 7 m. This peak is a bit more pronounced for the ALOS DEM. This peak can be explained by looking at the corresponding difference plots in comparison with a satellite image of the island, which are depicted in Figure 3.7, 3.8 and 3.9. A part of the island in the difference plots is blank; this part had elevation values higher than 10 m and was therefore not included in the error analysis. Again, it can be seen that the largest positive DEM errors correspond to densely forested areas. For the island of Aunuu, these forested areas are large relative to the entire island area and therefore have a strong influence on the shape of the histogram, causing a deviation from the normal distribution.

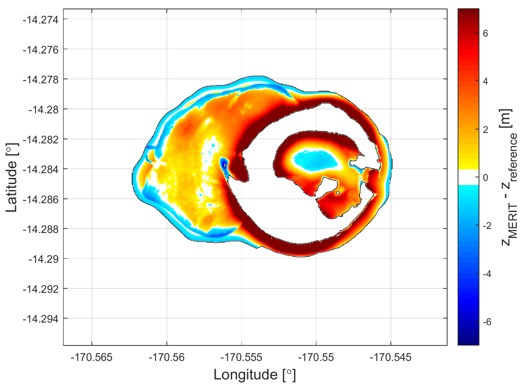


Figure 3.7: Difference plot MERIT DEM, for the island of Aunuu

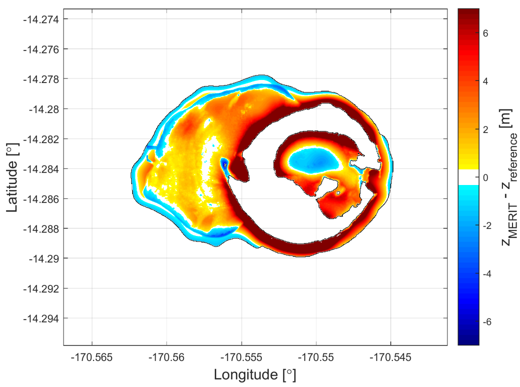


Figure 3.8: Difference plot SRTMvf DEM, for the island of Aunuu

Another interesting conclusion that can be drawn from the comparison of the difference plot for the SRTM vf DEM with the difference plot for the MERIT DEM, is that the positive DEM errors due to vegetation in the MERIT DEM are similar to the positive DEM errors in the SRTM vf DEM. This is surprising, as a correction for tree height bias is included in the construction process of the MERIT DEM. Apparently, the global tree density and tree height maps that are used in this correction step do not cover small islands like Aunuu. In these areas, the MERIT DEM is very similar to the original SRTMvf DEM.

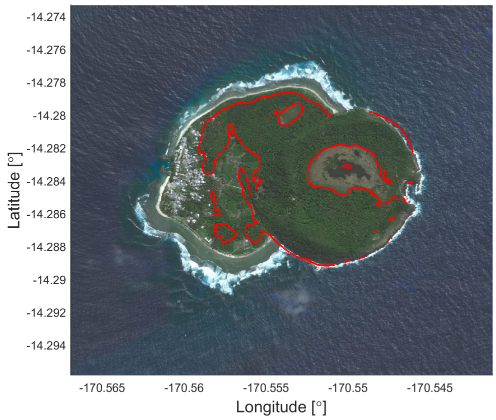


Figure 3.9: Satellite image for the island of Aunuu. On top of the satellite image, the red lines indicate areas for which the DEM error of the ALOS DEM is larger than 4.5 m.

3.3.3. Wadden islands

Similar to the coral atolls and the volcanic islands, the error statistics for the Wadden islands were calculated for each island seperately. A complete overview of the error statistics can be found in Appendix B. The results for the different islands are comparable, with the exception of Vlieland. The error statistics for Texel and Vlieland are depicted in Table 3.5 and 3.6. From these tables, it can be seen that the different global DEMs performed quite different for the two islands. The coverage of the TanDEM-X for the island of Vlieland was very poor, with high elevation errors as a result. The other global DEMs (with the exception of the ASTER DEM), performed quite good for Vlieland. For the island of Texel, and for the other Wadden islands as well, this was the other way around; the TanDEM-X performed generally better than the other global DEMs.

Table 3.5: Error statistics for the island of Texel

	Bias [m]	**MAE [m]**	**UMAE [m]**	**RMSE [m]**	**URMSE [m]**	**min [m]**	**max [m]**	**LE90 [m]**
ALOS	-0,94	1,64	1,31	2,04	1,81	-8,66	7,26	3,12
ASTER	7,27	7,33	2,26	7,86	2,98	-2,97	17,50	10,62
MERIT	-0,60	0,78	0,59	1,03	0,84	-4,22	2,81	1,54
SRTM	-1,02	1,33	0,89	1,59	1,23	-6,16	4,44	2,42
SRTMvf	-1,01	1,28	0,81	1,53	1,15	-5,96	4,20	2,19
TanDEM-X	0,26	0,75	0,82	1,52	1,49	-9,42	10,17	1,88

Table 3.6: Error statistics for the island of Vlieland

	Bias [m]	**MAE [m]**	**UMAE [m]**	**RMSE [m]**	**URMSE [m]**	**min [m]**	**max [m]**	**LE90 [m]**
ALOS	-0,34	1,55	1,45	2,22	2,19	-8,40	7,88	3,84
ASTER	4,50	5,03	2,92	5,83	3,69	-7,35	16,16	8,86
MERIT	-0,27	1,68	1,67	2,20	2,19	-7,63	6,99	3,62
SRTM	-0,08	1,69	1,68	2,18	2,18	-7,21	7,04	3,60
SRTMvf	-0,11	1,57	1,56	2,03	2,03	-6,77	6,47	3,35
TanDEM-X	1,75	2,93	3,26	5,69	5,42	-23,13	34,10	7,47

From Table 3.5, it can be seen that all DEMs are negatively biased except for the ASTER and TanDEM-X. This was the case for all 5 Wadden islands. Just like for the coral atolls and the vulcanic islands, the ASTER DEM has a very large positive bias, a large MAE and RMSE and is the least accurate DEM. The TanDEM-X has a small positive bias, which ranges from 0.06 m till 0.65 m over the different islands (only for Vlieland the positive bias of the TanDEM-X is very large: 1.75 m). The MAE and RMSE are also small compared to the other DEMs. However, it should be noted that the RMSE of the TanDEM-X is comparable to the SRTM and SRTMvf DEMs and even higher than the MERIT DEM, while the MAE of the TanDEM-X is the lowest. This indicates that although the mean error of the TanDEM-X is low, the DEM contains large local errors (larger than the other global DEMs). This is also clear from the comparison of the minimum, maximum and 90% error between the different DEMs. This was not only observed for Texel, but also for Terschelling, Ameland, and Schiermonnikoog.

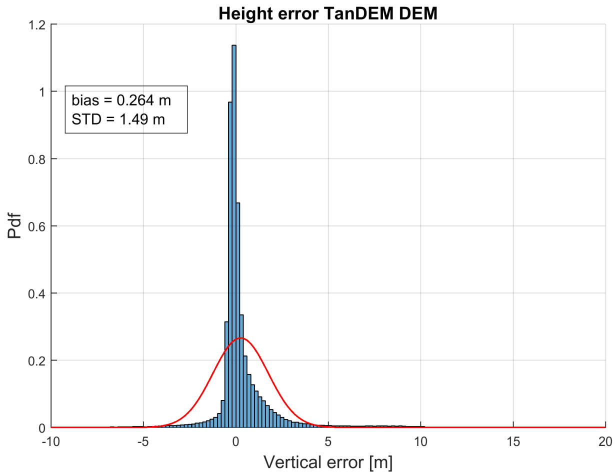


Figure 3.10: Histogram DEM error TanDEM-X, Texel

The error histograms for the different DEMs can be found in Appendix B. The error histogram of the TanDEM-X is depicted in Figure 3.10. The red line corresponds to the normal distribution. It can be seen that the TanDEM-X DEM errors are not normally distributed. This was also observed for the other DEMs at all islands.

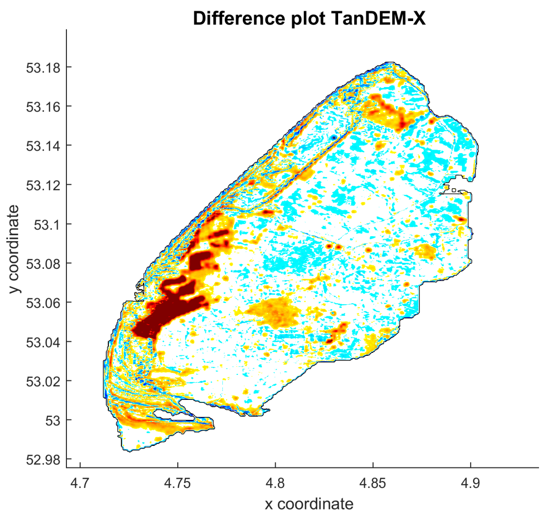


Figure 3.11: Difference plot TanDEM-X, Texel

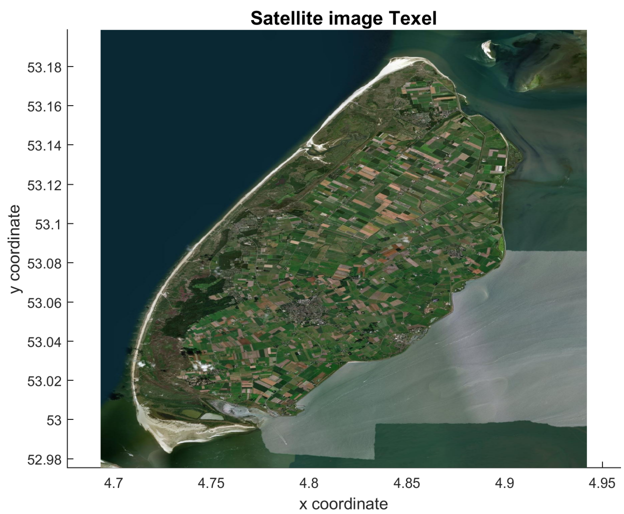


Figure 3.12: Satellite image Texel

Similar to the coral atolls and volcanic islands, difference plots for the different satellite-based DEMs were constructed for all Wadden islands, in order to analyse the spatial distribution of the DEM error. The TanDEM-X difference plot is depicted in Figure 3.11. The satellite image for the island of Texel is depicted next to it. From the comparison of these figures, we can draw similar conclusions as for the coral atolls and the volcanic islands. In the figure, it can be seen that the largest DEM errors occur in forested areas (i.e. the dark green

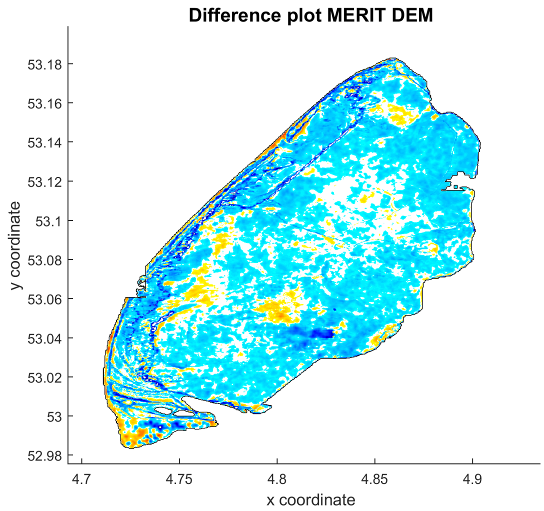


Figure 3.13: Difference plot MERIT DEM, Texel

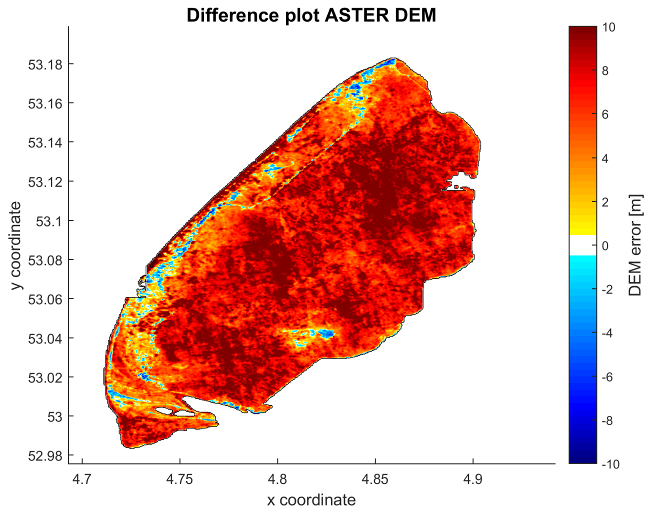


Figure 3.14: Difference plot ASTER DEM, Texel

spots in the satellite image). Furthermore, DEM errors occur in builded areas. In the TanDEM-X, the villages of Den Burg and Cocksdorp can be clearly seen. Also smaller villages like Oudeschild, Oosterend and Oost can be seen on the difference plot. The positive DEM error in these builded areas is smaller than the DEM error in the forested area, but still significant (in the order of 1-2 m).

The link between DEM error and forested areas can be seen for all islands for the different satellite-based DEMs, except for the MERIT and ASTER DEM. For the island of Texel, the MERIT and ASTER difference plots are depicted in Figure 3.13 and 3.14. From the MERIT difference plot, it can be seen that the DEM error in the forested areas is much lower compared to the TanDEM-X. This was observed for all Wadden islands. This is probably due to the tree height correction of the MERIT DEM (see Chapter 2). In contrast to the coral atolls, apparently the Wadden islands are included in the three height maps that were used for the tree height correction in the construction process of the MERIT DEM.

The link between positive DEM error and builded areas can also be observed in the MERIT DEM difference plot. Again, the DEM error in these areas is in the order of 1-2 m. In contrast to the other DEMs, the ASTER difference plot shows no link between DEM error and forested or builded areas. This was observed for all 5 Wadden islands, but the reason for this is not clear.

3.4. Concluding remarks

From the error analysis of the different satellite-based DEMs, it can be concluded that all satellite-based global DEMs contain (significant) errors.

The error is related to different factors, which were also found in literature (see Chapter 2). First of all, the DEM error is related to terrain slope. In literature it was found that this error is caused both by larger measurement errors and by large errors caused by the horizontal resolution of the DEMs in relation to the micro-relief of the terrain. This was confirmed in the error analysis: for the coral atolls and Wadden islands (which are generally flat) smaller satellite-based DEM errors were found compared to the DEM errors for the vulcanic islands, which have larger terrain slopes. Also, the influence of DEM resolution on the error was confirmed: for the islands of Tutuila and Ofu-Olosega larger errors were found for the global DEMs with a coarser resolution. This error was also apparent for the islands of Roi Namur and Ebeye. For these islands, the oceanward ridge is not accurately represented in the different global DEMs, because the spatial scale of these ridges is small compared to the horizontal resolution of the global DEMs.

Secondly, DEM error is related to land cover. From a comparison between the difference maps of the satellite-based DEMs and satellite images of the different islands, it can be seen that the DEM errors are correlated with forested and builded areas for almost all DEMs, except for the ASTER DEM. In general, forested areas lead to larger positive DEM errors (in the order of 7 m) than the builded areas (in the order of 1-2 m). For the MERIT DEM, smaller errors were found at the Wadden islands in forested areas. However, the errors in forested areas were comparable at the smaller islands in the Pacific Ocean (i.e. Roi Namur and Aunuu). This can be explained by the fact that the forested areas at these small islands are not included in the global vegetation maps that were used for the vegetation correction in the construction process of the MERIT DEM.

In general it can be stated that the ASTER DEM is the least accurate for all islands. For the different coral atoll and Wadden islands (except for Vlieland, where the TanDEM-X had a bad coverage) the TanDEM-X is the most accurate. It generally has the lowest bias, MAE and RMSE. However, it was also observed that the local errors can be larger for the TanDEM-X compared to the other DEMs; the TanDEM-X generally has larger minimum and maximum errors. Also, the coverage of the TanDEM-X is not accurate everywhere, as this DEM showed large errors for the island of Vlieland. For the volcanic islands, the ALOS DEM was the most accurate. It is expected that the difference in horizontal resolution between the ALOS (30 m) and TanDEM-X (90 m) causes the TanDEM-X to be less accurate in areas with steeper terrain slopes.

In general, in case a publicly available satellite-based DEM must be used for a certain island, the best choice depends on the terrain slope and on the landcover. Based on the analysis as described in this chapter, the ALOS DEM should be chosen for steeper sloping terrains. For mild sloping terrains, the TanDEM-X should be used. However, for mild sloping terrains that are densely forested, the MERIT DEM can be more accurate than the TanDEM-X. This depends on whether or not the island is included in the global landcover maps that were used in the construction process of the MERIT DEM.

4

Improving satellite-based DEMs: a building correction method

In the previous chapter, different satellite-based DEMs were compared to measured data for 11 islands. From this analysis, it was concluded that all global satellite-based DEMs contain significant errors. Furthermore it was concluded that these errors are linked to terrain slope, where larger terrain slopes lead to larger DEM errors, and to land cover. Especially forested and builded areas seem to be correlated with positive DEM errors.

In this chapter, a method to correct the satellite-based DEMs for the presence of buildings is suggested and tested. From the DEM analysis described in Chapter 3, it was concluded that forested areas and builded areas induce positive DEM errors. Forested areas generally cause larger DEM errors than built areas, but the errors in builded areas have a larger influence on the eventual coastal flood risk. These errors can be (partially) corrected if the location of forests and buildings is known. As was described in chapter 2, there are global vegetation maps that can be used to define the location of forests. These maps have also been used in the construction of the MERIT DEM. However, these maps have a very coarse horizontal resolution and many small islands are excluded in these maps. Without more accurate information on the location of forested areas for these islands, it is not possible to carry out a vegetation correction in an automatic manner. However, for the location of buildings, information from Open Street Map (OSM) can be used. A methodology to carry out a building correction based on OSM data is described. In Section 4.1, the OSM database is introduced and a methodology for removing building biases from satellite-based DEMs is suggested. In Section 4.2, the results are described for the islands of Ebeye and Texel. Finally, some concluding remarks are given in Section 4.3.

4.1. Materials and method

In this section, the suggested methodology for the building correction of satellite-based DEMs will be explained. In section 4.1.1, the OSM database will be shortly introduced. Subsequently, in Section 4.1.2, the workflow will be explained.

4.1.1. Open Street Map

OpenStreetMap is a collaborative project to create a free editable map of the world. It is based on an online database which is open to everyone. The aim of this database is to maintain data about, among others, the location and height of buildings. It is an open database, which means that everybody can contribute and add their data to the database. In open street map (OSM), a lot of information on the location of buildings is available on a global scale. In general, this information entails the location and type of buildings. In some areas, information on the height of buildings is available, but this information is generally scarce (contributors, 2019b). For the areas that were covered in the analysis as described in the previous chapter, this information was not available. The information that is available on the location and type of buildings is used to correct for buildings in the different satellite-based DEMs. The methodology that was applied to do this is described in the next section.

4.1.2. Suggested methodology

As was described above, in OSM a lot of information on the type and location of buildings is available on a global scale. From the OSM database, shapefiles can be downloaded that indicate the locations of buildings. Usually also some information is available regarding the type of building (e.g. hospital, school, house). For some locations in the world, also building information on the amount of floors and the height per floor is available. However, this information is rare and is not available for the islands that were included in the comparison.

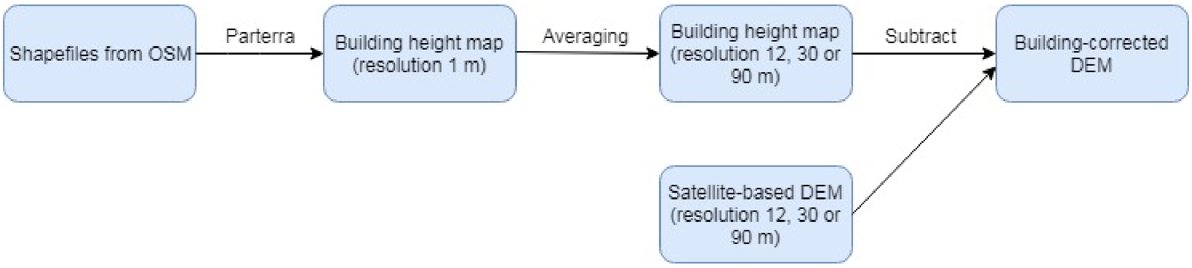


Figure 4.1: Building correction

The method to correct the satellite-based DEMs for buildings is summarized in a flowchart in Figure 4.1. For all islands included in the comparison, shapefiles of the buildings are downloaded from the OSM database. Using the Parterra toolkit in the Google Earth Engine (GEE), these shapefiles are converted to building height maps in raster format with a horizontal resolution of 1 meter. This small horizontal resolution was chosen in order to be able to accurately incorporate the buildings. For coarser horizontal resolution, the buildings are not very well represented in the produced building height maps. Since no information on building heights was available for the buildings on the considered islands, assumptions regarding the amount of floors and the height per floor are made.

In the determination of the amount of floors per building, a distinction is made between the Wadden islands and the islands in the Pacific Ocean. According to the PCRAFI report, over 97% of the buildings in the PICs have only one floor and less than 0.5% is higher than two floors (PCRAFI, 2013). Therefore, most buildings on the different islands in the Pacific Ocean are expected to have 1 floor only. For the Wadden islands, most buildings are expected to have 2 floors. For all islands, the height per floor is assumed to be 3 meters. For some buildings the building type is also available from the OSM database (e.g. whether a building is a hospital or a house). A list of different buildings types for the Wadden islands and for the islands in the Pacific Ocean is included in Appendix B. The assumed amount of floors and height per floor for the different building types is included as well. All points in the building height maps that are not covered by buildings are assigned an elevation of 0 meter.

Subsequently, these high resolution building height maps are aligned to the different satellite-based DEMs for the different islands. The aligned building height maps have the same resolution as the satellite-based DEMs (i.e. 30 or 90 meter, depending on the considered DEM). The elevation values for these low resolution building height maps are obtained by taking the mean value of all points in the high-resolution maps that are located inside a certain tile of the satellite-based DEMs. This value is then subtracted from the corresponding elevation of the tile in the satellite-based DEM.

As was explained in Chapter 3, the elevations of the satellite-based DEMs are determined by taking the average of all measurements within a certain tile. Substracting the average building height of that tile from the elevation value should therefore correct for the buildings present, assuming that the elevation of the satellite-based DEM is a perfect average of the terrain within the tile.

4.2. Results

The building correction method as described in the previous section is applied to all 11 islands that were included in the comparison as described in the previous chapter. Subsequently, the errors for these building-corrected DEMs were calculated in the same way as in Chapter 3. However, for many islands the builded area is only a small proportion of the total area of the island. For these islands, the difference between the error statistics before and after the building correction was very small. Only for the island of Ebeye, which is a small island that is almost entirely covered with buildings, there was a large difference on the scale of the entire island. The results for Ebeye will be discussed in Section 4.2.1. Furthermore, the error statistics before and after building correction were calculated for the city of Den Burg on the island of Texel. These results will be discussed in Section 4.2.2.

4.2.1. Ebeye

In the previous chapter, it was concluded that the island of Ebeye is almost entirely covered with buildings. Therefore, it is interesting to assess the effect of the building correction for this island. In Table 4.1 the error statistics for the island of Ebeye are depicted for the different global DEMs before and after building correction. The normal numbers indicate the error statistics before building correction, the bold numbers indicate the error statistics after building correction. From theis table, it can be concluded that the building correction decreases the bias and MAE for all global DEMs, except for the TanDEM-X. The TanDEM-X has a negative bias, which is increased due to the building correction. The MAE and RMSE increase as well due to the building correction, but the UMAE decreases. Furthermore, it should be noted that even though the errors are increased due to the building correction, the TanDEM-X is still the most accurate DEM after building correction. Even though the building-corrected TanDEM-X has the largest bias (except for the ASTER DEM), the MAE and RMSE are still the lowest.

Table 4.1: Error statistics for the island of Ebeye. The normal numbers indicate the error statistics before the building correction. Bold numbers indicate the error statistics after building correction.

	Bias [m]	**MAE [m]**	**UMAE [m]**	**RMSE [m]**	**URMSE [m]**	**min [m]**	**max [m]**	**LE90 [m]**
ALOS	1.74	2.13	1.35	2.45	1.73	-3.49	6.74	3.69
	1.03	**1.81**	**1.55**	**2.23**	**2.10**	**-4.21**	**6.35**	**3.52**
ASTER	5.42	5.45	5.45	5.97	2.50	-2.35	13.23	8.54
	4.75	**4.85**	**4.85**	**5.37**	**2.40**	**-3.58**	**12.20**	**7.83**
MERIT	0.76	1.64	1.45	1.93	1.77	-4.34	4.83	3.07
	0.07	**1.31**	**1.30**	**1.66**	**1.65**	**-5.94**	**3.90**	**2.74**
SRTM	1.12	1.56	1.11	1.85	1.41	-3.10	5.25	2.94
	0.48	**1.29**	**1.20**	**1.77**	**1.70**	**-4.30**	**4.88**	**2.70**
SRTMvf	1.12	1.60	1.19	1.87	1.50	-3.44	4.60	2.90
	0.45	**1.51**	**1.47**	**1.88**	**1.87**	**-4.82**	**3.94**	**2.72**
TanDEM-X	-0.27	0.92	0.94	1.23	1.20	-4.07	3.62	2.22
	-0.94	**1.18**	**0.84**	**1.53**	**1.21**	**-4.86**	**2.80**	**2.53**

In Figure 4.2 the TanDEM-X difference maps for the island of Ebeye before and after building correction are depicted. From these maps it can be seen that the DEM error after building correction indeed becomes negative almost everywhere on the island. This could be explained by the fact that apart from the DEM errors introduced by the presence of buildings, the TanDEM-X also has a negative bias at the island of Ebeye.

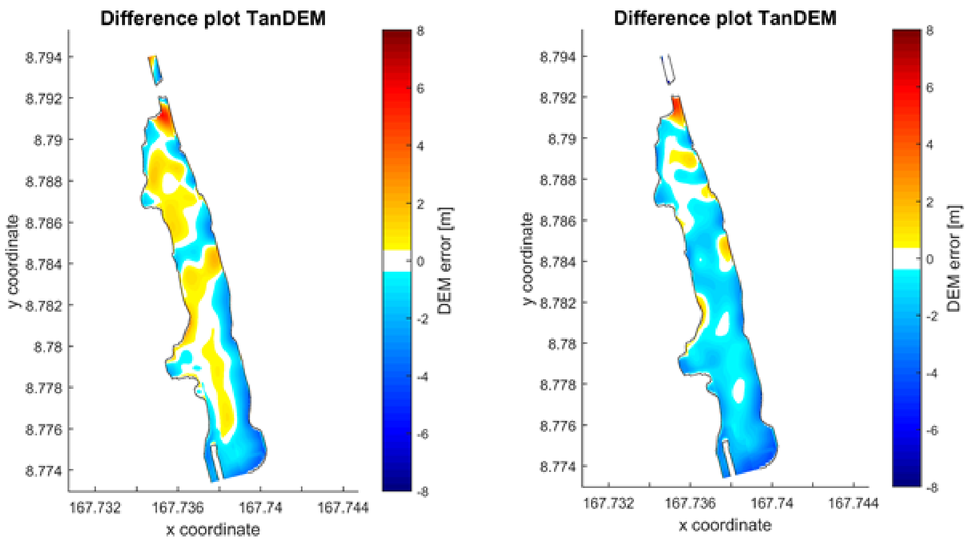


Figure 4.2: Difference plot TanDEM-X, Ebeye, before (left) and after building correction (right)

4.2.2. Den Burg, Texel

A building correction was also carried out for the island of Texel. Since the builded area for the island of Texel is small compared to the entire island, the effect of the building correction cannot be seen from a comparison of error statistics for the entire island. To assess the effect of the building correction, the error statistics were therefore calculated for the city of Den Burg only. The results are depicted in Table 4.2. The bold numbers indicate the error statistics for the city of Den Burg, after building correction.

Table 4.2: Error statistics for the city of Den Burg, Texel. The normal numbers indicate the error statistics before the building correction. Bold numbers indicate the error statistics after building correction.

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	1.85	1.97	1.01	2.28	1.33	-2.50	6.34	3.42
	0.41	**1.02**	**0.96**	**1.34**	**1.28**	**-3.87**	**4.97**	**2.15**
ASTER	8.39	8.39	1.25	8.54	1.58	3.97	13.26	10.33
	7.00	**7.00**	**1.52**	**7.26**	**1.91**	**1.45**	**12.84**	**9.45**
MERIT	0.50	0.64	0.49	0.80	0.62	-1.42	2.43	1.27
	-0.88	**1.01**	**0.64**	**1.20**	**0.82**	**-3.37**	**1.62**	**1.90**
SRTM	-0.03	0.80	0.80	1.01	1.01	-2.91	3.12	1.65
	-1.43	**1.64**	**0.99**	**1.91**	**1.26**	**-5.31**	**2.52**	**2.95**
SRTMvf	-0.03	0.68	0.68	0.86	0.86	-2.63	2.63	1.41
	-1.41	**1.53**	**0.76**	**1.71**	**0.97**	**-4.33**	**1.73**	**2.57**
TanDEM-X	1.38	1.40	0.51	1.53	0.66	-1.14	4.16	2.20
	0.01	**0.60**	**0.60**	**0.77**	**0.77**	**-3.02**	**2.77**	**1.28**

Similar to the island of Ebeye, it can be seen that the building correction improves the global DEM in case it is positively biased. For the city of Den Burg, this is the case for the ALOS, ASTER and TanDEM-X. For these global DEMs, the bias MAE and RMSE decrease after the building correction. However, for the MERIT, SRTM and SRTM void filled DEMs, the building correction only seems to decrease the DEM accuracy.

However, when considering a cross-section of the city of Den Burg as depicted in Figure 4.3, this is not entirely true. In Figure 4.4 and 4.5, the elevation profiles of the reference, the TanDEM-X and MERIT DEM are depicted. The black lines represent the reference DEM for the island, the red line the satellite-based DEM before building correction and the blue line the satellite-basd DEM after building correction. In Figure 4.4, it can be seen that the bias of the TanDEM-X is almost negligible in the areas around the city of Den Burg, where there are no buildings (see left and right side of the cross section). In the city, the DEM is positively biased due to the presence of buildings. This positive bias is significantly decreased due to the building cor-

Figure 4.3: Cross section Den Burg, Texel

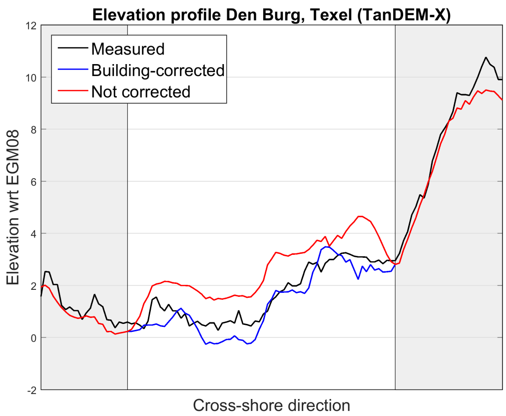


Figure 4.4: Cross section Den Burg, TanDEM-X

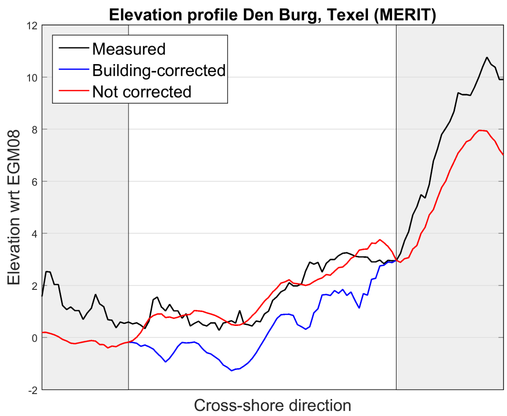


Figure 4.5: Cross section Den Burg, MERIT

rection. For the MERIT DEM however, Figure 4.5 shows that the DEM is negatively biased in the areas around the city. In the city, a combination of this negative overall bias and the positive error due to the buildings cancel each other (partly) out. By applying the building correction to this DEM, the errors in the urban area increase, due to the presence of the negative overall bias. However, when considering the general shape of the different elevation profiles rather than the absolute heights, the general shape of the builded-corrected blue line has a greater resemblance to the shape of the black, reference line than the uncorrected red line. If the MERIT DEM would also be corrected for the negative overall bias, the building-corrected DEM would be more accurate than the uncorrected DEM. The same was observed for the SRTM and SRTM void filled DEMs. The elevation profiles for these global DEMs can be found in Appendix C.

In Figure 4.6, the difference maps of the MERIT DEM for the island of Texel are depicted before and after building correction. The location of Den Burg is indicated with the black circle in both maps. It can be clearly seen that the positive errors in the city of Den Burg are decreased due to the building correction. As was already observed by studying the cross-section of Den Burg in Figure 4.5, the building-corrected MERIT DEM is too low in the city of Den Burg and the negative DEM errors are comparable to the negative bias of the areas around the city. A similar effect of the building correction was observed for the other global DEMs as well. The difference plots of these DEMs after building correction can be found in Appendix C. The only exception is the ASTER DEM. For this global DEM, there was no clear relation found between vegetation/buildings and DEM error (see previous chapter). The building correction of the ASTER DEM leads to a decrease in errors locally because the DEM has a very large positive bias. However, it not clear that the general shape of the ASTER DEM also improves due to the building correction.

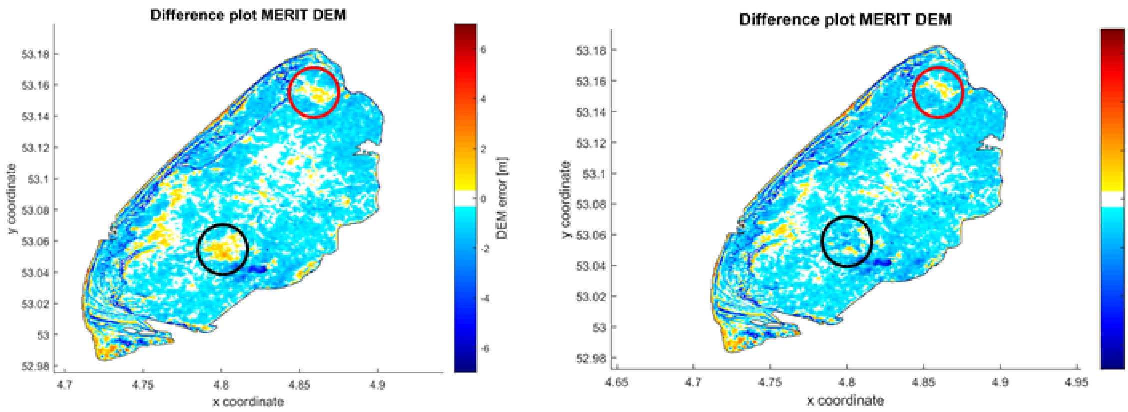


Figure 4.6: MERIT DEM difference plot before (left) and after (right) building correction

The comparison of the two difference plots also shows that the errors due to buildings are not completely removed due to the building correction. For example, the village of Cocksdorp in the northern part of the island, indicated with the red circle in Figure 4.6, is still present in the building corrected DEM, although the errors have decreased. This can be partly explained by the forested areas north of the village. The positive DEM error due to the presence of these trees is still present after building correction of the DEM. Also, based on a comparison between the OSM building map and satellite image for Texel, it could be concluded that OSM does not include all buildings for this area. Lastly, the assumed building heights may be too low or the assumption that the positive building error equals the average building heights in a DEM tile may not be valid everywhere.

4.3. Concluding remarks

A building correction based on data from OSM was suggested and carried out for the different satellite-based DEMs. From a comparison of the error statistics of the original DEMs and the building corrected DEMs, it could be concluded that due to the building correction the errors can both in- and decrease.

This is caused by the fact that the satellite-based DEMs are contaminated by different error sources. It was observed that when a DEM has a negative bias, this negative bias and the positive errors induced by the presence of buildings can (partly) cancel each other out. So, if a DEM is negatively biased, the building correction locally increases the errors. However, even if this is the case, the general shape of the DEM is still improved by the building correction. In cases where the DEM is not or positively biased, the errors are decreased after the building correction.

Lastly, it was observed that the building correction does not completely remove the errors due to buildings everywhere. This can have different causes. First of all, the heights of the buildings are not exactly known; assumptions regarding the height of different building types were made. Secondly, from a comparison between satellite images and OSM data, it was concluded that not all buildings are included in the OSM database. Lastly, the assumption that the error due to buildings is equal to the average building height in a certain area, may not be valid everywhere.

5

Flood model: from input to model formulation

An important part of a coastal flood risk assessment is the flood model which is applied. In the choice for a certain model, the balance between accuracy and computational demand should be tailored to the goal of the flood risk assessment. In the context of this thesis, the goal is to obtain a quick, reasonable estimate of the coastal flood risk for a very large area (i.e. all islands in the Pacific Ocean). Due to the desired spatial scale of the flood risk assessment, it is important that the flood model is low in terms of computational demand. Therefore, a quick model was developed from a combination of two other models. The setup of this quick flood model will be described in this chapter.

5.1. Model set-up

In many large-scale coastal flood assessments, coastal flood risk is assessed using the bathtub method on water levels (e.g. (PCRAFI, 2013) for SIDS in the Pacific Ocean). In the determination of the input waterlevels the offshore water level, tides and storm surge were taken into account. Waves were excluded in this coastal flood model. However, different studies showed waves to be an important contributor to coastal flooding on coral atolls (Storlazzi et al., 2015) (Merrifield et al., 2014). Therefore, it is expected that the coastal flood risk assessment will improve by taking these waves into account in the flood model. The aim of the simple flood model as described in this chapter is to predict the maximum water levels during a flood event as accurately as possible. The maximum water levels can subsequently be used as input in a flood risk assessment study.

There exist different simple parametric models to calculate the wave transformation in the inner surf zone. In Appendix D, a short overview of these models is given. For the simple model described in this chapter, the Janssen-Battjes model (Janssen and Battjes, 2007) was chosen. This model is an iteration on the original model developed by Battjes and Janssen (Battjes and Janssen, 1966). In the original model, the surf zone is assumed to be saturated (i.e. the wave height is limited by the local water depth). However, especially for surf zones with steeper slopes, this assumption is not valid. (Baldock et al., 1998) therefore adjusted the original model to improve the accuracy for steeper slope environments by releasing the saturated surf zone assumption. Janssen and Battjes subsequently improved the model developed by Baldock (Baldock et al., 1998), by correcting for an algebraic inconsistency in the model. This corrected model was chosen instead of the original Battjes-Janssen model because many coral atolls have steep beach slopes; for these environments, the original Battjes-Janssen model may be less accurate. In order to avoid confusion, in the remainder of this report the model that was used will be referred to as the Janssen-Battjes model, instead of the Battjes-Janssen model, to indicate that a later iteration of the original Battjes-Janssen model was used.

The Janssen-Battjes model was developed to calculate the dissipation of energy in random waves breaking on a sandy beach. The water levels in this model are solved using a momentum balance, where the gradient in radiation stress is balanced by a gradient in water level (see equation 5.1). The wave height can subsequently be calculated using an energy balance (see equations 5.4). At the type of beaches for which the Janssen-Battjes model was originally developed, the amount of long wave energy is usually low and short waves dominate the wavespectrum. However, for coral atolls fronted by a steep fore reef and a reef flat, the situation is different. Due to the generation of long waves in the breakpoint mechanism and the breaking and frictional dissipation of short wave energy over the reef, the wave spectrum changes from short wave dominated to long wave dominated towards the beach foot (see Figure 5.1). At the location of the beach foot, long wave energy accounts for a significant proportion of the total wave energy. Initial tests showed that the accuracy of the simple flood model improved when the short and long wave heights were calculated seperately; therefore the long and short wave heights are calculated using a long and short wave energy balance respectively.

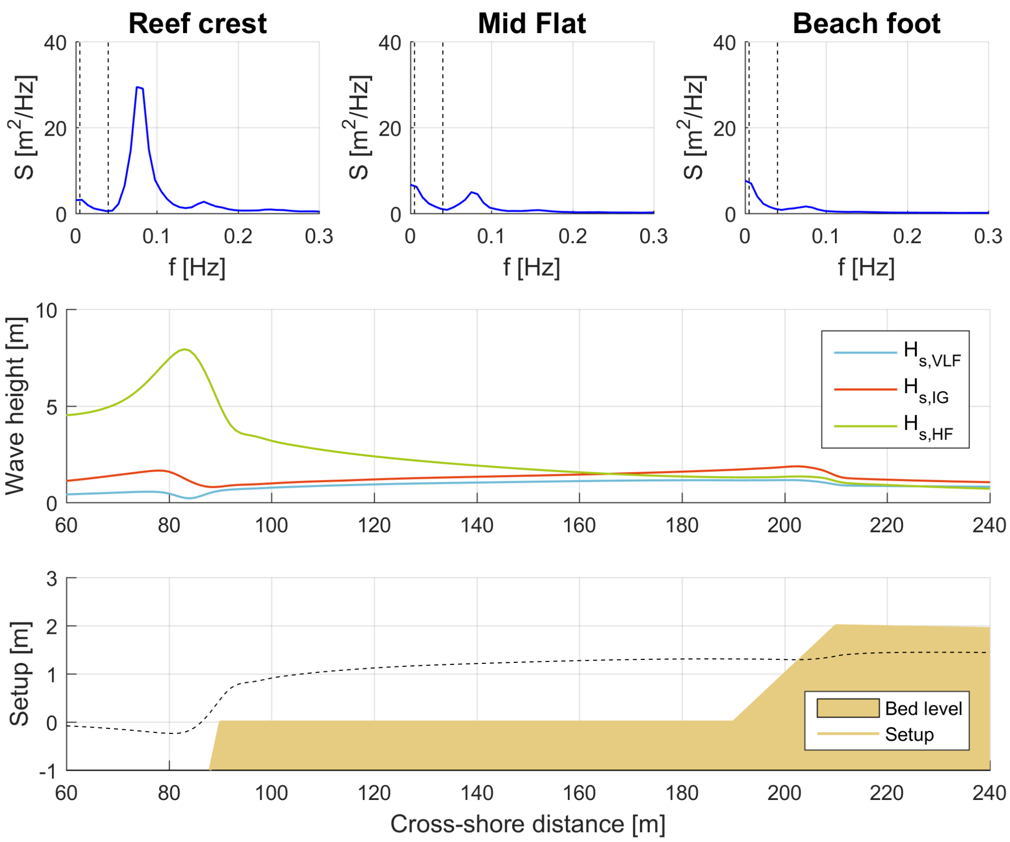


Figure 5.1: Cross-shore overview of the transformation of the different wave components and the wave spectra at 3 different locations: at the reef crest, mid flat and beach foot (H_{m0} = 5 m, β_f = 1/2, W_{reef} = 100 m, β_b = 1/10, z_{island} = 2 m, β_{island} = -1/1000)

The Janssen-Battjes model is only valid in areas with positive slopes. For these areas, the assumption in the momentum balance that the gradient in radiation stresses is balanced by a gradient in water level is valid. In flat or downslope areas, this assumption is not valid (the water cannot pile up) and the momentum balance can no longer be used to calculate the water level. Most coral atolls are flat or have negative slopes. For these islands, the water level on the island needs to be calculated using another method. In order to calculate the water levels on these islands, the parametric Janssen-Battjes model is combined with the flood intensity index model, or IW-model in short (Dottori et al., 2018). This model was originally developed as a semi-physical alternative to calculate large scale river flooding. In this model, the water level slope at each location is calculated based on the slope in the topography and the roughness (linked to the Manning value). At the island, the water levels are computed using the Iw-model, but the wave heights are still computed using a wave energy balance.

In Figure 5.2, the input conditions and the two different models are indicated related to the different locations on the island. These input conditions and different models will be described in more detail below.

5.2. Input conditions (BEWARE)

The input conditions for the flood model can be obtained from BEWARE ('Bayesian Estimator for Wave Attack in Reef Environments'). (Pearson et al., 2017) used a XBeach Non-Hydrostatic model to create a large

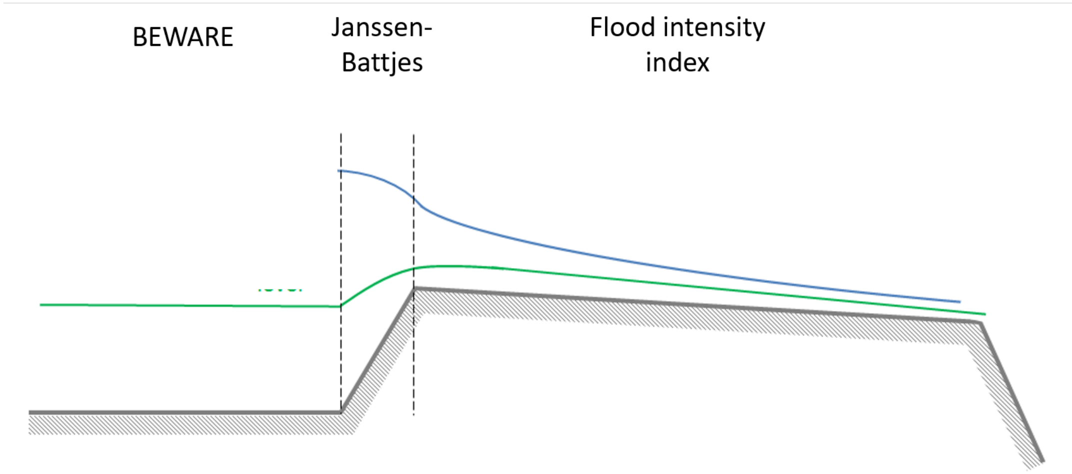


Figure 5.2: Model overview

synthetic database that can be used to link incident hydrodynamics and coral reef geomorphology to waterlevels and wave heights at the beach foot. Different parameters can be inputted in the database: offshore water levels η_0 and waves $H_{s,0}$, offshore wave steepness $H_{s,0}/L_0$, reef flat width W_{reef}, fore reef slope β_f, bed friction c_f and beach slope β_b. Given a certain combination of input parameters, the database can be used to obtain estimates of the waterlevel including wave setup, the significant sea/swell wave height (0.04 - 1 Hz) $H_{mo,SS}$ and the significant low-frequency wave height(0.001 - 0.04 Hz) $H_{m0,LF}$ at the location of the beach foot. These water levels and wave height components are assumed to be known as input for the flood model described in this chapter. For a detailed explanation of the BEWARE database, the reader is referred to (Pearson et al., 2017) and (Pearson, 2016).

5.3. Janssen-Battjes model

The Janssen-Battjes model is applied untill the start of the island (see Figure 5.2). As was already described above, in this model the variations in water levels are calculated using a momentum balance (see Equation 5.1) and the short and long waves are calculated using a short and long wave energy balance respectively (see Equation 5.4). The goal of the simple flood model is to obtain an estimate of the maximum water levels over the island during a certain flood event. It is assumed that these maximum water levels occur when the long waves, that can be quite significant in reef environments (see Figure 5.1), contribute to a temporary increase in water level. Since the local water depth is then temporarily increased under a long-wave crest, the short waves can also be higher. This can also be understood as if the highest short waves 'ride' on top of the long-wave crests. This positive correlation between the short and long wave height was found by, among others, (Janssen et al., 2003). The water level that is used in the calculations in the simple model therefore includes a long wave-component. Below, the calculation of the water level and the short and long wave height will be discussed in more detail.

5.3.1. Calculation of the water level

In the momentum balance, it is assumed that the gradient in radiation stress ($\frac{dS_{xx}}{dx}$) is compensated by a gradient in water level (Bosboom and Stive, 2012). As described above, the maximum water level is assumed to include a long wave component, equal to $Hs_{LF}/2$ (see equation 5.2).

$$\frac{dS_{xx}}{dx} + \rho g h \frac{d\tilde{\eta}}{dx} = 0 \tag{5.1}$$

in which

$$h = z_{s0} + \tilde{\eta} + Hs_{LF}/2 \tag{5.2}$$

and

$$S_{xx} = (\frac{1}{2} + \frac{2kh}{sinh(2kh)})E \tag{5.3}$$

In these equations, S_{xx} is the radiation stress in shore-normal direction, η the setup, z_{s0} the water depth (not including setup), h the water depth (including setup and a long wave component) and E is the wave energy (see Equation 5.6).

5.3.2. Short wave transformation

The short waveheight can be calculated using the short wave energy balance, see Equation 5.4. In this equation, P_x is the x-component of the time-mean energy flux per unit length, x is a horizontal coordinate normal to the still-water line and D is the time-mean dissipated power per unit area. The time-mean flux per unit length P_x is calculated using Equation 5.5, in which E is the wave energy and c_g is the group velocity. In this simple model, dissipation due to wave breaking (D_w) and due to bottom friction (D_f) are taken into account.

$$\frac{\delta P_x}{\delta x} = -D_w - D_f \tag{5.4}$$

$$P_x = Ec_g \tag{5.5}$$

in which

$$E = \frac{1}{8}\rho g H_{rms}^2 \tag{5.6}$$

and

$$c_g = \frac{2\pi f}{k}(\frac{1}{2} + \frac{kh}{sinh(2kh)}) \tag{5.7}$$

Dissipation due to wave breaking

In order to quantify the dissipation due to wave breaking, the Battjes-Janssen dissipation model for random waves is used. In this model, the energy dissipation rate in a broken wave is estimated from that in a bore of corresponding height (Battjes and Janssen, 1966). This leads to Equation 5.8 for energy dissipation due to wave breaking D_w.

$$D_w \sim \frac{1}{4} f \rho g \frac{H_b^3}{h} \tag{5.8}$$

In a random wave field, not all waves are equal in height and therefore not all waves are breaking. Equation 5.8 only applies to breaking waves; waves with a wave height higher than a certain maximum wave height H_b. The total energy dissipation rate due to wave breaking is found by multiplying the energy dissipation due to each broken wave by the fraction of broken waves Q_b, see equation 5.9. In this expression, $\bar{f}$ is the mean frequency and B is a calibration factor. In the simple model as described in this chapter, this factor is equal to 1.

$$D_w = \frac{B}{4h}\bar{f}\rho g H_{rms}^3 Q_b \tag{5.9}$$

Both Thornton and Guza (Thornton and Guza, 1983) and Baldock (Baldock et al., 1998) measured the distribution of wave heights at different points in the cross-shore during different wave flume experiments. They showed that the initial offshore Rayleigh distribution is modified by shoaling and breaking into new distributions which are again nearly Rayleigh, with some energy loss. Therefore, for the calculation of the proportion of broken waves, the short waves are assumed to be Rayleigh distributed, also in the surf zone. This is depicted in Figure 5.3. The waves are assumed to be breaking when its height exceeds a certain maximum wave height H_b. The proportion of broken waves is obtained by integrating the Rayleigh distribution over all waves for which H/H_{rms} > H_b/H_{rms}. This results in equation 5.10, where erf represents the error function.

$$D_w = \frac{3\sqrt{\pi}}{16} B\bar{f}\rho g \frac{H_{rms}^3}{h} \left[1 + \frac{4}{3\sqrt{\pi}} \left(\left(\frac{H_b}{H_{rms}}\right)^3 + \frac{3}{2}\left(\frac{H_b}{H_{rms}}\right)\right) exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right] - erf\left(\frac{H_b}{H_{rms}}\right)\right] \tag{5.10}$$

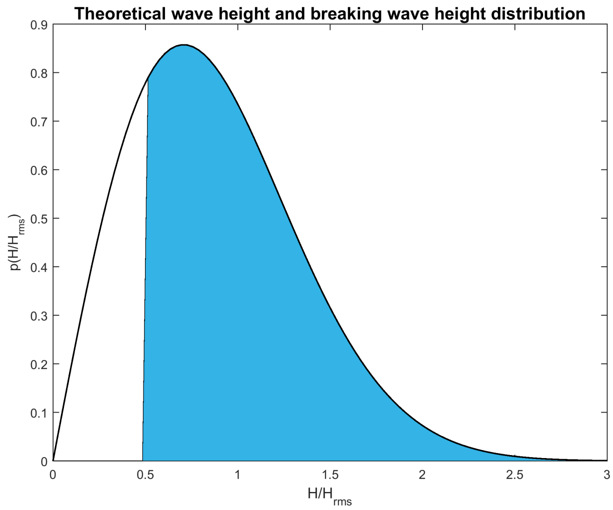


Figure 5.3: Theoretical wave height and breaking wave height distributions. Adjusted from (Baldock et al., 1998)

The maximum wave height H_b is calculated using Equation 5.11. In this equation, the breaker index γ is a (slightly) adjustable coefficient which can change depending on the beach slope and the relative water-depth. There exist different empirical expressions for the breaker index γ, which are all based on different experiments. In the simple model described here, γ is calculated using the expression of Su et al. (Su et al., 2011). Su et al. fitted the Janssen-Battjes model to experimental results from (Demirbilek et al., 2007), who conducted laboratory experiments of shoaling an breaking of irregular waves over coral reefs. This led to the formulation of empirical formulations for γ. In the simple flood model described in this chapter, the formulation for γ is used (see equation 5.12), because this empirical formulation was derived for the application of the Janssen-Battjes model to coral reef environments. In this equation, β is the beach slope angle. As can be seen, the breaker index γ increases with increasing beach slope. This corresponds to the observation that on steeper slopes the waves break at smaller depths. This could be explained by the fact that waves need time to break, during which they can travel to a smaller depth (Schiereck and Verhagen, 2012).

$$H_b = \gamma * h \tag{5.11}$$

$$\gamma = 0.431 + 1.032 * \frac{tan\beta}{kh} \tag{5.12}$$

For more details on the Janssen-Battjes random wave dissipation model, the reader is referred to (Janssen and Battjes, 2007), (Baldock et al., 1998) and (Battjes and Janssen, 1966).

Dissipation due to bottom friction

In the original Battjes-Janssen model, only wave dissipation due to wave breaking was included, since at most mildly sloping beaches (for which the model was originally developed), this is the most important dissipation mechanism. In this model, also dissipation due to bottom friction is taken into account, since this is expected to be the most important dissipation mechanism over the island (where the water depth is not decreasing that fast anymore, and wave breaking is thus less important). In this simple model, the wave dissipation due to bottom friction is modelled using the wave friction factor in analogy with the current friction factor (Jonsson, 1966). The magnitude of the instantaneaous dissipation due to bottom friction is calculated using Equation 5.13.

$$D_f = |\tau u| = \frac{2}{3\pi}\rho f_w |u_{orb}|^3 \tag{5.13}$$

$$u_{orb} = \frac{\pi H_{rms}}{T_p sinh(kh)} \tag{5.14}$$

With u_{orb} equal to the orbital velocity of the wave at a certain moment. The orbital velocity is calculated using linear wave theory in shallow water, see Equation 5.14. There exist different relationships to calculate the friction factor f_w. In this simple model, the expression of Jonsson rewritten by Swart is used, see Equation 5.15 (Bosboom and Stive, 2012). In this equation, ζ_0 is the particle excursion amplitude close to the bed (which can be calculated using linear wave theory in shallow water) and r is a measure for the bottom roughness, which can be linked to the friction factor c_f. An upper limit of 0.3 is assumed for f_w (Bosboom and Stive, 2012).

$$f_w = exp\left[-5.977 + 5.213\left(\frac{\zeta_0}{r}\right)^{-0.194}\right] \tag{5.15}$$

5.3.3. Long wave transformation

As was stated above in this simple model, a distinction between long and short waves is made at the location of the beach foot. The transformation of the short waves is calculated with a short wave energy balance, as described in the previous section. As can be seen from Figure 5.1, the long waves also transform over the cross-section. In Figure 5.1, it can be observed that (starting from the beach foot) the long infragravity waves (both the infragravity (IG) and the very low frequency (VLF) waves) first increase a bit and subsequently decrease. The transformation of the long waves is therefore incorporated in the simple flood model using the IG wave energy balance following the approach of van Dongeren et al. (van Dongeren et al., 2007), see equation 5.16.

$$\frac{d}{dx}\left(\sqrt{gh}\rho g H_{rms,LF}^2\right) = -D_{bot} - D_{br} \tag{5.16}$$

In this equation, D_{bot} represents the long wave energy dissipation due to bottom friction and D_{br} represents the long wave energy dissipation due to wave breaking. These dissipation terms are formulated according to equation 5.17 and 5.18 below.

$$D_{br} = \alpha_{br} \bar{f}_{LF} \rho g \frac{H_{rms,LF}^2}{4} \tag{5.17}$$

$$D_{bot} = f_{cw} \rho \left(\frac{g}{h}\right)^{\frac{2}{3}} \frac{H_{rms}}{\sqrt{8}} \frac{H_{rms,LF}^2}{8} \tag{5.18}$$

In these equations, α_{br} is a tuning parameter, which is set to 1 in the simple flood model. f_{cw} is the wave friction coefficient, which is calculated according to equation 5.15. Similar to the short waves, an upper limit of 0.3 is assumed. The main frequency that is assumed in the long wave energy balance is 0.005 Hz (i.e. T = 200 s). This is based on the wave spectra as obtained at the location of the beachfoot (see Figure 5.1), where it can be seen that most long wave energy is present at the VLF frequencies.

As described above, the short wave height is calculated by solving the energy balance. In the most extreme situation (leading to maximum water levels over the island), the maximum short wave height is assumed to be equal to two times the significant wave height $H_{s,SS}$. This is based on the assumption that the short waves are Rayleigh distributed and that there are many short waves. The maximum water level is therefore calculated by adding the short wave height $H_{s,SS}$ (calculated with the energy balance) to the water level (calculated with the momentum balance and the long wave energy balance), see Equation 5.19.

$$h_{max} = h + H_{s,SS} \tag{5.19}$$

5.4. Iw-model

In the Battjes-Janssen model, the water level is calculated by solving the momentum balance. However, this momentum balance is based on the assumption that the gradient in radiation stresses, caused by the dissipation of wave energy, is balanced by a gradient in water level. This assumption is only valid in situations where the water can pile up a positive slope. As soon as the terrain slope becomes zero or negative, this assumption is no longer valid. In these cases, the water level is calculated using the flood intensity index model, or Iw-model in short. This model was originally developed as a semi-physical alternative to the bathtub method (Dottori et al., 2018). The theoretical background stems from the 1D uniform flow equation for large rectangular channels, see Equation 5.20.

$$\frac{dH}{dx} = -\frac{u^2 n^2}{h^{4/3}} \tag{5.20}$$

where dH/dx is the water surface slope, u is the flow velocity, h is the waterdepth and n is the Manning coefficient. Equation 5.20 can be discretized, leading to Equation 5.21.

$$\frac{(H_i - H_j)}{d} = -\frac{u^2 n^2}{h^{4/3}} \tag{5.21}$$

where H_i and H_j are the water levels in two adjacent grid cells i and j, and d is the distance between these cells. In Equation 5.21, the term on the right-hand side can be replaced by a single coefficient λ. Then the equation can be rewritten to Equation 5.22.

$$H_i = H_j - \lambda * d \tag{5.22}$$

If grid cell j is assumed to be the source cell (so with a higher water level than grid cell i), the Flood Intensity Index (Iw) for cell i can be written like Equation 5.20, with Z_i the elevation in grid cell i.

$$Iw_i = H_{source} - Z_i - \lambda * d_{i,source} \tag{5.23}$$

In 2D applications of the Iw-model, the Intensity index is calculated using Equation 5.24. In this equation, the parameter nc_{flow} represents the number of cells that water can flow to from the source cells. As can be seen from the equation, the water level drops quicker when water can spread to multiple cells. However, in the current simple model, the Iw-model is applied in 1D so nc_{flow} is always equal to 1.

$$Iw_i = H_{source} - Z_i - \lambda * d_{i,source} * nc_{flow} \tag{5.24}$$

The value for λ is calculated as a weighted average of the slope along the flow direction and a reference value λ_r. The reference value λ_r is assigned based on the Manning roughness coefficient. The link between the value for λ_r and the Manning coefficients is established empirically. A table with values for λ_r linked to different Manning values can be found in Appendix E.

In cases where the slope of the island becomes zero or negative, the Iw-method is used to calculate the water level. The long and short wave heights are still solved using a wave energy balance and the maximum water levels are still calculated with equation 5.19.

6

1D flood model tests

In the previous chapter, the setup of the JBIW model was described. The goal of this model is to obtain a quick, reasonable estimate of the maximum water levels. Different 1D conceptual tests were done to test the accuracy of this model and compare it to other flood models. Both the setup and results of these tests are described in this chapter. The setup of the 1D tests is described in Section 6.1 and the results are presented in Section 6.2. Lastly, some concluding remarks are given in Section 6.3.

6.1. Set-up conceptual 1D tests

In order to test the model as described in the previous section, different conceptual tests were done in 1D and compared to the model outcomes of different flood models. The set-up of these conceptual tests is described in this section.

In order to test the model in 1D, the topography of the different islands has to be generalized. First, these simplified profiles are described in more detail in Section 6.1.1. Subsequently, the parameters that were varied and their range are described in Section 6.1.2. For each combination of parameters the flood level was calculated with four different models: XBNH+, the bathtub model, the JBIW model and the SFINCS model. The results of the XBNH+ model served as a reference, as there are no measurements available and this model is expected to give the most accurate results. The results of the other three models are therefore compared to the flood levels from XBNH+. The set-up of these different models is described in more detail in Section 6.1.3.

6.1.1. Simplified island topographies

There are many different small islands. A large part of these islands are fronted by coral reefs. These islands can be subdivided in three main categories: barrier, fringing and atoll islands. These different island categories represent subsequent stages in a submergence process, see Figure 6.1 (Woodroffe, 2008). Reefs that border the coast are termed fringing reefs and reefs that lie offshore, enclosing a lagoon, are called barrier reefs. Reefs that encircle a lagoon are atolls (Bosboom and Stive, 2012). Barrier and fringing reef islands are often vulcanic in nature and can therefore have large elevations and positive terrain slopes. Coral atolls, on the other hand, are often low-lying and relatively flat. Due to these topographic characteristics of coral atolls, they are generally very vulnerable to flooding.

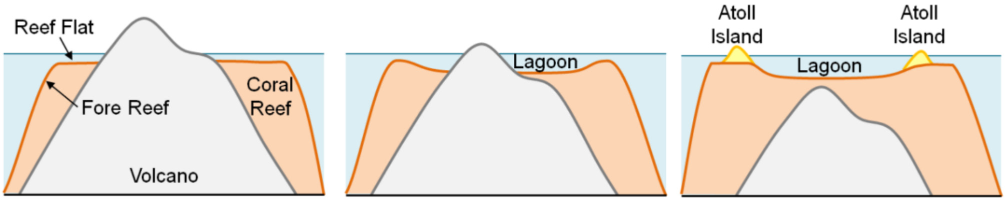


Figure 6.1: Different categories of reef fronted islands. From left to right: fringing, barrier and atoll. Barriers reefs and atolls develop from fringing reefs under the influence of relative sea-level rise; the reefs grow vertically upward with rising water levels. (Source: (Pearson, 2016))

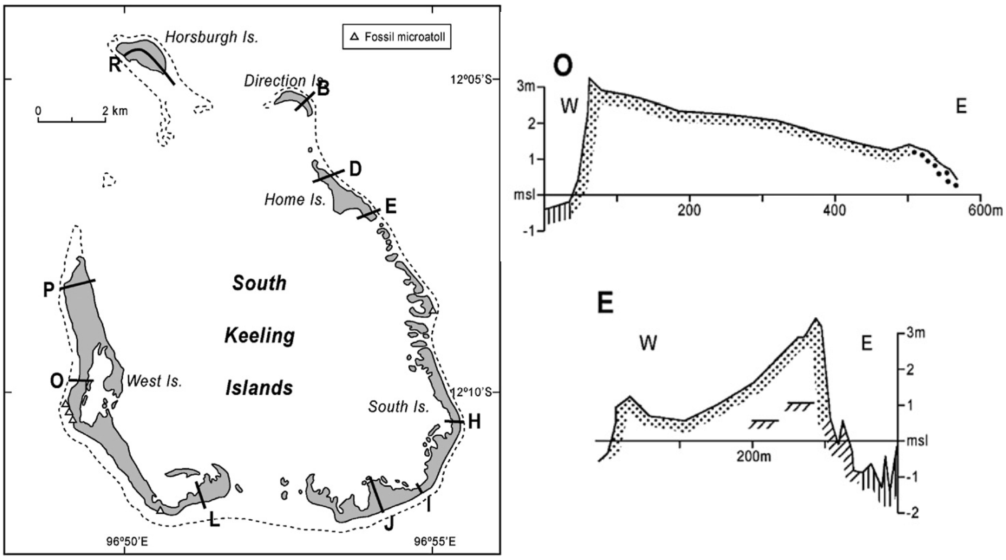


Figure 6.2: The Cocos (Keeling) Islands: the South Keeling Islands, forming the southern atoll and selected profiles across the reef islands (source: (Woodroffe, 2008))

In (Woodroffe, 2008), the topography and substrate characteristics of coral atoll islands were investigated. From this study, it is clear that coral atolls can have two general shapes; they either have a downward or bathtub shape. An example of both shapes (obtained from (Woodroffe, 2008)) is given in Figure 6.2. As most coral atolls consist of a ring of islands, a distinction is made between the oceanward and lagoonward side. Coral atolls are highest along their oceanward shores; at this side the largest wave attack and corresponding sediment transport is present. Due to the import of sediment during large wave events, an oceanward ridge is formed. Depending on the wave attack from the lagoon, a lagoonward ridge can be present. Since the wave attack from the ocean is larger than from the lagoon, the oceanward ridge is almost always higher than the lagoonward ridge. Depending on the wave attack from the lagoon, and thus on the height of the lagoonward ridge, coral atolls either have a downward or bathtub shape. This is also clear from Figure 6.2. At cross-section O, wave attack from the lagoon is expected to be limited; therefore the island is expected to have a downward shape. At cross-section E, wave attack from the lagoon is expected to be larger; a lagoonward ridge and thus a bathtub shape of the island is expected.

These observations are translated in three different simplified 1D cross-sections, which are depicted in Figure 6.3.

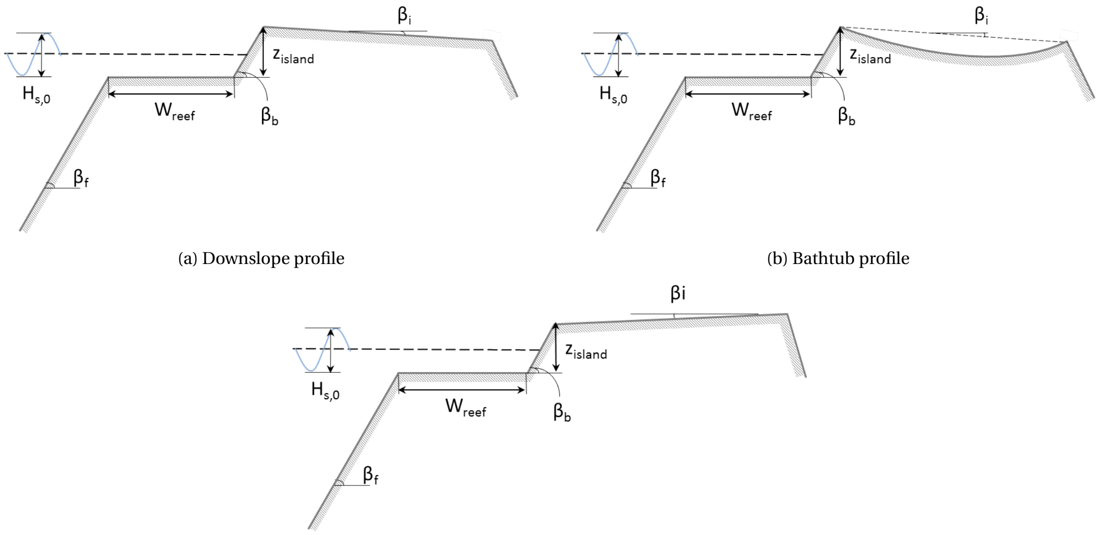
6.1.2. Parameter space

The parameters that were varied and their range are listed in Table 6.1. The selected parameters and their range are described in more detail below.

Table 6.1: Parameter space

Symbol	Parameter	Units	Values
$H_{s,0}$	Offshore wave height	m	3, 4, 5, 6, 7
β_f	Fore reef slope	-	1/2, 1/10
W_{reef}	Reef flat width	m	100, 250
β_{beach}	Beach slope	-	1/3, 1/10, 1/20
z_{island}	Island height	m	1, 2, 3, 4
β_{island}	Island slope	-	1/1000, 1/500, 1/250

The offshore significant wave heights $H_{s,0}$ that are included in the model have values of 3, 4, 5, 6 and 7 m. Smaller offshore wave heights of 1 and 2 m are excluded since these waves are not expected to result in (significant) flooding. An offshore wave height of 5 m corresponds to a 2-5 year return period for Kwajalein in the Marshall Islands (Giardino et al., 2018). (Quataert et al., 2015) reported maximum observed offshore wave



(a) Downslope profile

(b) Bathtub profile

(c) Upslope profile

Figure 6.3: 1D cross-shore profiles for the conceptual tests

heights of 6 m (at Hanalei, Hawaii). Due to climate change, the wave climate may become more extreme in the future. Therefore, maximum offshore wave heights of 7 m were included in the model.

In different studies it is described that many flood events at reef fronted islands are caused by large swell events in combination with high offshore water levels (Quataert et al., 2015) (Hoeke et al., 2013). Swell waves are generally not very steep; therefore the offshore wave steepness H_0/L_0 is assumed to be 0.02. Using Equation 6.1 the wave periods corresponding to the different offshore significant wave heights are calculated. This leads to offshore wave periods of 9.8, 11.3, 12.7, 13.9 and 15 seconds for the different offshore wave heights.

$$T_p = \sqrt{\frac{\left(\frac{H_0}{H_0/L_0}\right)}{g/2\pi}} \tag{6.1}$$

For simplicity, the fore reef slope is assumed to be planar. In (Pearson, 2016), fore reef slopes of 1/2, 1/10 and 1/20 are assumed. Since a steeper fore reef is expected to result in higher long waves at the beach foot (via long wave generation through the breakpoint mechanism (Baldock et al., 2000)) and thus to more extreme flooding, fore reef slopes of 1/2 and 1/10 are chosen.

For the reef flat width W_{reef} values of 100 and 250 m were chosen. (Kolijn, 2014) summarized different properties of reef fronted islands from different studies, among which the reef flat width. This study showed that the reef flat width is highly variable with values ranging from 0 to 2200 m. In general, longer reef flats will lead to less wave impact and thus less flooding at the island (Storlazzi et al., 2015). Therefore, quite short values of 100 and 250 m were chosen for the reef width. Although the exact topography of the reef flat can vary from island to island, a simple flat reef was assumed.

The beach slope is assumed to be planar. Based on the reflective nature of many reef-fronted beaches, it is assumed that beach slopes are quite steep for most reef fronted islands (Pearson, 2016). This was also observed from the measured data at the islands of Roi Namur, Ebeye and Majuro (see Chapter 3) and from inspection of the different cross-shore profiles in (Woodroffe, 2008). Beach slopes of (1/3), (1/10) and (1/20) were included.

The height at the oceanward border z_{island} ranges from 1 to 4 m wrt MSL. In (Woodroffe, 2008), multiple cross-sections at different coral atolls were examined. The height of the oceanward ridge ranges between 1 and 4 m wrt MSL for all these cross-sections. Most coral atolls had an oceanward ridge height between 2 and 3 m. Furthermore, for the coral atolls that were analysed in Chapter 3 (i.e. Majuro, Roi Namur and Ebeye) oceanward ridge heights in the same range were found.

(Kolijn, 2014) also reported on the tide level with respect to MSL on coral reef flats found in different studies.

Maximum tide levels were found to be lower than 2 m in almost all cases. The reef flat in the conceptual models is assumed to be located at MSL. The maximum tide level is assumed to be related to the island height z_{island}; if z_{island} is equal to 1 m, the maximum tide level is assumed to be lower (otherwise the island would flood every high tide). The offshore water levels $z_{s,0}$, related to different island heights, are listed in Table 6.2.

Table 6.2: Offshore water levels for the different island heights z_{island}

$\mathbf{z_{island}}$ **[m]**	$\mathbf{z_{s,0}}$ **[m]**
1	0.5
2	1.5
3	2
4	2

Lastly, the island slopes were assumed to be small. As was stated in Section 6.1.1, the topography of coral atolls is generally characterised by mild terrain slopes. Fringing and barrier reef islands, which can be vulcanic in nature, can have steeper slopes. However, it is assumed that the areas on these islands that are relevant for coastal flood risk assesments (e.g. the urban areas) have milder slopes. Therefore, island slopes of 1/1000, 1/500 and 1/250 are included.

6.1.3. Model set-up

In this section, the model set-up of the different models is shortly described. As was described in Section 6.1, the flood level over the island for each combination of parameters is calculated with 4 different flood models. First, the flood level is calculated with a 1D reduced 2-layer XBeach Non-Hydrostatic (XBNH+) model (Roelvink et al., 2015). Since there are no measurements available, the model outcomes of the XBNH+ runs are used as a reference to compare the outcomes of the other models to, as this model is expected to give the most accurate results. The XBNH+ model starts in intermediate water depths, while the other flood models start on the beachfoot. The input for the SFINCS, bathtub and BJIW model runs is directly obtained from the XBNH+ model runs. In this way, only the effect of a different flood model on the flood level on the island can be analysed.

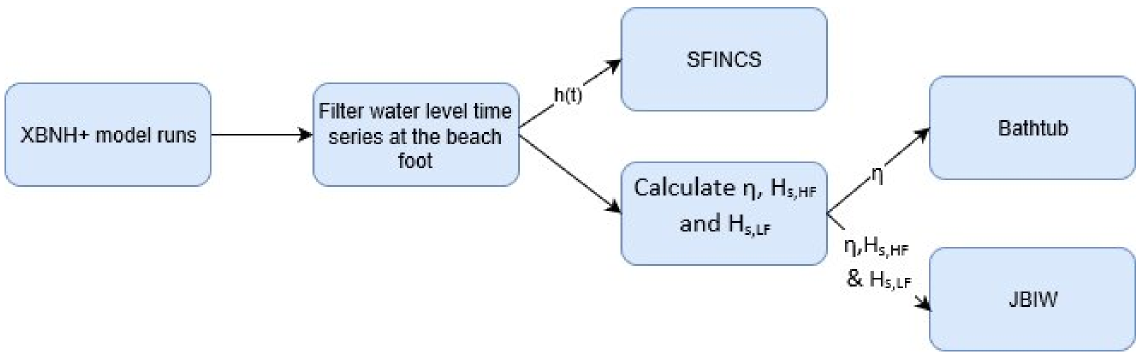


Figure 6.4: Flowchart model set-up

This procedure is depicted in Figure 6.4. A water level time series is directly obtained from an observation point in the XBNH+ model at the location of the beachfoot. Since the beach slopes that are modelled in the different runs are quite steep (see Section 6.1.2), a certain amount of reflection of wave energy is expected. Therefore, the water level time series is filtered to obtain only the incoming waves. This is done using the method of Guza et al. (Guza et al., 1984), using water level elevations and velocities. This filtered water level time series is directly used as input for the SFINCS model. To obtain input for the bathtub and JBIW flood models, the mean water level $\bar{\eta}$, the significant high-frequency wave height $H_{s,HF}$ and the significant low-frequency wave height $H_{s,LF}$ are calculated from the water level time series and used as input. The setup of the XBNH+ and SFINCS runs is described in Appendix E.

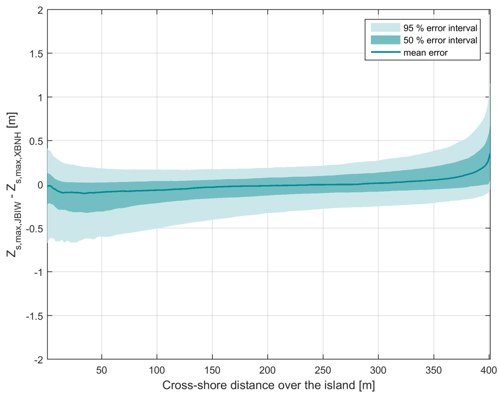
The XBNH+ model, which is used as a reference, is a phase-resolving model and models the individual waves. For a more detailed explanation of this model, the reader is referred to (Roelvink et al., 2015). However, the JBIW model that was described in the previous chapter is a phase-averaged model. In order to be able to make a good comparison between these different types of models, the XBNH+ phase-resolving model needs to be run for a long time in order to get stable wave characteristics. Therefore, the XBNH+ 1D runs were run with constant offshore forcing conditions for 6 hours. As was explained above, the water level time series from the XBNH+ runs at the location of the beach foot are used to calculate the mean water level, long and short wave heights used as input in the JBIW model.

6.2. Results conceptual tests

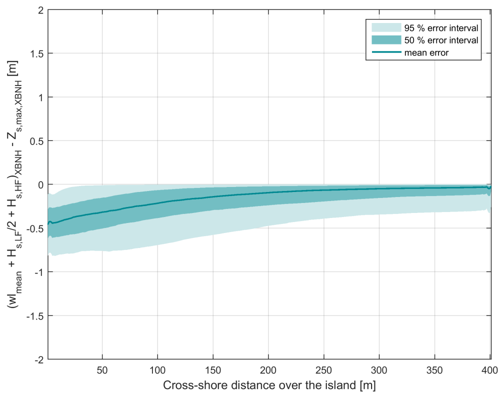
In this section, the results of the conceptual tests will be described and discussed. The results will be discussed for the different cross-shore profiles seperately. For each cross-shore profile, the differences between the JBIW and XBNH+ will be discussed. Furthermore, the JBIW model will be compared to the bathtub and SFINCS model runs.

6.2.1. Downslope profile

In order to evaluate the simple flood model, the difference between the maximum water levels calculated with the JBIW model are compared to the maximum water levels from the XBNH+ runs. In Figure 6.5a, these differences are plotted for all runs for the downslope profile. In this figure, the mean error, the 50% error interval and the 95% error interval are depicted. The x-axis represents the cross-shore distance over the island, starting from the side where the waves come from (x = 0 m) towards the end of the island (x = 400 m).



(a) $Z_{s,max,JBIW} - Z_{s,max,XBNH}$

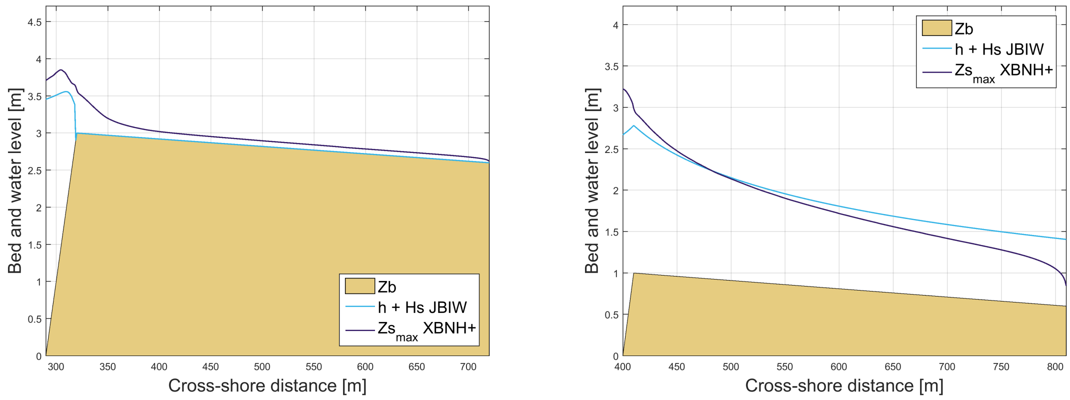


(b) $(Z_{s,mean} + H_{s,LF}/2 + H_{s,HF})_{XBNH} - Z_{s,max,XBNH}$

Figure 6.5: Left: difference between the maximum water levels calculated with the JBIW and XBNH+ model. Right: difference between the maximum water levels calculated with equation 5.19, with the mean water level, the long and short significant wave height obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+. The x-axis represents the cross-shore distance over the island.

From Figure 6.5a, it can be observed that the maximum water level calculated with the JBIW model at the start of the island can both be too high or too low. This can be explained by looking into the individual model runs in a bit more detail. From the JBIW model description in Section 5.1, it is clear that the JBIW model only calculates a water level on the island as long as the water depth, including the long wave component, is bigger than zero. However, if the water level including the long wave component does not reach the island, there can still be flooding on the island due to the overtopping of short waves. This overtopping of short waves is calculated with the XBNH+ model, but is not included in the JBIW model. An example is depicted in Figure 6.6a. As can be seen in this figure, the water level, including the long wave component, does not reach the island. In these cases, the maximum water level predicted by the JBIW model is therefore too low.

Furthermore, as was described in the previous section, the maximum water level in the JBIW model is calculated using Equation 5.19. In this equation, the water level is assumed to include a contribution of the long waves equal to 0.5 $H_{s,LF}$. The maximum water level is calculated by subsequently adding the significant short wave height $H_{s,HF}$, assuming that the maximum short wave height is equal to 2 times $H_{s,HF}$. However, the maximum water level calculated in the different XBNH+ model runs might differ from the values calculated with this equation. In order to test this, the maximum water levels from the XBNH+ runs were compared to the water levels computed with Equation 5.19, with the mean water levels and significant short and long wave height obtained from the XBNH+ model. The results are depicted in Figure 6.5b. From this figure it can be concluded that especially at the start of the island, the maximum water level calculated with Equation 5.19 is too low compared to the maximum water levels from the different XBNH+ runs.



(a) Run with $H_{s,0}$ = 3 m, β_f = 1/10, W_{reef} = 100 m, β_b = 1/10, z_{island} = 3 m and β_i = 1/1000

(b) Run with $H_{s,0}$ = 5 m, β_f = 1/10, W_{reef} = 100 m, β_b = 1/10, z_{island} = 1 m and β_i = 1/1000

Figure 6.6: Maximum water levels JBIW and XBNH+

From Figure 6.5b, it can be concluded that the maximum water levels calculated with equation 5.19 generally underestimate the 'real' maximum water levels, especially at the start of the island. However, from Figure 6.5a, it can be concluded that the maximum water level calculated with the JBIW model at the start of the island can also be too high. This is caused by the fact that both the long and short wave heights are generally overestimated in the JBIW model compared to the wave heights calculated with XBNH+. An example in depicted is Figure 6.7. In this figure, the long wave heights are indicated with solid lines and the short wave heights with dashed lines. The x-axis represents the cross-shore distance starting from the beach foot and the grey area indicates the island. It can be seen from the figure that the long wave height calculated with XBNH+ shoals before decreasing abruply till the start of the island. Over the island, the long wave height decreases as well, but more gradually. Compared to the XBNH+ runs, the long wave height calculated with the JBIW model continues to grow over a larger distance and decreases more gradually. This causes an overestimation of the long wave height at the start of the island, which decreases with distance over the island. A possible explanation for the difference in long wave propagation between the JBIW model and the XBNH+ runs could be that part of the long wave energy is reflected near the shoreline, comparable to the reflection of long waves at the reef crest of coral reef fronted islands. The sudden decrease in long wave energy just before the start of the island in the XBNH+ runs might be caused by the (partial) reflection of long waves, which is not incorporated in the JBIW model.

As was described in Chapter 5, the short wave heights are calculated based on a water depth that includes a long wave component. Since the long wave height is overestimated, this water depth is also overestimated. This might cause the overestimation of the short wave height as depicted in Figure D.4. Although Figure 6.7 shows the results of one run only, these patterns were observed for all model runs.

In conclusion it can be stated that the maximum water level is generally underestimated by equation 5.19, especially at the start of the island. However, both the water depth (including a long wave component) and short wave height are generally overestimated by the JBIW model compared to the XBNH+ runs, especially at the start of the island. In some cases, the overestimation of the water depth (including a long wave component) and short wave height is larger than the underestimation of the maximum water level by the use of equation 5.19, which results in an overestimation of the maximum water levels calculated with the JBIW model.

Furthermore, it can be observed that, at the end of the island, the maximum water level calculated with the JBIW model is too high compared to the maximum water level calculated with the XBNH+ model for almost all model runs. This can again be explained by looking into the individual model runs. In Figure 6.6b, the maximum water levels calculated with both models are depicted for the model run with an offshore wave height $H_{s,0}$ of 5 m, a forereef slope β_f of 1/10, a reef width W_{reef} of 100 m, a beachslope β_b of 1/10, an island height z_{island} of 1 m and an island slope β_i of 1/1000. In the XBNH+ runs, the water levels behind the island

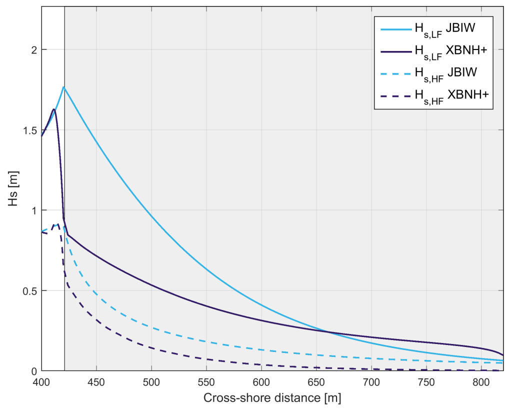


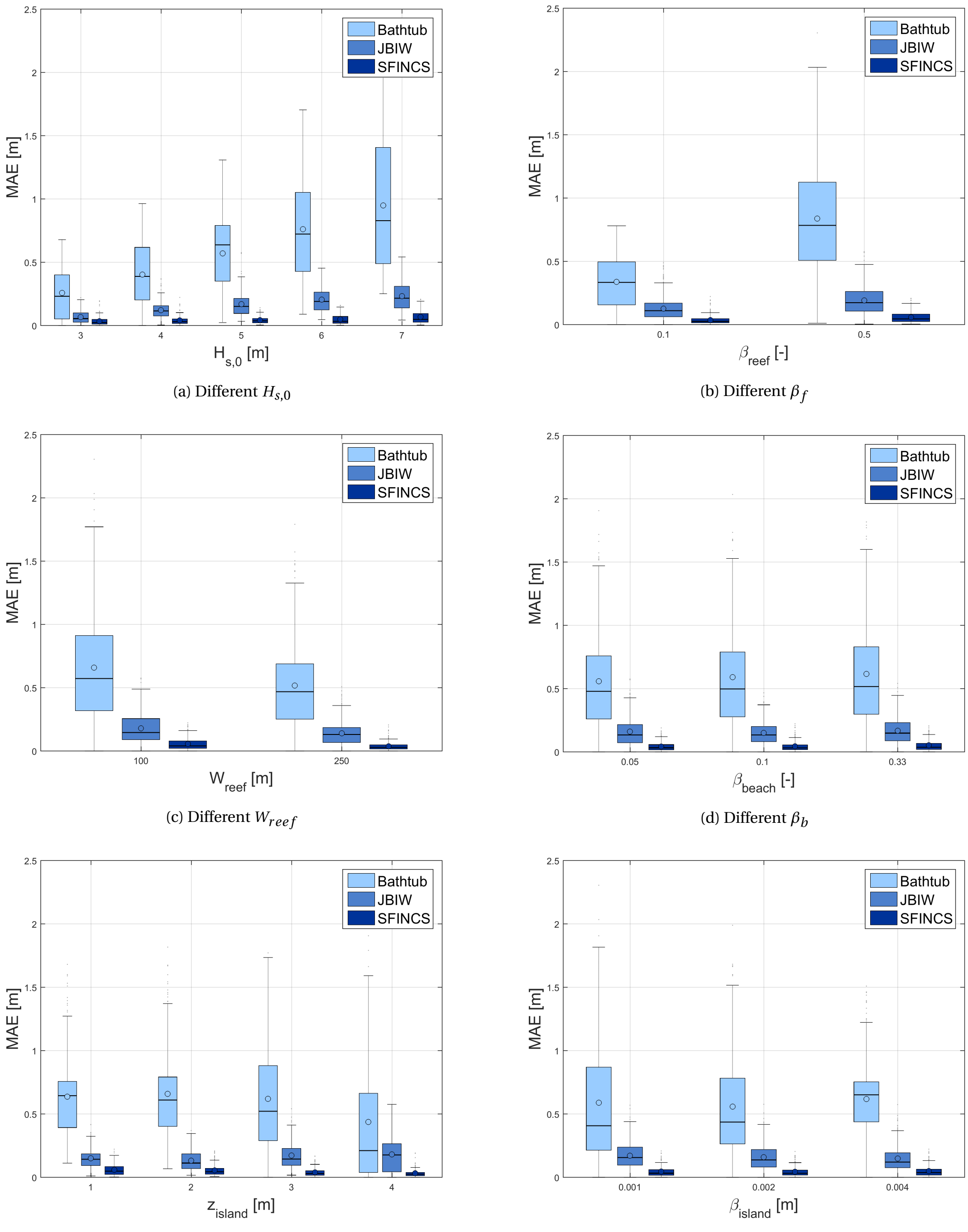
Figure 6.7: Significant short and long wave height calculated with XBNH+ and the JBIW model, for the run with: $H_{s,0}$ = 5 m, β_f = 1/10, W_{reef} = 100 m, β_b = 1/10, z_{island} = 2 m and β_i = 1/500

are equal to the offshore water levels in front of the island. In Figure 6.6b, this water level is equal to 0.5 m. This means that the water level is dropping towards the end of the island, where it flows into the bay behind the island. The JBIW model uses a forward-marching scheme to calculate the maximum water level. Therefore, information from the end of the island does not influence the calculation of the maximum water level. The error that is introduced by this forward-marching scheme depends on the difference between the water level on the island and the water level behind the island. However, in most practical applications, the water level behind the island will be lower, which introduces an error in the JBIW model. In the remainder of this chapter this will be referred to as the boundary effect from the end of the island.

In order to analyse how the error in maximum water levels predicted with the JBIW model depends on the value for different parameters, the mean error calculated with the JBIW model was analysed for different values of the different parameters. An elaboration of this analysis can be found in Appendix D. Here, the most important conclusions of this analysis will be given.

It could be concluded that the error in the maximum water levels calculated with the JBIW model increases for higher offshore wave heights. This is caused both by a larger underestimation of the maximum water levels at the start of the island and a larger overestimation of the maximum water levels at the end of the island for higher offshore waves. The underestimation at the start of the island is expected to be caused by the fact that the contribution of the waves to the maximum water levels seems to be underestimated in Equation 5.19. Larger offshore waves then lead to a larger underestimation. Similarly, larger offshore waves will lead to larger water depths over the island, which causes a larger overestimation at the end of the island due to the boundary effect from the end of the island. The same was observed for steeper fore reef slopes; for steeper fore reef slopes, both the amount of long and short wave energy at the location of the beachfoot increase, because the amount of long wave energy generated in the breakpoint mechanism is much larger for steeper fore reefs (Baldock et al., 2000). This results, similar to increasing offshore wave heights, in a larger underestimation of the maximum water level at the start of the island and a larger overestimation of the maximum water level at the end of the island. For longer reef flats, the amount of short wave energy at the island is lower, because a larger part of the short wave energy is dissipated over the reef flat. In was observed that the errors are smaller for longer reef flats, because the underestimation of the maximum water levels at the start of the island is smaller. Regarding the different beachslopes, it was observed that the overestimation of the water depths (including a long wave component) is larger for steeper beaches. This also results in a larger overestimation of the short wave height. For a beachslope of 1/10, the overestimation of the water depth and the short wave height in combination with an underestimation of the maximum water levels by Equation 5.19 led to the smallest errors. Lastly, regarding the different island slopes, the errors are somewhat larger for islands with milder slopes. This is expected to be caused by the boundary effect from the end of the island, which has a larger effect for milder island slopes.

Comparison to other flood models



(a) Different $H_{s,0}$

(b) Different β_f

(c) Different W_{reef}

(d) Different β_b

(e) Different z_{island}

(f) Different β_i

Figure 6.8: Mean absolute errors in the maximum water levels for the conceptual tests on the downslope profile, for the different flood models. The error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the different flood models ($Z_{s,max,model} - Z_{s,max,XBNH}$). The mean absolute error is subsequently calculated by first taking the mean value of all runs belonging to a certain parameter value and then taking the spatial absolute mean of the error.

As was described in Section 6.1, the maximum water level over the island for each combination of parameters is calculated with 4 different flood models. The results from the XBNH+ model runs are used as a reference, as this model is expected to be the most accurate. The results of the other 3 models (i.e. the bathtub method, the JBIW model and the SFINCS model) are compared to the XBNH+ model runs. The difference to the XBNH+

results is assumed to be the error made in the other 3 models. In Figure 6.8, the MAE of the 3 different models are compared for different parameter values.

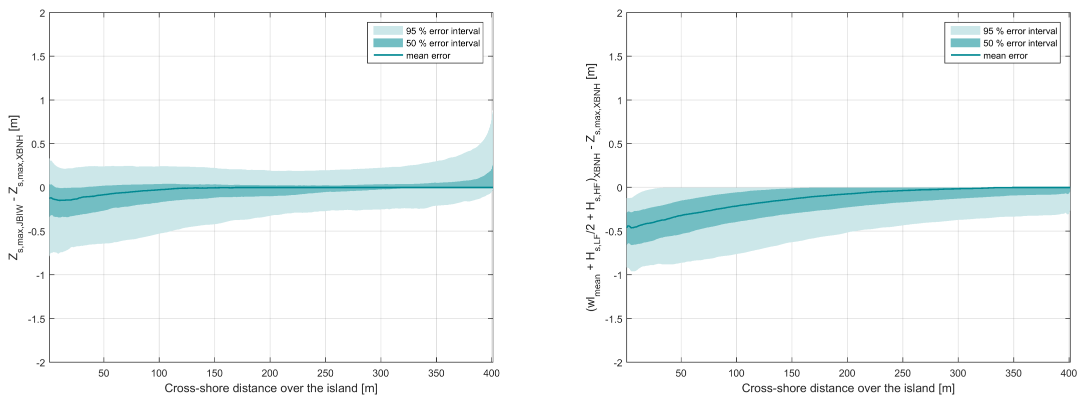
From the figure, it can be concluded that the JBIW model is more accurate than the bathtub method. The difference in accuracy between the bathtub method and the JBIW model is larger for runs with higher waves at the beach foot, because the contribution to flooding by waves is not included in the bathub method. Furthermore, the JBIW is less accurate compared to the SFINCS model. In terms of computational time, the JBIW model is about as fast as the bathtub method and runs in less than a second. The SFINCS model runs in a few minutes and the XBNH+ model runs took a bit less than an hour. In Table 6.3, the averaged MAE (i.e. over all runs with a downslope topography), the minimum MAE, and the maximum MAE are listed for the different models. In Table 6.6, the averaged MAE and runtime are included for the different models for all runs.

Table 6.3: Averaged MAE [m] (i.e. averaged over all runs with a downslope profile) for the different models. The values between brackets indicate the range in MAE over all runs.

	MAE [m]
Bathtub	0,59 (0 - 2,31)
JBIW	0,16 (0 - 0,58)
SFINCS	0,05 (0 - 0,22)

6.2.2. Upslope profile

In Figure 6.9a, the mean difference between the maximum water levels calculated with the JBIW model and XBNH+ is depicted, together with the 50% and 95% difference interval for the upslope profile. As can be seen from the figure, the differences are quite similar to the downslope profile. At the start of the island, the maximum water levels calculated with the JBIW model can be both too high and too low compared to the XBNH+ runs, while at the end of the island, the maximum water levels calculated with the JBIW model are generally too high.



(a) $Z_{s,max,JBIW} - Z_{s,max,XBNH}$

(b) $(Z_{s,mean} + H_{s,LF}/2 + H_{s,HF})_{XBNH} - Z_{s,max,XBNH}$

Figure 6.9: Left: difference between the maximum water levels calculated with the JBIW and XBNH+ model. Right: difference between the maximum water levels calculated with equation 5.19, with the mean water level, the long and short significant wave height obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+. The x-axis represents the cross-shore distance over the island.

Similar to the downslope profile, the maximum water levels predicted by the JBIW model at the start of the island can be too low compared to the XBNH+ runs because overtopping of short waves is not included in the model. Furthermore, similar to the downslope profile, the maximum water levels calculated with equation 5.19 seem to be too low compared to the maximum water levels calculated with XBNH+, especially at the start of the island (see Figure 6.9b). It could be concluded that the underestimation of the maximum water level calculated with Equation 5.19 was a bit larger for the upslope profile compared to the downslope profile, especially for larger waves; this is depicted in Figure 6.10. This might be explained by the reflection of waves on the upslope profile, which also adds to the maximum water levels in the XBNH+ runs, but is not incorporated in the JBIW model. The overestimation of maximum water levels by the JBIW model can, similar to the downslope profile, be explained by the overestimation of both the water depth (including a long wave component) and short wave height.

The overestimation at the end of the island (x=400) is caused by the boundary effect from the end of the island. For runs with high offshore wave heights and relative low island heights, the entire island is flooded and there is a boundary effect from the end of the island, which has a larger effect for larger water depths. However, this effect is not expected to occur in practical applications in fringing or barrier reef contexts. In the model runs, the island was assumed to be 400 m wide. However, fringing and barrier reef islands are usually wider than coral atolls (i.e. wider than 400 m) and the slope on the island usually increases in inland direction. Therefore, it is not expected that fringing or barrier reef islands will be entirely flooded and this boundary effect will not be present in practical applications on these island types.

Similar to the downslope profile, the dependence of the error in maximum water levels calculated with the JBIW model on the values for the different parameters were analysed. The results were similar to the downslope profile and will therefore not be repeated here. This analysis can be found in Appendix D.

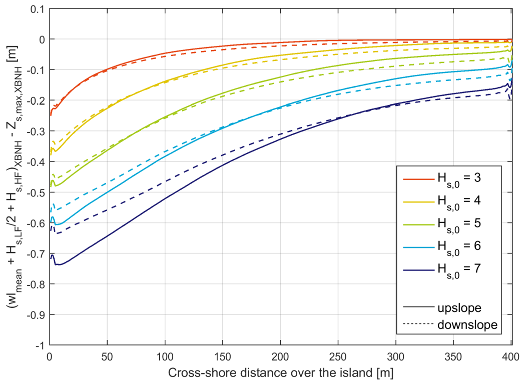


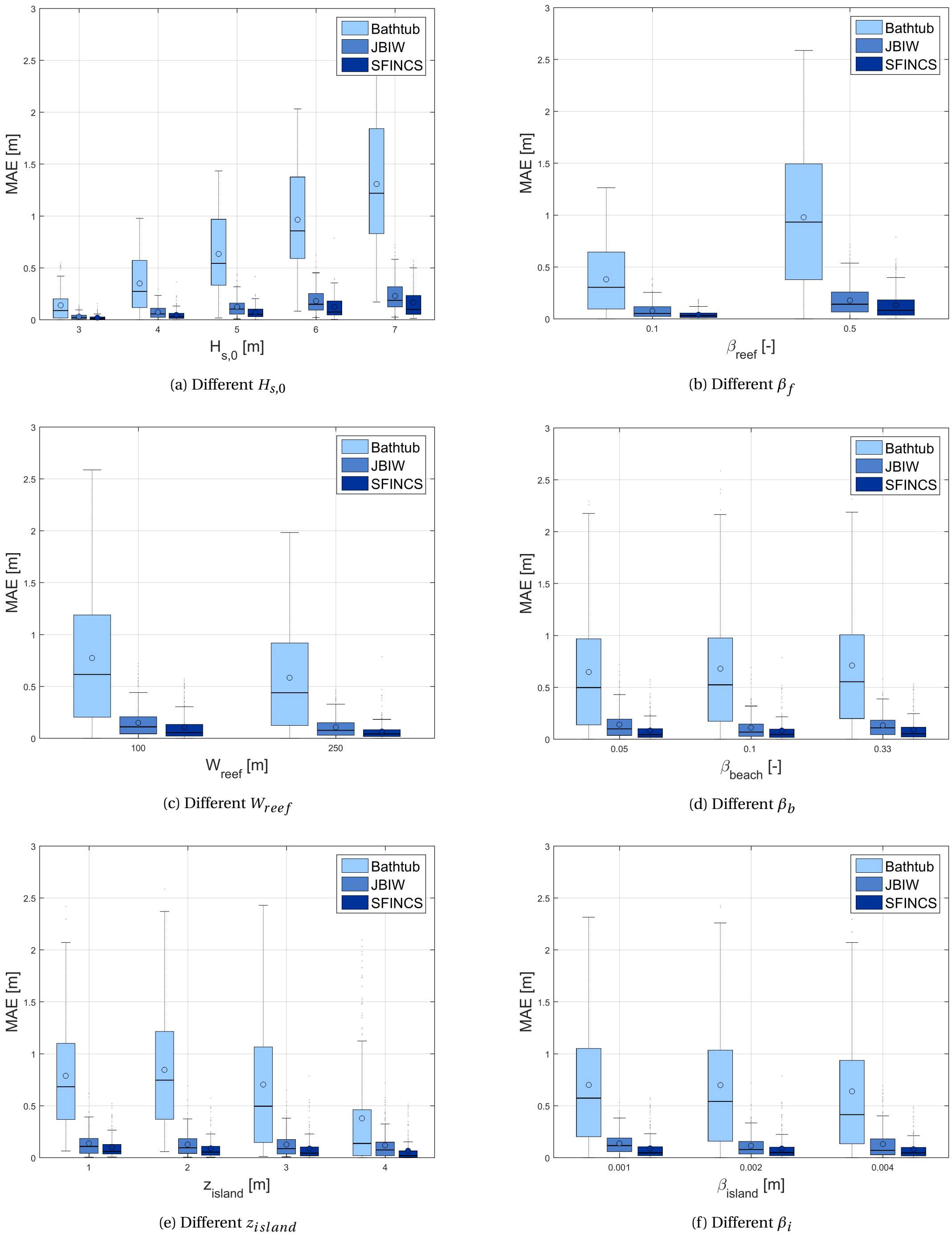
Figure 6.10: The different lines represent the difference between the maximum water levels calculated with XBNH+ and the maximum water levels calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs. The differences are averaged over all runs belonging to a certain offshore wave height $H_{s,0}$. The dashed lines (−−) represent the downslope profile, and the solid lines (–) represent the upslope profile. The x-axis represents the cross-shore distance over the island.

Comparison to other flood models

Similar to the downslope profile, the difference to the XBNH+ results for the different models (i.e. the bathtub method, JBIW model and SFINCS) are compared for different parameter values. The results are depicted in Figure 6.11. From this figure, it can be concluded that the bathtub method becomes less accurate for runs with higher waves at the beach foot, similar to the downslope profile. Furthermore, the difference in accuracy between the JBIW and SFINCS model is less compared to the downslope profile. In Table 6.4, the averaged MAE (i.e. over all runs with a upslope topography), the minimum MAE, and the maximum MAE are listed for the different models.

Table 6.4: Averaged MAE [m] (i.e. averaged over all runs with an upslope profile) for the different models. The values between brackets indicate the range in MAE over all runs.

	MAE [m]
Bathtub	0,68 (0 - 2,59)
JBIW	0,13 (0 - 0,72)
SFINCS	0,09 (0 - 0,58)



(a) Different $H_{s,0}$

(b) Different β_f

(c) Different W_{reef}

(d) Different β_b

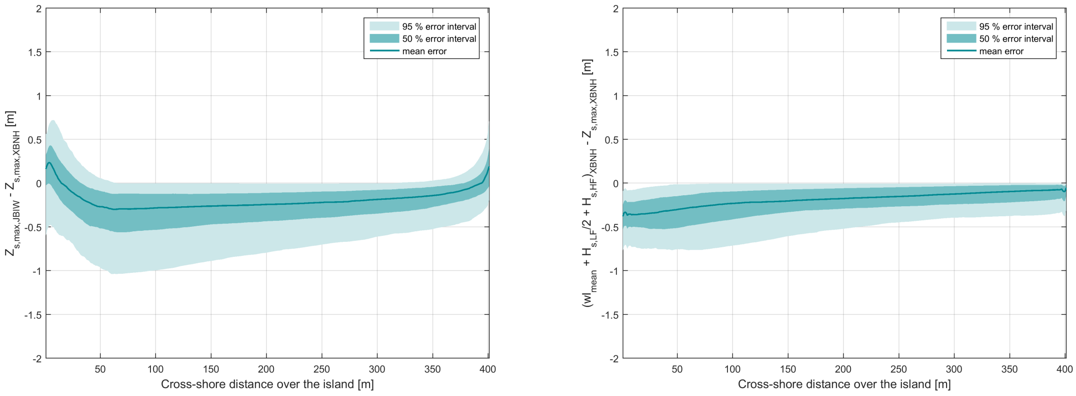
(e) Different z_{island}

(f) Different β_i

Figure 6.11: Mean absolute errors in the maximum water levels for the conceptual tests on the upslope profile, for the different flood models. The error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the different flood models ($Z_{s,max,model} - Z_{s,max,XBNH}$). The mean absolute error is subsequently calculated by first taking the mean value of all runs belonging to a certain parameter value and then taking the spatial absolute mean of the error.

6.2.3. Bathtub profile

In Figure 6.12a, the mean difference between the maximum water levels calculated with the JBIW model and the XBNH+ runs is depicted for the runs on the bathtub profile. In this figure, the 50 % and 95 % difference intervals are also depicted. As can be seen from the figure, the differences are a bit different from the results for both the downslope and upslope profile.



(a) $Z_{s,max,JBIW} - Z_{s,max,XBNH}$

(b) $(Z_{s,mean} + H_{s,LF}/2 + H_{s,HF})_{XBNH} - Z_{s,max,XBNH}$

Figure 6.12: Left: difference between the maximum water levels calculated with the JBIW and XBNH+ model. Right: difference between the maximum water levels calculated with equation 5.19, with the mean water level, the long and short significant wave height obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+. The x-axis represents the cross-shore distance over the island.

Especially at the start of the island, the maximum water levels calculated with the JBIW model often overestimate the maximum water levels from the XBNH+ runs. This can be explained by Figure 6.13. These figures show the difference between the maximum water level calculated with equation 5.19, with the mean water level, long and short wave height obtained from XBNH+, and the maximum water levels from the different XBNH+ runs. For all three profiles, the maximum water level calculated with equation 5.19 underestimates the maximum water level from the XBNH+ runs at the start of the island. However, the underestimation of the maximum water levels calculated with equation 5.19 at the start of the island is smaller for the bathtub profile, compared to the downslope and upslope profiles.

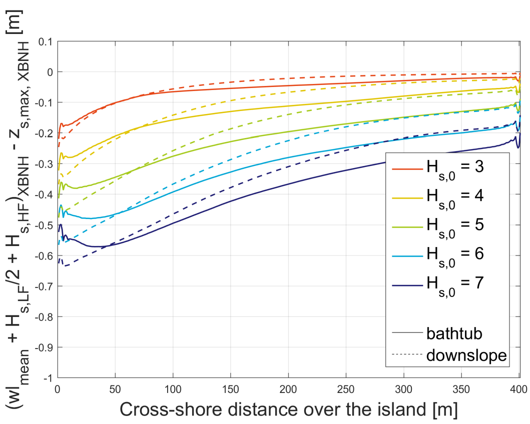


Figure 6.13: The different lines represent the difference between the maximum water levels calculated with XBNH+ and the maximum water levels calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs. The differences are averaged over all runs belonging to a certain offshore wave height $H_{s,0}$. The dashed lines (−−) represent the downslope profile, and the solid lines (–) represent the bathtub profile. The x-axis represents the cross-shore distance over the island.

As was described in Section 6.2.1 and 6.2.2, both the water depths (including a long wave component) and the short wave heights at the start of the island are generally overestimated by the JBIW model compared to XBNH+. This overestimation of the water depths and the short wave heights partly cancels out the underestimation of the maximum water level by equation 5.19. The water depths and short wave heights, and therefore the maximum water levels, calculated with the JBIW model are the same at the start of the island for the three different profiles. For the bathtub profile, the overestimation of the water depths and short wave heights is larger than the underestimation of the maximum water level by equation 5.19, which leads to an overestimation of the maximum water levels at the start of the island.

The maximum water level at the start of the island calculated with the JBIW model can also be too low. Similar to the other profiles, this is caused by the fact that overtopping of short waves is not included in the JBIW model. This was already discussed for the downslope and upslope profiles.

Furthermore, it can be seen from Figure 6.12a that from the start of the island untill a distance of about 50 m, the difference in maximum water level drops and at a distance of about 50 m, the maximum water level from the JBIW model generally underestimates the maximum water levels from XBNH+. This can be explained by the fact that the decrease in mean water level depends on the value for λ in the IW-method. In this method, the value for λ depends on the bottom roughness and the slope. At the start of the island, the slope is quite steep; therefore the water level decreases quite strongly. Apparently, this decrease in mean water level is too strong and leads to an underestimation of the maximum water level.

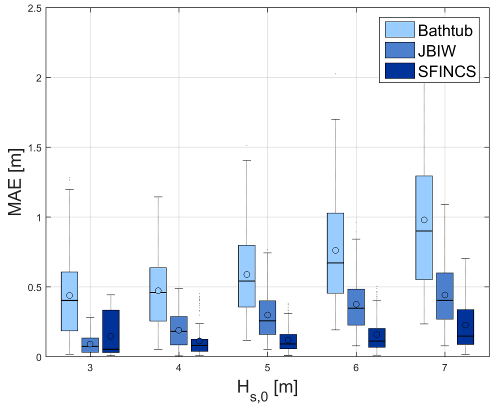
Comparison to other flood models

Similar to the downslope and upslope profile, the difference to the XBNH+ results for the different models (i.e. the bathtub method, the JBIW model and SFINCS) are compared for different parameter values. The results are depicted in Figure 6.14. As can be seen from this figure, the performance of the JBIW model is less for the bathtub profile compared to the downslope and upslope profile. However, the JBIW model is still more accurate than the bathtub method in all cases.

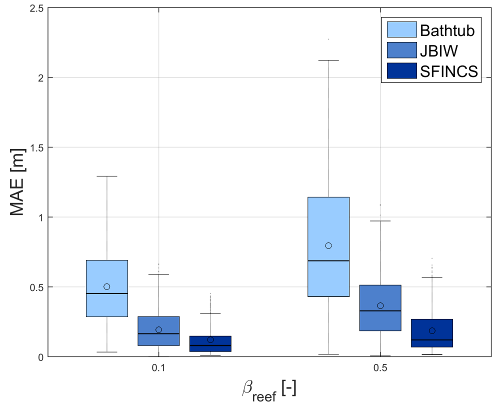
Furthermore, it can be observed that the errors of the SFINCS model are higher compared to the downslope and upslope profiles. This is mainly caused by the fact that in the SFINCS runs, the island does not 'fill up' as quickly as in the XBNH+ runs. Therefore, the maximum water level on the island is often underestimated in the SFINCS runs. This is mainly an issue when there is occasional overtopping of waves; in that case, the maximum water levels are underestimated by the SFINCS model. In Table 6.5, the averaged MAE (i.e. over all runs with a bathtub topography), the minimum MAE, and the maximum MAE are listed for the different models.

Table 6.5: Averaged MAE [m] (i.e. averaged over all runs with a bathtub profile) for the different models. The values between brackets indicate the range in MAE over all runs.

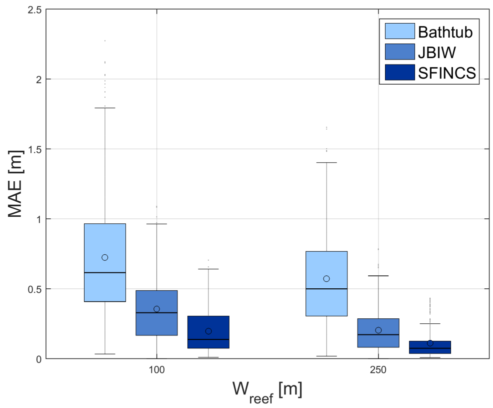
	MAE [m]
Bathtub	0,65 (0 - 2,27)
JBIW	0,28 (0 - 1,01)
SFINCS	0,15 (0 - 0,71)



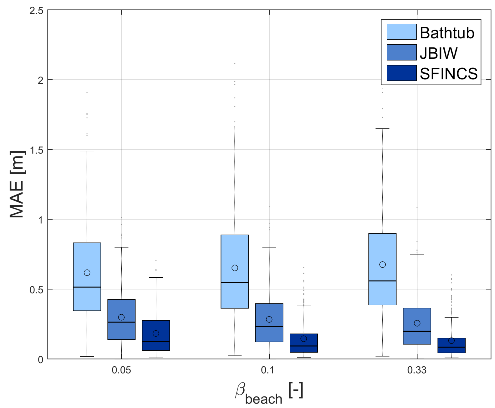
(a) Different $H_{s,0}$



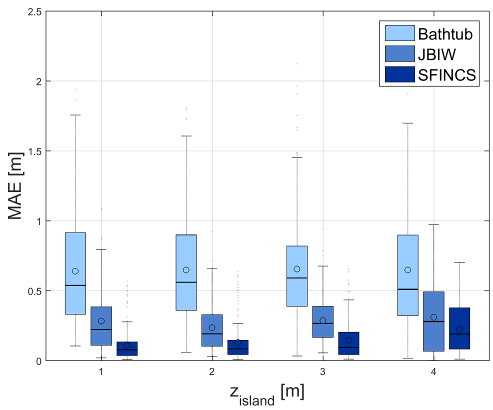
(b) Different β_f



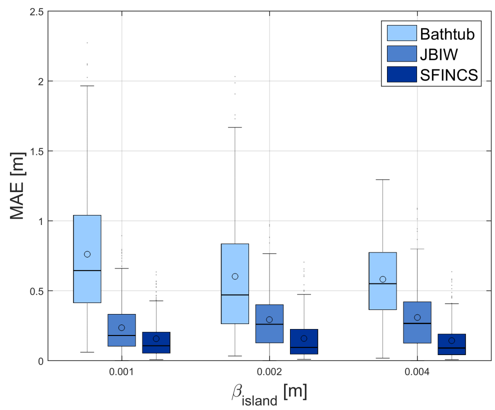
(c) Different W_{reef}



(d) Different β_b



(e) Different z_{island}



(f) Different β_i

Figure 6.14: Mean absolute errors in the maximum water levels for the conceptual tests on the bathtub profile, for the different flood models. The error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the different flood models ($Z_{s,max,model} - Z_{s,max,XBNH}$). The mean absolute error is subsequently calculated by first taking the mean value of all runs belonging to a certain parameter value and then taking the spatial absolute mean of the error.

6.3. Concluding remarks

In this chapter, the simple JBIW model as introduced in Chapter 5 was tested in 1D for different island topographies and compared to other flood models. In this comparison, the bathtub method, the JBIW model, the SFINCS model and the XBNH+ model were included. As there were no measurements available, the results of the XBNH+ model runs were used as a reference to compare the results of the other models too.

The results indicated that in the JBIW model, the long wave height at the start of the island is overestimated. This is probably caused by the fact that the reflection of long wave energy is not incorporated in the JBIW model. Since the long wave is overestimated, the water depth in the JBIW model (including a long wave component) is a bit too high; therefore the short wave height is also overestimated. However, Equation 5.19 that is used to calculate the maximum water levels in the JBIW model underestimates the contribution of waves to the maximum water levels. The overestimation of the water depths and the short wave heights and the underestimation of the maximum water levels by Equation 5.19 (partly) cancel each other out. Depending on the overestimation and underestimation, the maximum water level at the start of the island calculated with the JBIW model can both be too high or too low. Furthermore, the maximum water level at the start of the island calculated with the JBIW model can be too low, since overtopping of short waves is not included in the JBIW model. Lastly, the JBIW model often overestimates the maximum water level at the end of the island, due to the boundary effect from the end of the island.

The MAE in the calculated maximum water depths over all island topographies for the different models are listed in Table 6.6. It could be concluded that for all tested 1D island topographies, the JBIW model is more accurate than the bathtub method, but less accurate than the SFINCS model. However, in terms of computational time, the JBIW model is comparable to the bathtub method (i.e. both models run in less than a second), while the SFINCS model requires more computational time (i.e. a few minutes). Lastly, it could be concluded that the JBIW model is most accurate for the upslope island profiles and least accurate for the bathtub profiles.

In order to indicate what these runtimes would mean in the context of a large-scale coastal flood assessment including all SIDS, a quick back-of-the-envelope calculation can be made. There are 58 SIDS in the world. There is a large variability in the coastline length between these SIDS, but the average coastline length is 1002 km (UN-OHRLLS, 2013). This means a total coastline length of 58,116 km. Assuming coastal flooding is calculated for a cross-section every 500 m, this amounts to 116,232 cross-sections. Using the averaged runtimes listed in Table 6.6, this would mean that it would take 8.58 years to calculate coastal flooding with an XBNH+ model, 163.72 days to use the SFINCS model and 6.78 hours to use the JBIW model. However, this is only for one offshore condition. In a coastal flooding assessment, the consequences of different offshore conditions need to be tested.

This comparison is not entirely fair, since the XBNH+, SFINCS and JBIW model also require different input conditions and start at different locations (i.e. the XBNH+ model starts in deep water, while the SFINCS and JBIW model start at the beach foot. When the SFINCS or JBIW model are used, the input conditions at the location of the beach foot need to be obtained, which will increase the computational time). However, from this calculation it can still be seen that the JBIW model could be useful in large-scale coastal flooding assessments to obtain a first estimate of coastal flooding. However, it is important to note that the model is not accurate enough to obtain accurate predictions of the maximum water levels.

Table 6.6: Averaged runtime [s] and averaged MAE [m] (i.e. averaged over all runs) for the different models. The values between brackets indicate the range in MAE over all runs.

	MAE [m]	Runtime [s]
Bathtub	0,64 (0 - 2,59)	0,005
JBIW	0,19 (0 - 1,01)	0,21
SFINCS	0,10 (0 - 0,71)	121,7
XBNH	-	2330,04

7

2D case study for Ebeye

In the previous chapter, the simple flood model as described in Chapter 5 was tested in 1D for different island types (i.e. downslope, upslope and bathtub profiles) and for different parameters. The results showed the JBIW model to be more accurate compared to the bathtub method, which is currently being used in large-scale flood risk assessments (PCRAFI, 2013). In this chapter, the JBIW model will be applied in 2D for the island of Ebeye and compared with the bathtub method. Furthermore, the JBIW model will be applied in 2D in combination with both the more accurate reference DEM for the island of Ebeye and with two building-corrected satellite-based DEMs: the TanDEM-X and the MERIT DEM. Lastly, the water depths calculated with the JBIW model (both in combination with the more accurate reference DEM and with the building-corrected satellite-based DEMs) and with XBNH will be used in combination with an exposure map of the island and a depth-damage curve to calculate the risk in terms of economic damages to the buildings for different conditions. In Section 7.1, the setup of the 2D case study will be described. In Section 7.2, the results will be discussed and lastly, in Section 7.3 some concluding remarks will be listed.

7.1. Set-up 2D case study

The goal of this 2D case study is to compare the accuracy of the JBIW model and the bathtub method for the island of Ebeye. Similar to the 1D tests described in the previous chapter, since there are no measured data available the XBNH+ model is used as a reference to compare both the results from the JBIW model and the bathtub method to. Since both the JBIW model and the bathtub method start from the beach foot, while the XBNH+ model starts in intermediate waterdepths, the input for the JBIW model and the bathtub method are obtained from the XBNH+ runs at the location of the beach foot. In this way, only the effect of the used flood model is assessed. In Subsection 7.1.1, the reference XBNH+ runs will be described in a bit more detail. Subsequently, the way in which the JBIW model was applied in this 2D case study is explained in Subsection 7.1.2.

7.1.1. Reference XBNH+ runs

As a reference, different XBNH+ model runs were used. The XBNH+ model was based on a model that was developed as part of an earlier Deltares project (Giardino et al., 2018). The topography and bathymetry of the island that are used in the model are based on local measurements with a GPS device, as was described in Chapter 3. The offshore wave heights and water levels corresponding to different return periods were also obtained from (Giardino et al., 2018). These are listed in Table 7.1 and were used as input in the different reference runs as well. Similar to the 1D reference runs, the 2D reference runs for the island of Ebeye were run for 6 hours, in order to get stable wave characteristics at the beach foot.

Table 7.1: Offshore water levels and waveheights for different return periods, for the island of Ebeye

	RP = 1	**RP = 5**	**RP = 10**	**RP = 30**	**RP = 50**
Hs [m]	3,13	3,56	3,74	4,04	4,17
Zso [m]	1,32	1,37	1,40	1,43	1,45

7.1.2. JBIW model and bathtub method

In Chapter 5, the setup of the JBIW model is described. This model was implemented in 1D in matlab. In order to apply the model to a 2D case, several steps were taken. These steps are depicted in Figure 7.1 and will be shortly described below.

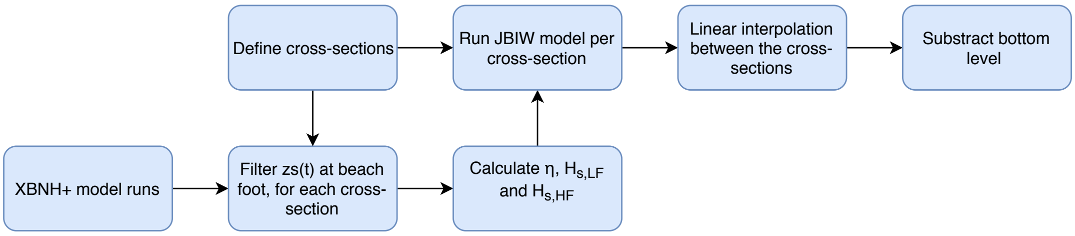


Figure 7.1: Set-up of the JBIW model runs in 2D

First, different 1D cross-sections are identified on the island. For the island of Ebeye, the JBIW model was applied to 11 cross-sections. The location of these cross-sections is depicted in Figure 7.2. For each of these 11 cross-sections, the water level time series at the beach foot was obtained from the reference XBNH+ runs. The water level time series were filtered to obtain only the incoming signal. For the filtered time series, the mean water level η, the significant long and short wave height $H_{s,LF}$ and $H_{s,HF}$ were calculated. Using these input conditions, the maximum water levels were calculated with the JBIW model for each cross-section seperately. Subsequently, the maximum water levels are interpolated between the different cross-sections. Lastly, the bed levels are subtracted from the maximum water levels to obtain the maximum waterdepths on the islands; negative waterdepths are set to zero.

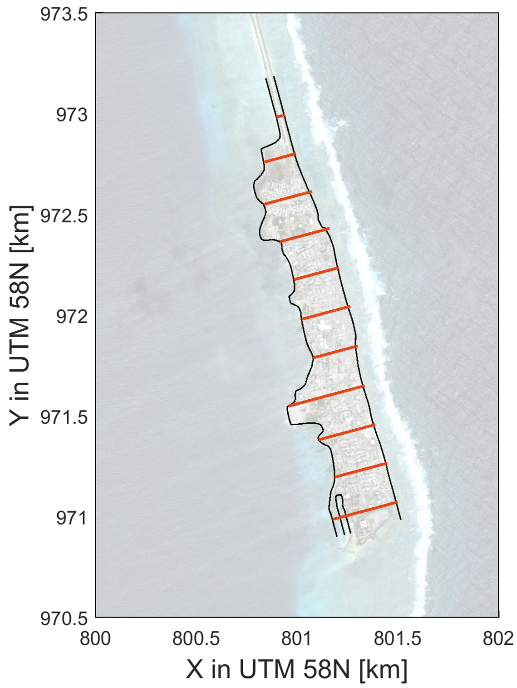


Figure 7.2: Location cross-sections for the island of Ebeye. The thin black line indicates the contour of the island. The orange lines indicate the locations of the cross-sections.

Apart from the JBIW model, the bathtub method was also applied to the island. The water level that was used as input for the bathtub method was also obtained from the reference XBNH+ runs. At each cross-section, the mean water level at the beach foot was determined from the XBNH+ reference runs. Since the alongshore variation in mean water level was very small (the difference between the different cross-sections is smaller than 5 cm), the mean water levels were averaged. This value was compared to the bed levels everywhere on the island to calculate the waterdepth.

Both the JBIW model and the bathtub method are combined with the accurate DEM that was also used as input for the XBNH+ model, and with the building-corrected TanDEM-X and MERIT DEM. Only the TanDEM-X and MERIT DEM were used, since from the analysis described in Chapter 4 it could be concluded that these satellite-based DEMs are the most accurate for the island of Ebeye. In order to use these building-corrected satellite-based DEMs, these DEMS (that have a coarse horizontal resolution) were interpolated on the grid of the more accurate DEM, following the same procedure as described in Chapter 3. The accurate DEM used in the XBNH+ model is vertically defined relative to local MSL. The vertical datum of the building-corrected satellite-based DEMs was adjusted in such a way that these DEM were also defined with respect to local MSL.

7.2. Results 2D case study

In this section, the results of the 2D case study are described. In Section 7.2.1, the results are described for the different models, all used in combination with the accurate DEM for the island of Ebeye that was also used as input in the XBNH+ model. In Section 7.2.2, the results are described for the JBIW model in combination with the building-corrected satellite-based DEMs. Lastly, in Section 7.2.3, the results of the damage calculation, using both the maximum water depths calculated with the JBIW model (both in combination with the accurate reference DEM and the satellite-based DEMs) and XBNH, are described.

7.2.1. Reference DEM

In Table 7.2, the results are listed both for the JBIW model and the bathtub method. The errors are calculated with respect to the water depths calculated with the reference XBNH+ runs. In this table, the MAE and the LE90 (indicating the absolute value for which 90% of the errors are lower) are listed for the different methods, for the different return periods. From these error statistics, it can be seen that, similar to the 1D tests in the previous chapter, the JBIW model is more accurate than the bathtub method; for all return periods, both the MAE and LE90 error are (much) lower. However, the error in the maximum water levels calculated with the JBIW model can still be significant.

Table 7.2: Error statistics for the 2D case study of Ebeye, for the JBIW model and the bathtub method.

		RP = 1	**RP = 5**	**RP = 10**	**RP = 30**	**RP = 50**
JBIW	MAE	0.21	0.27	0.26	0.28	0.30
	LE90	0.50	0.63	0.62	0.67	0.68
Bathub	MAE	0.80	0.83	0.83	0.86	0.89
	LE90	1.59	1.69	1.71	1.75	1.82

These error statistics do not provide information on the spatial distribution of the maximum water depths and the errors. Therefore, the water depths calculated with the different methods for a return period of 5 years are depicted in Figure 7.3 and 7.4, for the entire island. From these figures, it can be seen that indeed the errors in the bathtub method are larger than for the JBIW model. Firthermore it can be seen that with the bathtub method, it is not possible to identify the areas that are most vulnerable to flooding (i.e. the areas with the largest water depths). This was also expected, since the island of Ebeye has a downslope profile, that does not fill up. For this type of profile, the bathtub method does not apply.

From Figure 7.4, it can be seen that the JBIW model is in general able to estimate the maximum water depths. With this model, it is possible to identify the most vulnerable areas on the island. However, similar to what was found in the 1D tests, the accuracy of the JBIW model is not high enough to accurately predict the maximum waterdepths. Lastly, it can be observed in Figure 7.4 that the water depths at the end of the island are not modelled correctly. This is an artefact introduced by the interpolation of the maximum water levels between the different cross-sections.

In Figure 7.5, a difference plot for the maximum water depths calculated with the JBIW model with respect to the XBNH+ model results is depicted. The difference is calculated by subtracting the maximum water depth from the XBNH+ model from the maximum water depth calculated with the JBIW model. Positive values in the difference plot therefore indicate that the maximum water depth calculated with the JBIW model is too high. From this figure, it can be seen that for a large part of the island, the calculated water depths at the start of the island (i.e. the oceanward side) are a bit too low. Furthermore, the maximum waterdepth at end of the island (i.e. the lagoonward side) are for a large part a bit too high. This can also be observed in the cross-sections as depicted in Figure 7.6a and 7.6b.

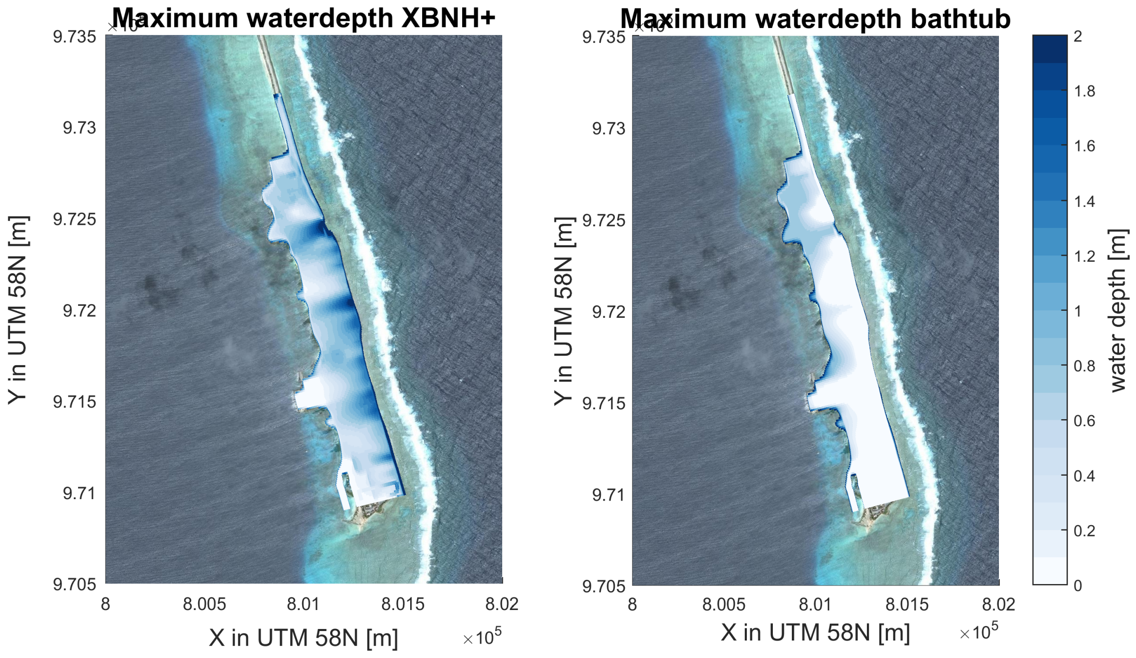


Figure 7.3: The left figure shows the maximum water depths for the island of Ebeye, for a return period of 5 years, calculated with the XBNH+ model. The right figure shows the same, but here the maximum water depths are calculated with the bathtub method.

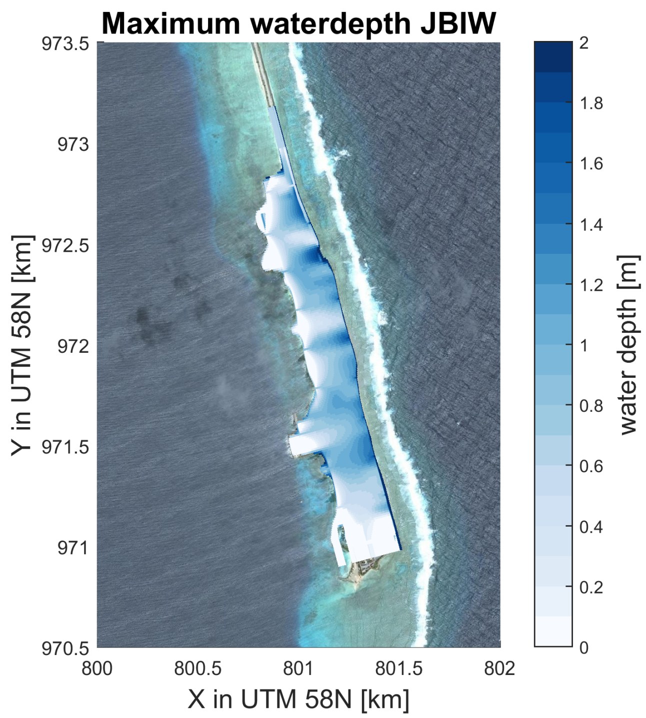


Figure 7.4: Maximum water depths calculated with the JBIW model, for a return period of 5 years.

In these figures, the maximum water levels calculated with the JBIW model and XBNH+ are depicted. In the cross-section in Figure 7.6b, it can be seen that the maximum wate rdepth calculated with the XBNH+ model decreases very quickly over the island. This happens much faster than was observed in the 1D XBNH+ model runs. This can be explained by the fact that in a 2D case, water will also flow to the sides, especially when a point is higher than its surroundings. This effect is not included in the JBIW model and can therefore introduce additional errors in addition to the ones discussed in the previous chapter for the 1D tests.

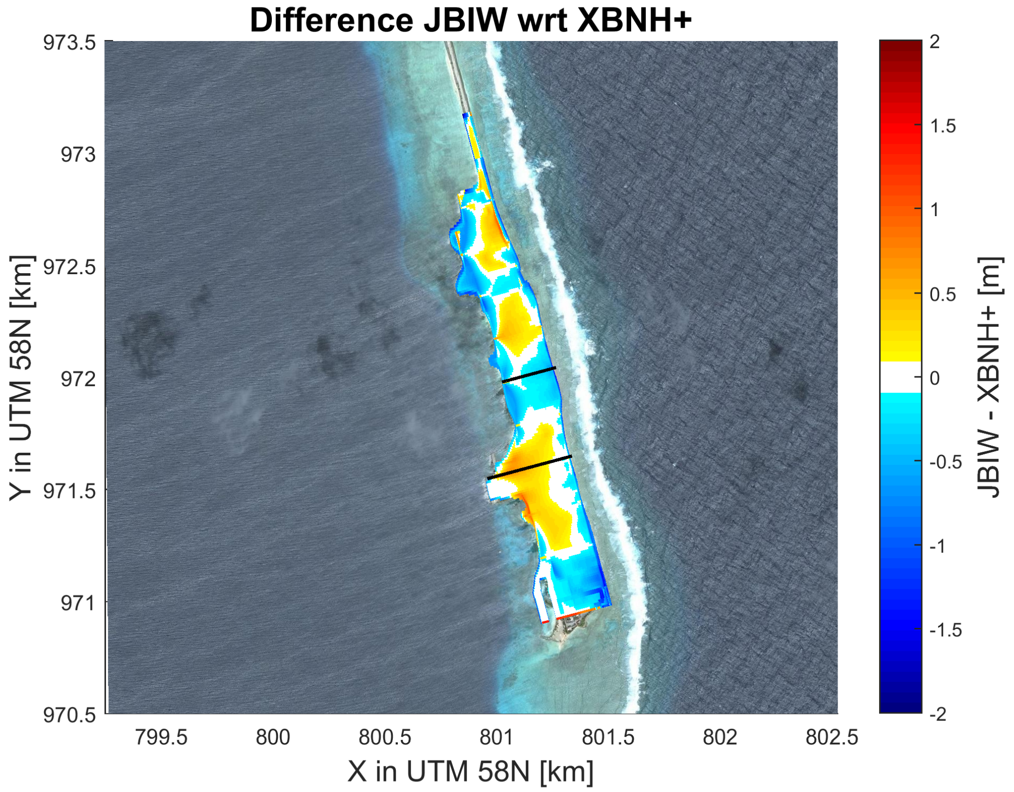
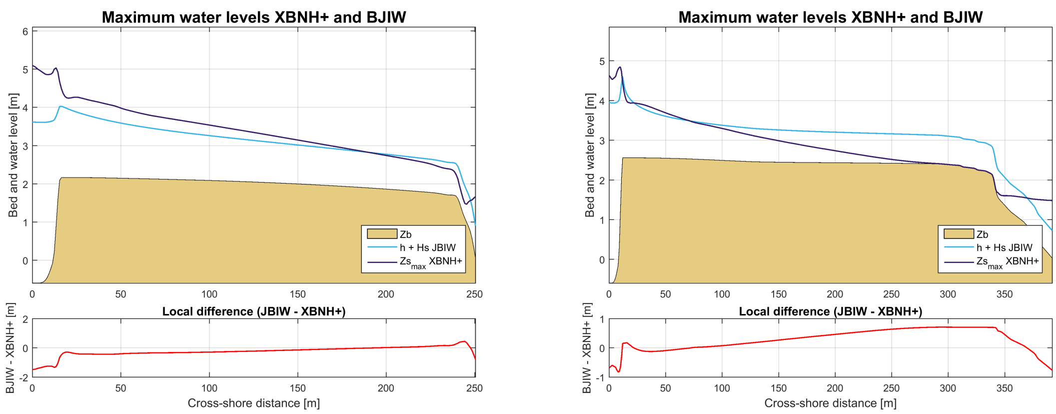


Figure 7.5: Difference plot, comparing the maximum water depths for the island of Ebeye, calculated with the JBIW model and with XBNH+, for a return period of 5 years.



(a) Cross-section 6

(b) Cross-section 8

Figure 7.6: Figure (a) shows the maximum water level calculated with the JBIW model and the maximum water level calculated with XBNH+, for cross-section 6. Figure (b) shows the same, but for cross-section 8. For both cross-sections, the lower plot indicates the error of the JBIW model with respect to XBNH+.

7.2.2. Satellite-based DEM

In Table 7.3, the results are listed for the JBIW model in combination with both the building-corrected TanDEM-X and MERIT DEM. Again, the MAE and the LE90 are listed. When comparing these error statistics to the ones listed in Table 7.2, it can be seen that the errors become 3 to 4 times as big when using the building-corrected satellite-based DEMs instead of the more accurate reference DEM.

Table 7.3: Error statistics of the JBIW model in combination with the building corrected TanDEM-X and MERIT DEM, for the 2D case study of Ebeye.

		RP = 1	**RP = 5**	**RP = 10**	**RP = 30**	**RP = 50**
TanDEM-X	MAE	0.90	0.96	0.98	1.00	0.98
	LE90	1.90	1.97	2.01	2.01	2.04
MERIT	MAE	0.69	0.76	0.80	0.84	0.88
	LE90	1.73	1.76	1.76	1.75	1.83

Again, in order to analyse the spatial distribution of the maximum water depths and errors, the water depths are plotted for the entire island. In Figure 7.7, the water depths calculated with the JBIW model in combination with the building-corrected TanDEM-X and MERIT DEM are depicted. In Figure 7.8, the water depths calculated in the reference XBNH+ run are depicted. From Figure 7.4 in the previous section, it can be concluded that even though the JBIW model is not accurate enough to predict the exact water depths over the island, it is possible to identify the most vulnerable areas. However, when applying the JBIW model in combination with the building-corrected satellite-based DEMs, this is no longer the case. The errors in the topography are so large, that not only the exact values of the maximum water depths are far off, but also the spatial variation in water depth is significantly different compared to the reference runs.

From the comparison of the different flood maps, it is striking that the general shape of the island is significantly different for the different DEMs. This is caused by the fact that both the TanDEM-X and the MERIT DEM have a horizontal resolution of 90 m. Since the island of Ebeye is very small (i.e. the widest part of the island is about 500 m wide), this results in a different shape of the island. Furthermore, it can be seen that the water depths calculated by the JBIW model in combination with the building-corrected TanDEM-X are much larger than the water depths calculated in combination with the building-corrected MERIT DEM. This is in agreement with the error statistics as calculated in Chapter 4; in general, the building-corrected TanDEM-X is too low (bias of -0.94 m), while the building-corrected MERIT DEM is in general a bit too high (bias of +0.07 m). This results in larger water depths for the TanDEM-X.

7.2.3. Damage computation

The final goal of a large scale coastal flooding assessment for the different small islands is to obtain an estimation of the risks for the different islands. An estimation of the risk caused by coastal flooding for all different small islands can subsequently be used to prioritize more detailed risk assessments and adaptation measures for these islands. Risk is often expressed in economic terms (e.g. in dollars). In order to obtain an estimate of the uncertainty in economic risk that is introduced by the errors in satellite-based DEMs and the use of a simple flood model, the maximum water depths calculated in the different runs were used to calculate the economic risk to the buildings for the island of Ebeye. This is done for the reference runs, for the runs with the JBIW model and for the runs with the JBIW model in combination with the building-corrected satellite-based DEMs. The damages calculated for the runs with the JBIW model (both in combination with the more accurate reference DEM and with the building-corrected satellite-based DEMs) are used to calculate the percentage difference with respect to the reference runs.

In order to obtain values for the economic risk to buildings in terms of dollars, a building map for the island of Ebeye is used. This building map is based on data available trough (PCRAFI, 2013) and was available from an earlier project of Deltares for the island of Ebeye (Giardino et al., 2018). The data from the PCRAFI project contain information on the location and economic value (expressed in terms of dollars) of the buildings. This information is combined with the different flood maps and a depth-damage curve obtained from (Paulik et al., 2015). This depth-damage curve is depicted in Figure 7.9 and gives the damage for a certain water depth (in the range of 0 to 4 m) in percentages of the total value of the building.

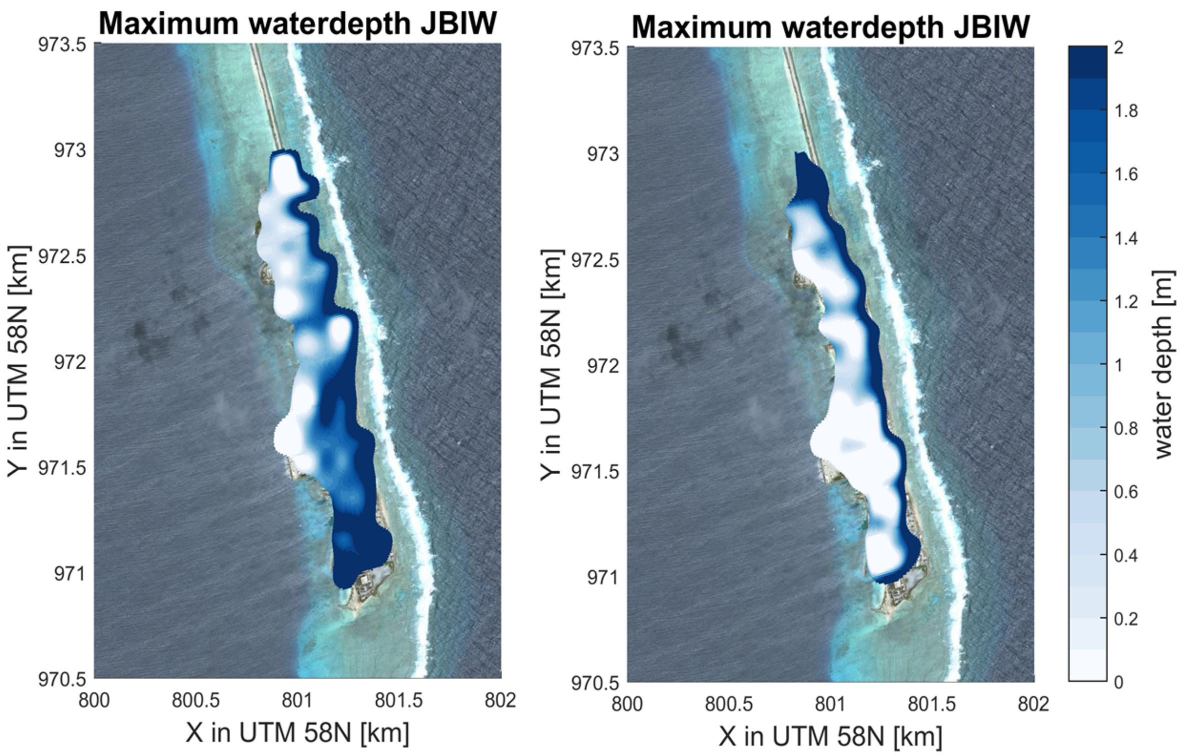


Figure 7.7: The left figure shows the maximum water depths for the island of Ebeye, for a return period of 5 years, calculated with the JBIW model in combination with the building-corrected TanDEM-X DEM. The right figure shows the same, but with the MERIT DEM.

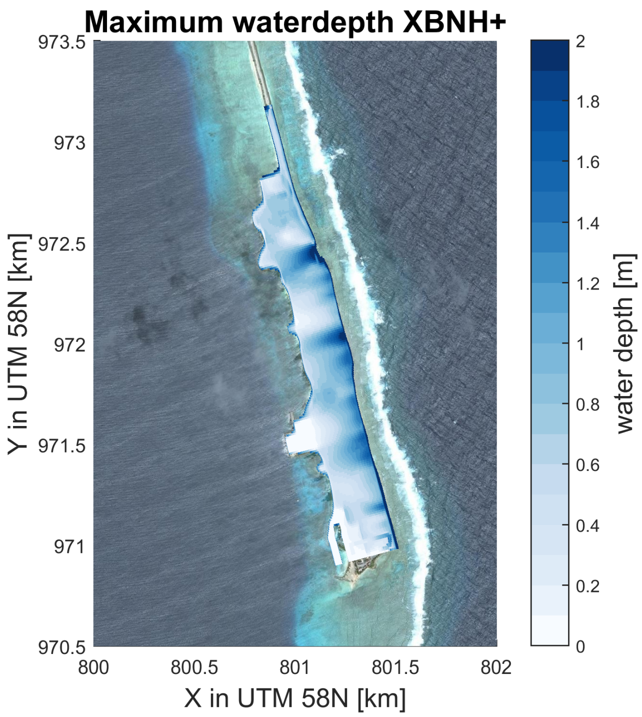


Figure 7.8: Maximum water depths calculated with the XBNH+ model, for a return period of 5 years.

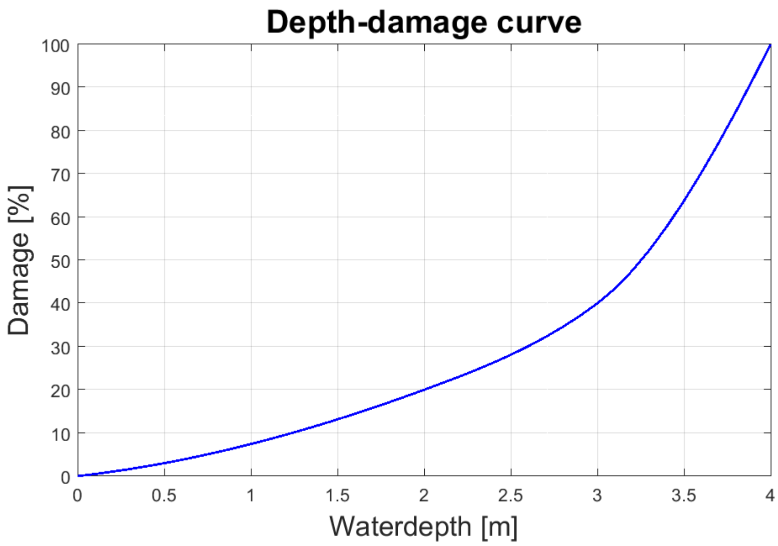


Figure 7.9: Used depth-damage curve (Paulik et al., 2015). The values on the y-axis indicate the percentage of the total value that is damaged.

The results are depicted in Table 7.4 and 7.5. In these tables, the economic damages (in dollars) are listed for different return periods. Furthermore, the percentage differences with respect to the reference values are listed in bold. From the values listed in Table 7.4, it can be seen that the deviations in economic damage for the runs with the JBIW model can be up to almost 10%. Furthermore, from Table 7.5 it can be concluded that the deviations in economic damage for the runs with the JBIW model in combination with the building-corrected satellite-based DEMs are much larger and can be up to almost 3 times the economic value in the reference run. In all cases, the economic damage is overestimated in the runs calculated with the JBIW model in combination with the satellite-based DEMs. These results indicate that with the use of a simple flood model, it is possible to obtain a first estimate of the economic damages for the island of Ebeye. However, when applying the simple flood model in combination with the building-corrected satellite-based DEMs, this is no longer possible; the accuracy of these DEMs is too low.

Table 7.4: Economic damages to the buildings for the reference runs and for the runs with the JBIW model, for different return periods.

		RP = 1	RP = 5	RP = 10	RP = 30	RP = 50
Reference	Damage [million $]	4,17	6,43	7,30	9,00	10,65
JBIW	Damage [million $]	4,28	6,13	7,16	8,52	9,64
	Difference [%]	**2,55**	**-4,58**	**-1,98**	**-5,21**	**-9,43**

Table 7.5: Economic damages to the buildings for the reference runs and for the runs with the JBIW model in combination with the building-corrected satellite-based DEMs, for different return periods.

		RP = 1	RP = 5	RP = 10	RP = 30	RP = 50
Reference	Damage [million $]	4,17	6,43	7,30	9,00	10,65
TanDEM-X	Damage [million $]	16,16	20,81	22,88	25,14	27,93
	Difference [%]	**287,25**	**223,76**	**213,40**	**179,54**	**162,30**
MERIT	Damage [million $]	8,11	10,40	11,30	12,48	14,54
	Difference [%]	**94,38**	**61,80**	**54,77**	**38,79**	**36,58**

7.3. Concluding remarks

In order to apply the JBIW model to a 2D case study for the island of Ebeye, the model was used to calculate the maximum water levels in 1D for different cross-sections. Subsequently, these maximum water levels were interpolated and lastly, the bed levels were subtracted to obtain the maximum water depths over the island. The water depths calculated in this way were compared to water depths calculated with XBNH+. The error statistics showed that this method gives quite good results (i.e. the errors were comparable to the 1D conceptual tests) and suggested that it is not necessary to extend the JBIW model into a 2D version. However, it must be noted that the alongshore variability in topography is quite small for islands like Ebeye (i.e. coral atolls). For islands with a larger alongshore variability, the amount of cross-sections should be higher.

Futhermore, the JBIW model was applied in combination with both the building-corrected TanDEM-X and MERIT DEM. The introduction of these building-corrected satellite-based DEMs caused the errors to become 3 to 4 times as big, compared to the runs with the JBIW model in combination with the more accurate reference DEM. This indicates that about $65-75\%$ of the combined error in maximum water depths over the island can be attributed to the use of less accurate, satellite-based DEMs, while only 25-35 % can be attributed to the use of a more simple flood model. When applying these satellite-based DEMs, not only the exact values of the maximum water depths are off, but also the spatial variation in water depth was significantly different when the building-corrected satellite-based DEMs were used. It can therefore be concluded that with the current freely available satellite-based DEMs, it is not possible to obtain a reasonable estimate of coastal flooding for reef-fronted small islands on a large scale. This is mainly caused by the inaccuracies in the satellite-based DEMs; only a smaller part can be attributed to the use of a more simple flood model.

Lastly, the errors in the prediction of the maximum water depths over the island were translated into the errors in the prediction of the economic damage to the buildings. The building map for the island of Ebeye was combined with the different flood maps and a depth-damage curve to obtain estimates of the economic damage to the buildings for the different return periods. The results indicated that with the use of the simple JBIW model, it is possible to obtain a first estimate of the economic damages to the buildings for the island of Ebeye. However, when applying the JBIW model in combination with the building-corrected satellite-based DEMs, the errors in economic damages become very large.

8
Discussion

In this chapter, the results and insights obtained from this study will be discussed. This discussion is subdivided in two parts. In the first part, the results related to the comparison and improvement of the satellite-based DEMs will be discussed. In the second part, the simple flood model and its applications will be discussed.

8.1. Satellite-based DEMs

In this section, the results related to the satellite-based DEMs will be discussed. In Section 8.1.1, some remarks regarding the reference DEMs and the date of the different satellite-based DEMs will be made. Subsequently, in Section 8.1.2, the uncertainties introduced by the interpolation method and differences in horizontal grid resolution wll be discussed. Lastly, in Section 8.1.3, the way in which accuracy assessments of satellite-based DEMs are usually carried out is discussed and another method is proposed.

8.1.1. Reference DEMs

As described in Chapter 3, the different satellite-based DEMs were compared to reference DEMs for 11 different islands. However, the reference DEMs for these different islands originate from different sources. These reference DEMs are measured with different methods (i.e. GPS and LiDAR), at different times and probably with a different accuracy. For some reference DEMs, the accuracy is given, but for others, the accuracy is not known. However, the accuracy of these different reference DEMs is expected to differ between the different islands. Comparing the error statistics of the different satellite-based DEMs for the different islands is therefore not entirely fair.

Furthermore, both the different satellite-based DEMs and the reference DEMs for the different islands are all measured in different years. The fact that the different satellite-based DEMs, which all originate from different years, are compared to the reference DEM, which may originate from again another year, can introduce uncertainties in the calculated error statistics. This is especially the case for areas where the topography and/or the land cover have a large temporal variation. This might for example introduce some uncertainties in the analysis for the Wadden islands, where especially the coastal area (i.e. the beach and the dunes) is expected to be quite variable in time.

8.1.2. Interpolation method

As described in Chapter 3, the different satellite-based DEMs were interpolated on the grid of the reference DEMs for the different islands. It was found that, especially for the smaller islands, the calculated error statistics are quite sensitive to the way in which this interpolation is carried out. Furthermore, the different satellite-based DEMs only contain points that are on the island. The surrounding water tiles are not assigned a value. However, in order to carry out the interpolation, these tiles also required a value. Therefore, these values were assumed to be zero with respect to the EGM08 geoid. This might result in an underestimation of the elevation at the border of the island. Especially for the smaller coral atolls, this is expected to introduce an error, as the (oceanward) borders of these islands are usually quite high (see also Chapter 3). It is not expected that the way in which the interpolation is carried out will influence the conclusion on which satellite-based

DEM is the most accurate for a certain area, but it might influence the calculated error statistics for the different satellite-based DEMs.

As was stated above, for all islands the different satellite-based DEMs were interpolated on the grid of the reference DEM. However, the reference DEMs for the different islands had different horizontal grid resolutions. This may also cloud the comparison of the error statistics of the different satellite-based DEMs among the different islands. It is expected that, especially for areas with steeper slopes, the calculated error statistics will increase for increasing horizontal resolution of the reference DEM. For these areas, the micro-relief (i.e. the topography at a scale smaller than the horizontal resolution of the satellite-based DEM) cannot be captured accurately, which will lead to higher error statistics.

8.1.3. Accuracy assessment of satellite-based DEMs

In the conclusion in Chapter 9, it was mentioned that the error statistics calculated for the different satellite-based DEMs on the different islands can be used to draw conclusions on which satellite-based DEM is the most accurate. However, these statistics cannot be used as a proxy for the accuracy of these DEMs in other areas. This is caused by the way in which the analysis is carried out.

In many literature studies concerning the accuracy of satellite-based DEMs, a comparison is made between one or more satellite-based DEMs and a DEM which is (assumed to be) more accurate, for a certain area. This area is often defined based on some topographic border, for example a (part of a) country, or a certain region. The same approach was applied in this thesis, where the error statistics were calculated for the different islands seperately. These studies lead to averaged error statistics, like the RMSE or the MAE of a certain satellite-based DEM for that region. These averaged error statistics are usually also the only accuracy indicators provided by the constructing agency of a satellite-based DEM (for most satellite-based DEMs, only the RMSE and in some cases the LE90 is provided). Many studies found in literature that try to incorporate the uncertainty of the used satellite-based DEM in their analysis, assume this error to be constant and normally distributed everywhere. However, the analysis done as part of this thesis indicated that the DEM error is far from constant (or normally distributed) and is strongly correlated with terrain cover, especially with the presence of forest and buildings, and with the slope of the terrain. This was also found in different literature studies (e.g. (Hawker et al., 2019)).

This fact indicates that it might not be very useful to compare satellite-based DEMs to a reference DEM for a certain area, based on some sort of topographic border. One of the main aims of performing such an analysis is to gain insight in the error of a certain satellite-based DEM, in order to obtain information on the accuracy of this satellite-based DEM in areas where no reference DEMs are available. However, the error statistics that are calculated for an area, based on a certain topographic border, do not provide a proxy for the error statistics in another area, because the terrain cover and/or slope can be totally different. Therefore, it would be more useful to compare one or more satellite-based DEMs to a reference DEM for a certain area, based on the terrain cover and slope of that area. In this way, it might be possible to couple the DEM error to terrain cover and/or slope. Such error statistics might serve as a proxy of the accuracy of a certain satellite-based DEM in another area (where no reference DEMs are available), if more information on the terrain cover and approximate terrain slope of that area is known.

Such an analysis should be based on larger areas than the ones incorporated in this thesis. This probably means that areas in different parts of the world should be incorporated in such an analysis. It is important to keep in mind that the differences in DEM error found between areas with different terrain cover might not be attributed solely to differences in terrain cover. The instrumental error in satellite-based DEMs can also differ for different places in the world. For example, the general bias in a satellite-based DEM differs globally. This can be attributed to the measuring method of satellite-based DEMs (see also Appendix A). Both with SAR interferometry and radar stereogrammetry, it is difficult to determine the absolute elevation of a certain point; it is more easy to determine relative elevation differences between different points. This can introduce a bias in the satellite-based DEM. In order to correct for this possible bias, accurately measured ground control points (GCPs) are often used in the construction process of a satellite-based DEM in order to correct for this bias. However, in some areas in the world, these GCPs are more abundant than in others.

8.2. Simple flood model

In this section, the results related to the flood modelling will be discussed. In Section 8.2.1, the calculation of the maximum water level in the JBIW model will be discussed. In Section 8.2.2, the uncertainty that is introduced due to the use of the XBNH+ model results as a reference is discussed. In Section 8.2.3, the consequences of the comparison between phase-resolving and phase-averaged models is discussed. Lastly, in Section 8.2.4, some remarks regarding the practical application of the different flood models in large-scale flood assessments are made.

8.2.1. Calculation of the maximum water level in the JBIW model

In the current version of the JBIW model, the maximum water levels are calculated using Equation 5.19. In this equation, it is assumed that long waves can lead to a temporary increase in water depth. The contribution of the long wave to the water depth is assumed to be equal to $H_{s,LF}/2$. Subsequently, the short waves are calculated on top of this water depth. The short waves are assumed to be Rayleigh distributed and therefore, the maximum short wave height is assumed to be equal to $2H_{s,HF}$. The maximum water level is therefore calculated by adding $H_{s,HF}$ to the water depth (including the long wave component). However, from the results from the 1D conceptual tests in Chapter 6, it could be concluded that this equation is not correct and underestimates the contribution of waves to the maximum water levels (as calculated with the XBNH+ model). For further development of the JBIW model, this should be looked into; this will be further elaborated in Chapter 10.

8.2.2. Model-model comparison

In order to test the accuracy of the JBIW method, the model was applied to different simplified 1D topographies and compared to other flood models. In this comparison, the results of the XBNH+ model served as a reference, as this model was expected to be the most accurate. Furthermore, the JBIW model was applied in a 2D case study for the island of Ebeye. Again, the results from the XBNH+ model served as a reference. For both cases, the results of the XBNH+ model were used as a reference, because there were no measured data available. Although different studies showed the XBNH+ model to be able to model the water levels accurately in reef-fronted coasts, the comparison to this model still introduces some uncertainty in the calculated errors of the JBIW model. It is important to keep in mind that the calculated error statistics for the JBIW model are deviations from the XBNH+ model results, not from the 'ground truth'.

8.2.3. Phase-resolving vs. phase-averaged

Both XBNH+ and SFINCS are phase-resolving models, which means that they resolve the sea surface. Changes in the sea surface are solved in space and in time. The JBIW model is not a phase-resolving model, but a phase-averaged model. The changes in the sea surface in this model are only solved in space, not in time. In order to make a fair comparison between these different types of models, the XBNH+ and SFINCS models were run with the same offshore water levels and wave conditions for 6 hours. This was done in order to get stable wave characteristics at the location of the beach foot, that could be used as input for the JBIW model. In this way, a comparison between the different models could be made.

However, in practice offshore water levels and wave conditions are not constant for such a long period of time. In general, these water levels and wave conditions will be present for a much shorter duration. This will influence the maximum water levels over the island; these will probably be lower. It is important to keep in mind that this is not incorporated in the JBIW model; the maximum water levels calculated with the JBIW model may therefore overestimate the maximum water levels that occur in practice.

8.2.4. Practical application of different flood models

Both for the 1D conceptual tests and for the 2D case study for the island of Ebeye, different flood models were compared to each other (i.e. the bathtub method, the JBIW model, the SFINCS model and the XBNH+ model). The XBNH+ model that served as a reference starts in intermediate water depths. The other three models all start at the location of the beach foot. In order to be able to compare only the differences in accuracy due to difference in flood model, the input conditions for the bathtub method, JBIW model and SFINCS model were obtained directly from the XBNH+ model runs. However, when one of these 3 models is applied in a large-scale flood assessment, these input conditions need to be obtained in another way, for example from BEWARE (Pearson et al., 2017). This will introduce additional uncertainties in the prediction of the maximum water levels over the island.

These uncertainties can be significant, since in general there is only very scarce data available regarding the nearshore bathymetry for reef-fronted small islands. Since the nearshore bathymetry for these types of islands is very uncertain, it is not certain that the use of an XBNH+ model will result in more accurate input conditions at the location of the beach foot than for example BEWARE.

9 Conclusion

In this chapter, the research question as formulated in the introduction of this part (see Chapter 1) will be answered. In order to do this, first the different sub-questions will be answered. Lastly, an answer to the main research question will be formulated.

1. Which publicly available satellite-based DEM is the most accurate to use in large-scale coastal flood assessments for SIDS and what is the accuracy of this DEM?

In order to answer the first sub-question, 6 different satellite-based DEMs were validated against more accurate reference elevation data for 11 islands, which were subdivided in 3 different groups: coral atolls, vulcanic islands and the Waddden islands. The 6 satellite-based DEMs that were included in the analysis are: the ALOS DEM, the ASTER DEM, the MERIT DEM, the SRTM DEM, the SRTMvf DEM and the TanDEM-X. These different DEMs are all publicly available, but differ from each other in terms of construction method, horizontal resolution and accuracy.

From this analysis, it could be concluded that the ASTER DEM is the least accurate for all islands and suffers from a large positive elevation bias. Furthermore, the TanDEM-X is generally the most accurate for the different coral atolls and for most Wadden islands (with the exception of the island of Vlieland, which is poorly covered in the TanDEM-X); this DEM has the smallest bias (ranging from -0.27 m till +0.65 m, with the exception for Vlieland with a bias of +1.75 m), MAE (ranging from 0.75 m till 1.86 m, with the exception for Vlieland with a MAE of 2.93 m) and RMSE (ranging from 1.23 m till 2.14 m, with the exception for Vlieland with a RMSE of 5.69 m). However, the minimum and maximum errors in the TanDEM-X are larger (down to -9.8 m and up to +11.74 m) than for some of the other satellite-based DEMs (e.g the MERIT DEM). This indicates that, although the averaged error statistics on the scale of an entire island indicate that the TanDEM-X is the most accurate, local errors in this DEM can be larger than in other satellite-based DEMs. In general, the TanDEM-X was more accurate for the Wadden islands than for the coral atolls.

For the vulcanic islands, the ALOS DEM was found to be the most accurate. For these islands, the errors in the TanDEM-X were significantly higher than for the coral atolls and Wadden islands. This can be explained by the coarse horizontal resolution of the TanDEM-X (i.e. 90 m) compared to the ALOS DEM (i.e. 30 m). In areas with steeper terrain slopes, this coarser resolution introduces larger errors.

Furthermore, positive DEM errors in the different satellite-based DEMs (with the exception of the ASTER DEM) were found to be correlated with forested and builded areas. The positive DEM errors were largest for forested areas (up to 6-7 meters) and smaller, but still significant, in builded areas (up to 1-2 meters).

In general, it could be concluded that the TanDEM-X is the most accurate for terrains with mild slopes and the ALOS DEM is the most accurate for terrains with steeper slopes. An important note here is that the TanDEM-X is the most recent satellite-based DEM and the currently available version contains areas which are not well covered (this was the case for the island of Vlieland). Before applying the TanDEM-X to a certain area, the coverage of the TanDEM-X in that area should first be checked. Furthermore, it is important to note that the error statistics that were calculated for the different islands can be used to compare the different satellite-based DEMs to each other to draw conclusions on which one is the most accurate. However, these error statistics cannot be used as a proxy for the accuracy of the DEMs in other areas, as the DEM error was found to depend strongly on the terrain cover and the terrain cover may be very different for other areas.

2. Can the accuracy of these publicly available satellite-based DEMs be improved by applying a building correction?

The DEM errors related to vegetated and builded areas can be (partly) removed if more information regarding the location and height of the trees/buildings is available. In the context of coastal flood modelling, it is especially relevant to have accurate elevation data for builded areas. In order to improve the accuracy of the satellite-based DEMs in these areas, a methodology for building-correction of satellite-based DEMs based on OSM data was suggested and applied. From a comparison of the error statistics before and after the building correction, it could be concluded that the building-correction procedure can both in- and decrease the DEM error.

This is caused by the fact that the satellite-based DEMs are contaminated by different error sources. In some cases, the satellite-based DEMs have a negative overall bias. The positive DEM error in builded areas and this negative overall bias then (partly) cancel each other out. In these cases, the building-correction procedure locally increases the DEM error. However, in case the overall bias is zero or positive, the DEM errors are decreased after the building correction. However, in all cases it could be concluded that the general shape of the satellite-based DEM was improved after building correction.

3. What is a suitable methodology for large-scale calculation of coastal flooding for reef-fronted small islands when taking into account the level of accuracy and the computational time?

In order to answer this question, different flood models were compared to each other. There are many different models that can be applied to calculate coastal flooding. Currently, the static bathtub method is often applied for large-scale coastal flooding assessmentss. This method is the most simple way to calculate coastal flooding and is therefore very low in terms of computational time. However, from initial calculations with this method, it was concluded that this method is not fit to apply to reef-fronted island coasts, among others because waves are not included in this method. Also, many coral atolls have a downslope shape, and the underlying assumption in the bathtub method that the land is 'filled up' with water is therefore not valid.

On the other end of the modelling spectrum, there are sophisticated models like XBeach, which are very accurate. However, these models require more input conditions and are high in terms of computational time. A computationally more efficient alternative is the SFINCS model, which was designed to model all relevant processes, but in a computationally more efficient way. Although this model is more efficient than the XBeach model, its computational time is still much longer than for the bathtub method. Also, the model requires more input conditions than the bathtub method.

Therefore, a simple flood model was developed in this thesis, which is more sophisticated than the bathtub method, but less sophisticated than the SFINCS model. The JBIW model is a combination of the Janssen-Battjes model for short wave dissipation (Janssen and Battjes, 2007) and the IW-method, which was originally developed for large-scale river flooding calculations (Dottori et al., 2018).

These 4 different models (XBNH+, SFINCS, JBIW and the bathtub method) were compared in different 1D tests. The results of these tests showed that the JBIW model is much more accurate compared to the bathtub method, but comparable in terms of computational time (both models run in less than a second). For the bathtub method, a MAE in the calculated maximum water depths of 0,64 m was found (the MAE ranged from 0 till 2,59 m for all 1D runs); for the JBIW model a MAE of 0,19 m was found (the MAE ranged from 0 till 1,01 m for all 1D runs). Furthermore, these tests showed that the JBIW model is less accurate than the SFINCS model; for the SFINCS model a MAE of 0,10 m was found (with the MAE ranging from 0 till 0,71 for al 1D runs). However, the SFINCS model requires a longer computational time (i.e. a few minutes) and more input conditions. From the 1D tests it could be concluded that it is possible to give a reasonable estimation of the maximum water depth under different conditions with the JBIW model. However, the exact value of the maximum water levels cannot be accurately predicted with the JBIW model. Lastly, the 1D tests indicated that the JBIW model is most accurate for upslope profiles ((MAE of 0,13 m, ranging from 0 till 0,72 m for all runs with an upslope profile) and least accurate for bathtub profiles (MAE of 0,28 m, ranging from 0 till 1,01 m for all runs with an bathtub profile) of the island topography.

4. What is the accuracy of coastal flood calculations using this methodology in combination with a publicly available satellite-based DEM?

In order to answer this question, the JBIW model that was developed as part of this thesis, was applied in 2D for the island of Ebeye. The JBIW model was implemented in 1D in Matlab. The choice was made not to extend the model to 2D, as that would increase the computational time of the model. In order to apply it to a 2D case, the model was therefore run in 1D for different cross-sections of the island of Ebeye. Subsequently, the water levels were interpolated between the different cross-sections and compared with the bed levels to obtain the maximum water depths on the island. Similar to the 1D tests, the obtained water depths were compared with the water depths from reference XBNH+ runs and with the water depths obtained with the bathtub method. From this comparison, it could be concluded that also in 2D, the JBIW model is much more accurate compared to the bathtub method. For the JBIW model, averaged over the different runs, the MAE was 0,26 m and the 90 % linear error (i.e. the value for which 90 % of the errors is lower, LE90) was 0,62 m. For the bathtub method, an MAE of 0,62 m and a LE90 of 1,71 m were found. Furthermore, it could be concluded that the maximum water depths obtained with the JBIW model in 2D were a reasonable estimate of the maximum water depths calculated with XBNH+. However, similar to the 1D tests, the JBIW model is not accurate enough to calculate exact values of the maximum water levels.

Furthermore, the JBIW model was also applied in 2D in combination with two different building-corrected satellite-based DEMs (i.e. the TanDEM-X and the MERIT DEM) for the island of Ebeye. The calculated maximum water depths were again compared to the water depths from the reference XBNH+ runs. The results indicated that the error that is introduced by the use of a satellite-based DEM is much larger than the error that is introduced by the use of the simple JBIW model. For the TanDEM-X, a MAE of 0,96 m and a LE90 of 1,99 m were found. The errors that were found for the MERIT DEM are slightly lower: a MAE of 0,79 and a LE90 of 1,77 were found.

Lastly, the calculated water depths were combined with a building exposure map for the island and a depth damage curve in order to calculate the economic damages to the buildings for different condition. From the results of these calculations, it could be concluded that, at least for the island of Ebeye, the simple JBIW model can be used to obtain a first estimate of the risk in terms of economic damages; the calculated damages deviate up to 10 %. However, when applying the JBIW model in combination with the building-corrected satellite-based DEMs, the error in the calculated damages becomes very large; for the TanDEM-X the calculated damages deviate up to almost 300 % and for the MERIT DEM up to almost 100 %.

What is a suitable approach for upscaling the calculation of coastal flooding for reef-fronted small islands in the Pacific Ocean and can this approach be used in combination with freely available topography data?

In order to answer the main research question for this part of the thesis, it could be concluded that the simple JBIW model that was developed in the context of this thesis can be used to obtain a first estimate of maximum water depths and an indication of which areas are most prone to flooding. However, the model is not accurate enough to obtain accurate predictions of the maximum water depths; for such exact predictions, sophisticated models like XBNH+ or SFINCS could be used. Furthermore, the results of the 2D case study for the island of Ebeye indicated that the JBIW model cannot be used in combination with publicly available satellite-based DEMs to obtain a reasonable estimate of coastal flooding; the errors that are introduced by the use of satellite-based DEMs are much higher than the errors that are introduced by the use of the JBIW model. Using these satellite-based DEMs resulted in very large deviations in the calculated risks (i.e. expressed in terms of economic damages to the buildings). These results indicate that for further studies focussing on the upscaling of coastal flood assessments for reef-fronted SIDS, obtaining higher accuracy elevation data is an important focus point.

10
Recommendations

In this chapter, different directions for further research will be described. Similar to the discussion, this chapter is subdivided in two parts. In the first part, some suggestions for further research related to the satellite-based DEMs will be given. In the second part, some suggestions for further research related to coastal flood modelling will be given.

10.1. Satellite-based DEMs

In this section, different recommendations for further research will be given in relation to the satellite-based DEMs. In Section 10.1.1, different suggestions to improve the accuracy of satellite-based DEMs and the accuracy of these DEMs in coastal flood assessments will be described. Furthermore, in Section 10.1.2, some suggestions for improved accuracy assessment of satellite-based DEMs will be given.

10.1.1. Improving the accuracy of satellite-based DEMs

As part of this thesis, a method to correct for the DEM error due to the presence of buildings was suggested and tested. It was concluded that this method improves the general shape of the different satellite-based DEMs in all cases and that it decreases the errors in case the satellite-based DEM is not, or positively, biased. However, there are many other error sources that influence the accuracy of the different satellite-based DEMs.

Another important error source is introduced by the presence of trees. In Chapter 2, it was described that in the construction process of the MERIT DEM, global tree density and tree height maps were used to correct for these errors. However, these global maps have a very coarse horizontal resolution (in the order of 1 km) and many small islands in the Pacific Ocean are not included on these maps. The tree height correction based on these maps is therefore assumed to be quite coarse in most areas and totally absent in others, like for example in small islands. Another approach to correct for the error introduced by the presence of trees might be based on satellite images. Currently, there are many studies in the field of remote sensing that focus on the identification of different vegetation covers using satellite imagery. It would be interesting to investigate whether such methods could also be used to identify forested areas. Such methods could then be coupled to a correction algorithm to try to remove the DEM error in these forested areas.

Furthermore, it was already described in Section 8.1.3 that many satellite-based DEMs suffer from biases, because it is difficult to measure absolute elevations. This can be (partly) solved by using GCPs to correct for this bias. A logical recommendation would therefore be to collect as many GCPs as possible for the area of interest and use these to correct the satellite-based DEMs. Although the collection of these points is a costly and time-consuming practice, especially considering the amount of small islands, it is still much less costly and time-consuming than measuring the exact topography for all these islands. In case these GCPs would be used to correct the satellite-based DEM(s), this should be done after correcting for the presence of buildings and/or trees. Since buildings and trees introduce positive DEM errors, they could otherwise cloud the calculation of the bias in the satellite-based DEMs relative to the GCPs.

Lastly, during the analysis of the different satellite-based DEMs, it was observed that many of these DEMs seem to contain quite some noise. The spatial variation in the different satellite-based DEMs was observed to be much higher than the spatial variation in the reference DEMs. It would therefore be interesting to investigate whether a smoothing filter could be applied to the satellite-based DEMs to remove this noise.

10.1.2. Improved accuracy assessment of satellite-based DEMs

As was already discussed in Section 8.1.3, it would be more useful to calculate the error statistics of the different satellite-based DEMs for areas with a homogeneous land cover and try to couple the errors to land cover types. In that way, the calculated error could be used as a proxy for the accuracy in other areas as well. This is therefore recommended for further research. In the context of coastal flood assessments, it is recommended that such an accuracy assessment focuses on coastal areas. Especially builded coastal areas are of interest, since the risks in these area are the main subject of interest in coastal flood assessments.

10.2. Coastal flood modelling

In this section, different recommendations for further research will be given in relation to the fast flood modelling. In Section 10.2.1, different recommendations will be discussed to further improve the JBIW model. In Section 10.2.2, some ideas regarding the operationalization of the JBIW model will be given.

10.2.1. Simple flood model

In Chapter 6, it was described that in the current version of the JBIW model, the long wave height is generally overestimated at the start of the island. It is expected that this is caused by the fact that the reflection of long waves is not included in the JBIW model. Inclusion of long wave reflection in the model might therefore improve the prediction of the long wave evolution over the island. It is expected that this will also improve the prediction of the short wave height. Currently, the short wave heights predicted by the JBIW model are a bit too high. Since the short wave height is calculated for a water depth including a long wave component, this is expected to be a result of the overestimation of the long wave height.

In case the prediction of the long wave heights (and therefore the prediction of the short wave height) could be improved, for example by the inclusion of long wave reflection, the equation that is currently used in the model to calculate the maximum water levels (equation 5.19) should also be revised. It was concluded in Chapter 6 that this equation currently underestimates the maximum water levels, especially at the start of the island. This is probably caused by an underestimation of the contribution of the waves to the maximum water level. Currently, the overestimation of the waves and the underestimation of the maximum water level (partly) cancel each other out.

Equation 5.19 might be improved by applying an optimization algorithm on the results of the XBNH+ runs to determine the contribution of the long and short waves to the maximum water levels. In that case, it might be beneficial to extent the amount of XBNH+ runs, in order to increase the input for such an optimization algorithm. It is expected that this contribution will a.o. depend on the slope of the island. In Chapter 6, it was observed that the underestimation of the maximum water level by Equation 5.19 is larger for upslope profiles.

However, the aim of the JBIW model is to obtain a quick estimate of the maximum water levels using a simple, quick method. Trying to include the reflection of long waves into the model might make it too complicated for this aim. A more practical approach could therefore also be to optimize the equation for the calculation of the maximum water level in the JBIW model, using the long and short wave heights as calculated with the JBIW model. In case such an approach would be applied, it is important to note that in the JBIW model, the short wave height depends on the contribution of the long wave height to the maximum water level.

In this thesis, the JBIW model has been applied to different idealized 1D profiles. Furthermore, it was applied in a 2D case study for the island of Ebeye. However, it would be useful to apply it in more case studies, for islands with different profiles than the island of Ebeye and check the accuracy of the JBIW model for these profiles in 2D. Furthermore, it would be interesting to investigate the amount of cross-sections that are needed to obtain a reasonable estimate of coastal flooding and look into the optimal locations of these cross-sections. The amount of cross-sections that are needed will depend on the variability of the island topography. For coral atolls, that are usually low-lying and have mild terrain slopes, this variability is generally low. For the 2D case-study for the island of Ebeye 11 cross-sections were used, but less might have been sufficient as well. Regarding the optimal location of the cross-sections, it is expected that it is best to choose cross-sections at the lowest locations.

10.2.2. Operationalization of the simple flood model

As was described above, the aim of the JBIW model is to obtain a quick estimate of the maximum water levels under certain conditions for reef-fronted coasts using a simple, quick model. In contrast to more sophisticated models like XBNH+ and SFINCS, the JBIW model has the potential to be implemented in a tool or application that could be used by people without a technical background as well. For many reef-fronted small islands in the Pacific Ocean, such a tool could be useful. Since the financial resources of these islands are generally limited, they often do not have the means to hire technical companies to help them with a coastal flood assessment for their island. Even though the accuracy of the JBIW model is not good enough to give exact values of the maximum water levels and depths, for these islands it could still be a useful tool to identify the vulnerable areas and to give a first estimate of flooding levels under different conditions. It would therefore be interesting to furter investigate the potential of such a tool and the format in which such a tool would be most useful.

11
Introduction

11.1. Research background

Worldwide, there are 57 Small Island Developing States (SIDS), that each consist of multiple (small) islands. These island nations can be found throughout the world, but most of them are located in tropical regions: the wider Caribbean and South Pacific regions (UNFCCC, 2005). Because many of these islands are located in tropical and subtropical zones and on active tectonic plate boundaries, they are particularly exposed to natural hazards such as earthquakes, volcano eruptions, tropical cyclones and flood events. The threat of these multiple natural hazards is expected to increase in the future under the influence of climate change (Kaly et al., 2002) (Storlazzi et al., 2015). The adverse effects of these multiple natural hazards is a serious threat to the security of SIDS and their inhabitants and a challenge for their transition towards a sustainable future. Coastal flooding is an important threat for many of the SIDS, especially for low-lying coral atolls. For some of these SIDS, the effects of climate change may be such that they become uninhabitable within 50 to 100 years (because of frequent flooding of these islands, which also affects their freshwater lences and therefore the freshwater availability) (Storlazzi et al., 2015).

Over the last decades, international attention for the issues that many SIDS face has increased. The 1994 Declaration of Barbados and the Barbados Programme of Action marked the first international cooperation between SIDS to address these issues and heightened international concern with the particularities of SIDS development trajectaries, constraints and opportunities (Campling, 2006). This heightened international concern has led to many studies and projects, funded by developed countries and institutions like the World bank and aimed at analyzing the impacts of climate change and helping the SIDS to adapt to the adverse effects of climate change (e.g. by building flood defenses, drainage systems, harbours, better houses etc.).

Although the heightened international concern and aid certainly help the SIDS, it is important to realize that many of these projects and initiatives are not focused on increasing the capacity of these countries themselves to deal with the issues they are facing. This means that despite the allocation of more resources to studies and projects aimed at assisting SIDS in adaptation to climate change, these countries are still to a large extent dependent on international assistance for their adaptation, which makes them vulnerable. This vulnerability is amplified by the growing number of islands that are expected to be at risk and thus require assistance in their adaptation to climate change, relative to the available resources of developed countries and institutions like the World Bank.

In many studies related to SIDS, the capacity to deal with risks (e.g related to climate change) is referred to as 'adaptive capacity'. (Barnett and Waters, 2016) defines adaptive capacity as 'the capacity of social systems to manage risks so that impacts are avoided or reduced'. According to (Barnett and Waters, 2016), in order to analyze the possible impacts of increased natural hazards for a certain island, it is important to distinguish between the environmental drivers and the adaptive capacity of the island. Differences in adaptive capacity to increasing natural hazards partly explain why there is a variation in the impacts of climate change among different islands (and countries in general) (Sjöstedt and Povitkina, 2017). Many SIDS have a low adaptive capacity to the different natural hazards that they face, which makes them largely dependent on external parties and international organizations for the means to adapt to climate change.

Coastal flooding is an important natural hazard for many SIDS, especially for low-lying coral atolls. The sophisticated, numerical models that are often used to calculate coastal flooding by international consultants (e.g. Deltares) cannot be used by the people in the SIDS themselves. Although the studies that are carried out with these models certainly benefit the SIDS, the fact that the people in these countries cannot use the models themselves keeps them dependent on international aid. In the previous part of this thesis, the development of a simple flood model was described. This flood model can be used to obtain a first, quick estimate of coastal flooding. Especially for low-lying coral atolls, which are often vulnerable to coastal flooding, this model gives more accurate flood levels and areas than other simple, fast methods like the bathtub model. This part of the report focuses on investigating how this simple flood model can be used to increase the adaptive capacity of SIDS in relation to coastal flooding.

11.2. Context: São Tomé and Principe

Investigating the way in which a simple flood model could increase the adaptive capacity of all SIDS is a very broad research goal. Therefore, the scope of this research was narrowed down to one case study. In the start-up phase of this research, the opportunity to join a field trip to São Tomé came up. Therefore, in the context of this part of the thesis, a case study was carried out for the country of São Tomé and Principe. The location of this island country is depicted in Figure 11.1a.

(a) Location São Tomé

(b) Map São Tomé

Figure 11.1: São Tomé (Maps obtained from (contributors, 2019a))

São Tomé and Principe is an independent island country, located in front of Gabon (see Figure 11.1a). The country consists of multiple islands, but only two are inhabited: São Tomé and Principe. São Tomé is the largest island and has a surface area of about a 1000 square kilometer. The country used to be a Portuguese colony, but became independent in 1975. The country is one of the African SIDS and is one of the smallest economies in Africa. According to the World Bank, the country is a lower income, developing small island state with a fragile economy, which is highly vulnerable to exogeneous shocks. The economy of São Tomé and Principe is largely dependent on agriculture, the fishing sector and (eco) tourism. The country has a population of about 200,000 people, of whom the most live on the largest island São Tomé. About one-third of the population lives on less than 1.9 dollar per day and more than two-thirds of the population is poor, using a poverty line of 3.2 dollar per day.

Even though many people in São Tomé and Principe are poor, the country scores quite well on the Human Development index as developed by the UNDP in comparison to other sub-Saharan African countries. The average life expectancy is 66 years, the mortality rate of children uder 5 years old is 51 per 1000 live births, 97% of the population has access to an improved (drinking) water source and 60 % of the population has access to electricity. Furthermore, almost all children attend primary school, although the percentages are much lower for high school and higher education (The World Bank, 2019).

Both in São Tomé and Principe, many people live together in so-called comunidades; these are comparable to villages. These comunidades are located both along the coast and inland, often close to a river or the coastline. These communities are exposed to flooding both from the river (i.e. both the island and coastal communities) and the coast (i.e. only the coastal communities). Deltares carried out several projects in the country in the past. The last project was focussed on the risks related to coastal flooding and coastal erosion in six different coastal communities. The people in São Tomé do not have the means and/or knowledge to use sophisticated models like XBeach or Delft3D (these numerical models are used in the context of coastal studies by Deltares); currently they do not have a model to calculated coastal flooding themselves. Therefore, this country seemed suitable as a case study for this thesis project.

11.3. Problem statement and research questions

The goal of this (part of the) thesis is to investigate if and how the simple flood model as developed in the previous part of this thesis can be used to increase the adaptive capacity to coastal flood-related disasters in São Tomé.

The question that this study aims to answer is therefore: How can the simple flood model, as developed in the hydraulic engineering part of this thesis, be used to increase the adaptive capacity to coastal flood-related disasters of São Tomé? In order to answer this research questions, different sub-questions were formulated:

1. What is adaptive capacity and how can it be defined for a certain system?
2. What are the factors inhibiting the adaptive capacity to coastal flood-related disasters in São Tomé?
3. How can (part of) these inhibiting factors be adressed with a tool based on the simple flood model developed in the previous part of this thesis?
4. What could the design of a tool based on the simple flood model look like in order to address these inhibiting factors?

11.4. Research approach

In order to answer the different sub-questions and eventually the main research question, a design-based research approach was applied. In short, design-based research means that the research process constantly switches between theory and practice. This approach is often applied to complex design problems, in which there is sociological uncertainty about the outcomes of the research and difficulty in defining a single problem (van der Sanden and de Vries, 2016). This research approach is not further elaborated here, but is explained in more detail in Chapter 12.

The outline of the research to answer the research questions is depicted in Figure 11.2. The different steps that are included in the figure and how these contribute to answering the research question will be elaborated below.

1. What is adaptive capacity and how can it be defined for a certain system?

The first sub-question is answered based on a literature review. The outcome of this literature review is a theoretical framework that is used to answer the other subquestions. This theoretical framework consists of two parts. In the first part, the focus is on the role of adaptive capacity in social vulnerability assessments compared to technical risk assessments and the definition of adaptive capacity ('What is adaptive capacity?'). The second part focuses on the development of a practical assessment framework of the concept that can be used as a basis to analyze the adaptive capacity for a certain system ('How can adaptive capacity be defined for a certain system?').

2. What are the factors inhibiting the adaptive capacity to coastal flood-related disasters in São Tomé?

The second sub-question is answered based on information obtained from semi-structured interviews with different actors related to coastal flooding in São Tomé, a questionnaire held among the people living in different coastal communities on the island, and some additional information sources (e.g. literature on São Tomé, own observations). This research step results in a system description of São Tomé based on the theoretical framework as described above. Based on the system description for São Tomé, the barriers to adaptive capacity are identified and discussed.

3. How can (part of) these inhibiting factors be adressed with a tool based on the simple flood model developed in the previous part of this thesis?

The third sub-question is answered based on the system analysis and the description of inhibiting factors to adaptive capacity as described above. In this research step, it is discussed which factors could be adressed

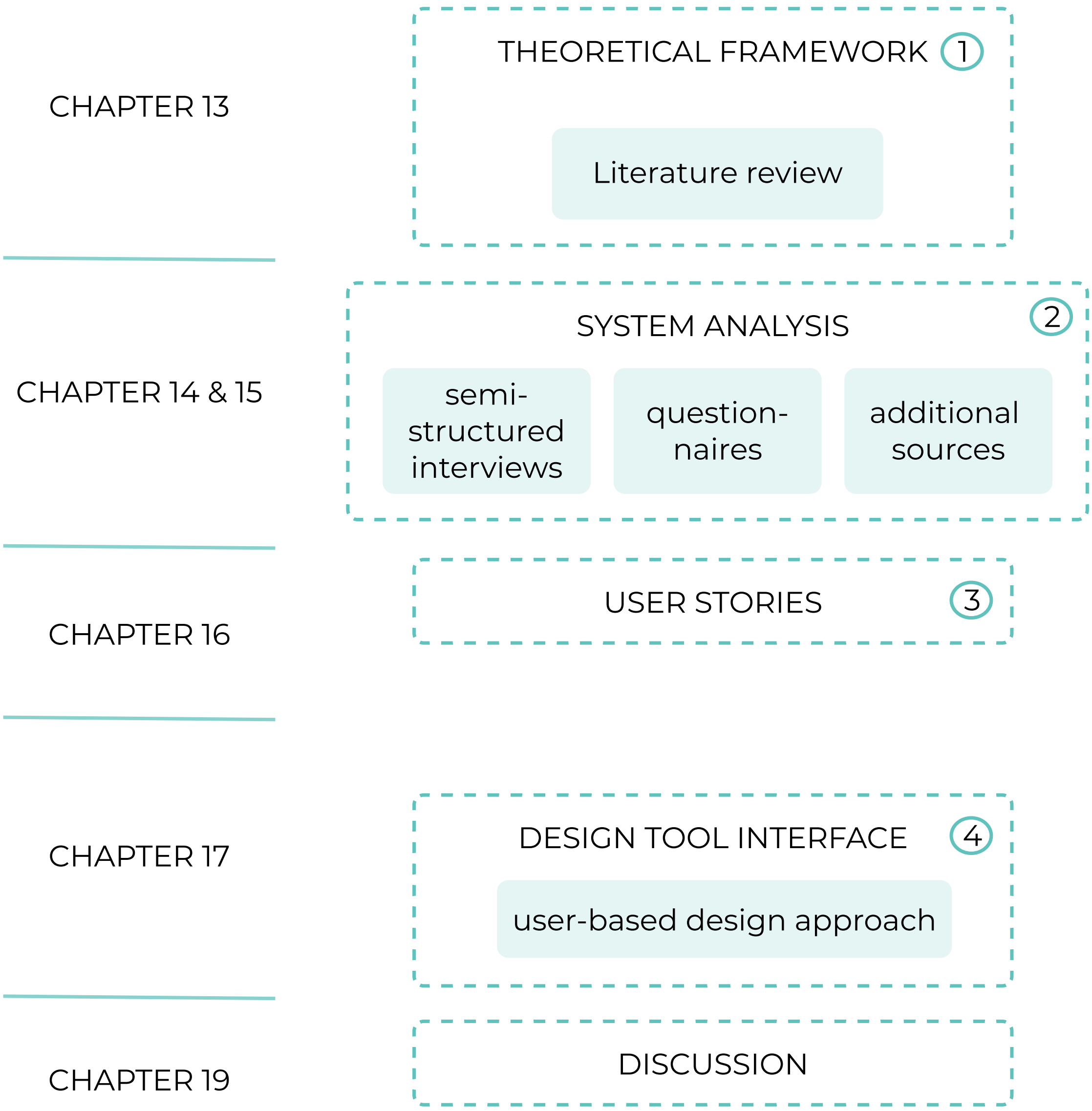


Figure 11.2: Research outline for this part of the thesis. The different deliverables of the research (i.e. the theoretical framework, the system analysis, the user stories, the final design and the discussion) are represented by dotted blocks. The means to obtain these deliverables are indicated with lightblue blocks inside the dotted blocks. Furthermore, the figure indicates which chapters focus on the different deliverables and where the different sub-questions are answered (i.e. see the numbered circles in the figure).

with a tool based on the simple flood model. This results in the development of multiple user stories (related to different actors in the system) that define the requirements of the tool for different actors in order to adress (part of) the inhibiting factors that they face.

4. What could the design of a tool based on the simple flood model developed in the previous part of this thesis look like in order to adress these inhibiting factors?

The fourth sub-question is answered based on the user stories as described above. Based on these user stories, a design for the tool interface is made. This design is an iteration on the initial design for the tool interface that is made during the first phase of the project. This initial design is used in the interviews during the field trip.

11.5. Reading guide

In the next chapter, Chapter 12, a short description of the design-based research approach and its advantages is given. Subsequently, the roadmap for this research is explained, including the different research steps and the switches between theory and practice. The remaining chapters zoom in on different parts of this roadmap.

Chapter 13 describes the theoretical framework that was developed as a basis for this study. The theoretical framework consists of two main parts. In the first part, the meaning of adaptive capacity is derived from a comparison between social vulnerability assessments and technical risk assessments. In the second part, the development of a practical assessment framework for the concept of adaptive capacity is described. The goal of this framework is to provide practical guidance to mapping the adaptive capacity for a certain system.

In Chapter 14, the structure of the semi-structured interviews, the development of the questionnaire and the first design of a tool are explained in more detail. These different elements were all developed during the preparation of the field trip to São Tomé and Principe.

The results of the field trip are summarized in a system description in Chapter 15. In this chapter, a system description of the adaptive capacity of São Tomé in relation to coastal flood events is given, based on the assessment framework described in Chapter 13. This leads to an overview of barriers to the adaptive capacity for the island of São Tomé.

As was already indicated in Section 11.4, not all barriers to the adaptive capacity in São Tomé can be adressed by a tool based on the simple flood model. The discussion on which inhibiting factors to adaptive capacity can be adressed with a tool based on the simple flood model and the different user stories are described in Chapter 16.

The final design and a reflection on the tool in the context of São Tomé are described in Chapter 17. This chapter consists of two main parts. In the first part, the final design of the tool interface, based on the user stories described in Chapter 16, is described. In the second part, a discussion is given on the potential impact of the tool in the context of São Tomé and the additional measures that could amplify this potential impact.

In Chapter 18, the answers to the different sub questions and the main research question are summarized in the conclusion. The results of this part of the thesis are subsequently discussed in Chapter 19. In this chapter, the contribution of this research to the theory on adaptive capacity is discussed. Furthermore, different limitations and opportunities for further research are given.

12

Approach

In this chapter, the general approach taken in this thesis is described. As was already described in Chapter 11, the general approach taken in this part of the thesis is the design-based research (DBR) approach.

In section 12.1, the origin and aim of DBR in general are described. Subsequently, in Section 12.2, the general outline of this research is introduced in the form of a roadmap. The different steps that were taken are explained in more detail. The remaining chapters of this report will focus on different parts of the roadmap as introduced in this chapter.

12.1. Design-based research

The design-based research (DBR) approach has its origins in educational research. This research paradigm is based on the general consensus among educational researchers, policy makers and practitioners that educational research was often detached from the problems and issues of everyday practice and that there was a need for new research approaches that speaks directly to problems encountered in practice (The Design-Based Research Collective, 2002). DBR aims to bridge the gap between theory and practice, using theory to design necessary interventions, develop these further in collaboration with participants from practice and use the insights obtained from practice to further enhance the existing theory. This approach is based on the belief that in many studies the practical context is as important as the theory and that studying the combination of the two will result in more effective tools or interventions and will add to the development of more 'usable (theoretical) knowledge'.

The advantages of this approach are two-fold. One advantage of this research approach is that it includes interacting with the target group. Without target group interaction, a large risk is that the developed tool or intervention is too much based on theory and does not fulfill its intentions in a real-world context. Secondly, design-based research goes beyond merely designing and testing particular interventions for a certain practical context, which is the main goal in more traditional design methods. It also aims to add to the theory by using insights obtained in practice. For a more detailed description of the DBR approach, the reader is referred to (The Design-Based Research Collective, 2002) and (Wang and Hannafin, 2005).

The DBR approach is characterized by multiple iterations while constantly switching back and forth between theory and practice. Apart from educational studies, the research field from which this approach originates, DBR has been applied to many other research fields and is applied in this thesis as well. In the next section the DBR approach taken in this thesis will be described.

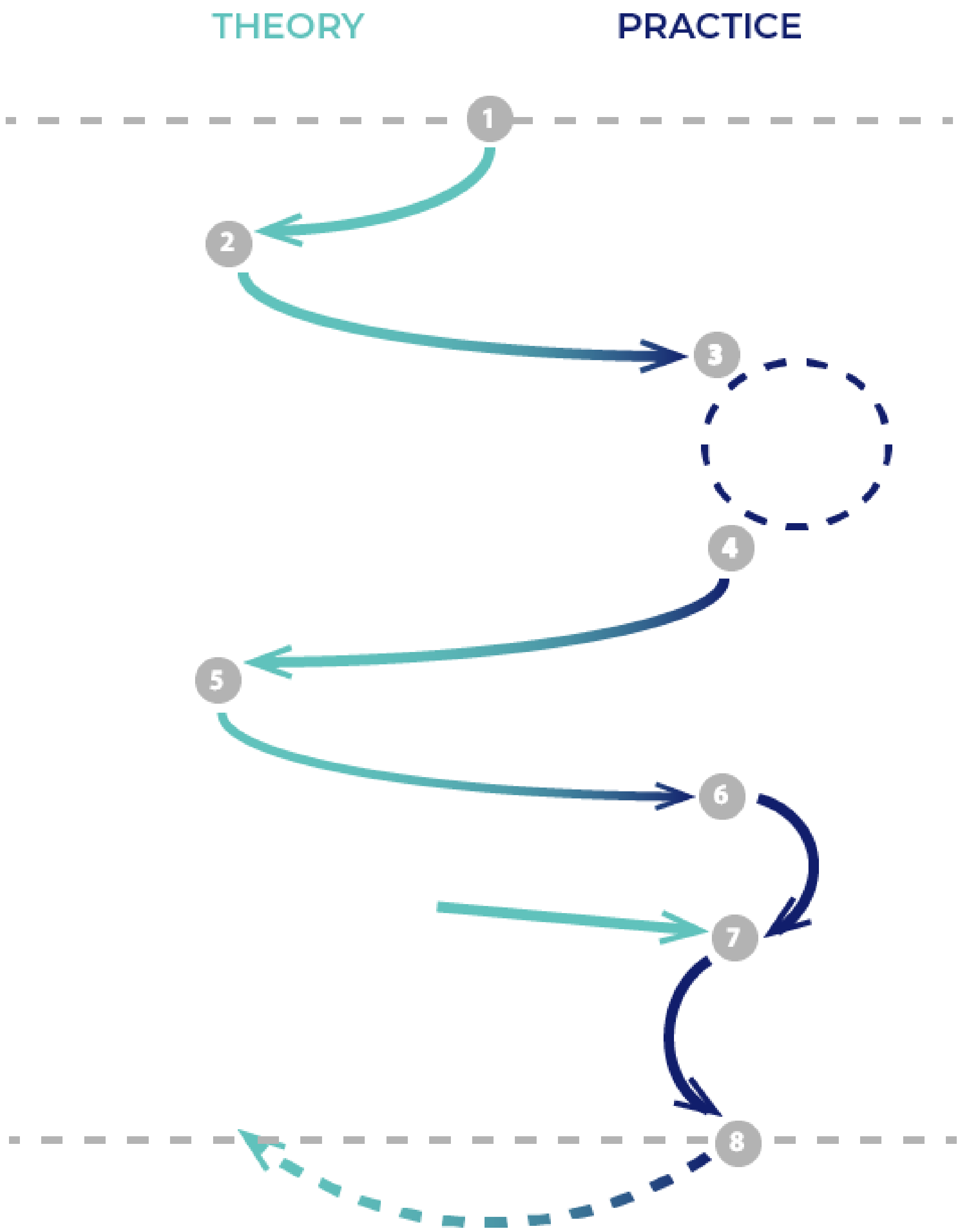


Figure 12.1: The different research steps outlined in a roadmap. The arrows represent the different steps taken in the research; the numbered dots represent different research stages. As can be seen in the figure, different switches between theory and practice were made during the research; this is depicted by the different colors.

12.2. Roadmap

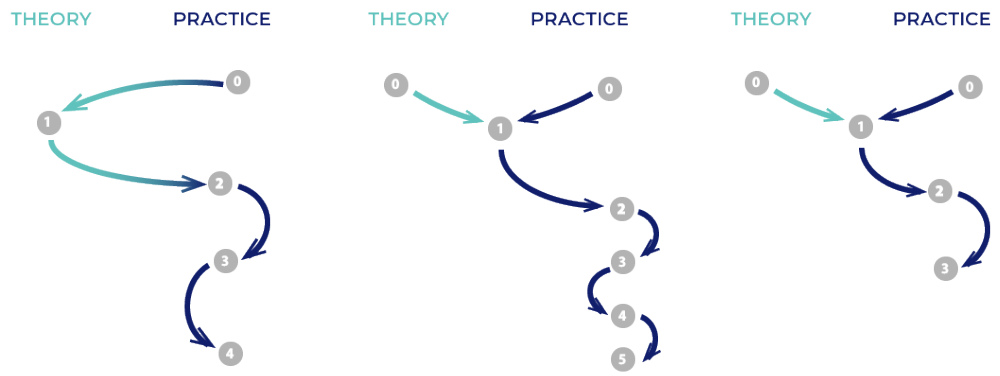
The general approach taken in this part of the thesis is outlined in a roadmap in Figure 12.1. The different arrows represent the different steps taken in the research. These arrows connect different stages of the research, which are depicted as (numbered) dots in the roadmap. As can be seen from Figure 12.1, during the research several switches between theory and practice were made. Below, the main steps taken in the research will be described in a bit more detail. The methods used during the different steps in the research are mentioned in this chapter, but are not yet described in detail. In the remainder of this report, reference will be made to this roadmap, as the different chapters will focus on different parts of the process. In each chapter, the methods that were employed are described in more detail.

The first dot represents the kick-off meeting for this part of the thesis. During this meeting, the aim and first research set-up were discussed. The aim of the study was to investigate whether the simple flood model as described in the first part of this thesis could be used by local people at the SIDS in order to increase the adaptive capacity of these countries.

After the kick-off meeting, an initial exploratory literature research was carried out (i.e. the 1st arrow in Figure 12.1). Important questions during this research step were 'What is adaptive capacity?', 'Where does it come into play?' and 'How can it be assessed for a certain situation?'. This led to an initial theoretical framework (i.e. the 2nd dot in Figure 12.1). While doing the exploratory literature research, there was an opportunity to join a field trip to São Tomé and Principe. A team from Deltares was going there for a flood-related project and I had the opportunity to come along. Therefore, São Tomé and Principe became the case study of this research. This slightly changed to aim of the research: instead of investigating the possibility to increase the adaptive capacity of SIDS in general, the study focused on the situation of São Tomé specifically.

Subsequently, the context of São Tomé and Principe was analyzed using reports and interviews with Deltares employees who had visited the island 6 months before (i.e. the 2nd arrow in Figure 12.1). Based on this analysis and advice from people who have project experience in other developing countries, the choice was made to develop an initial design for a tool interface (based on the simple flood model) and to use this in the interviews during the field trip (i.e. the 3rd dot in Figure 12.1).

Following this choice, the preparation for the field trip started. The preparation for the field trip entailed three different elements that were developed in parallel to each other. These three elements were a questionnaire, the interview protocol(s) and an initial design for the tool interface. This is represented by the dotted circle in Figure 12.1. The sub-roadmaps for each of this elements are depicted in Figure 12.2a, 12.2b and 12.2c below. These sub-roadmaps are further explained in Chapter 14.



(a) Initial tool design (b) Interview protocol (c) Questionnaire

Figure 12.2: Different elements in the preparation of the field trip

After the field trip, a lot of insights on the local context of São Tomé and Principe had been gained (i.e. the 4th dot in Figure 12.1). Using these practical insights to evaluate the assessment frameworks for adaptive capacity found during the first exploratory literature research, led to the conclusion that these existing assessment frameworks could not be used to map the barriers to adaptive capacity for the island of São Tomé and Principe. Following this conclusion, an additional exploratory literature research was carried out (represented by the 3rd arrow in Figure 12.1) to develop a new theoretical assessment framework with the specific aim to provide practical guidance in determining the barriers to adaptive capacity for a certain system (represented by the 5th dot in Figure 12.1). This theoretical assessment framework is described in Chapter 13. In this chapter, both the findings from the first exploratory literature search and the description of the new theoretical assessment framework based on the insights from the field trip are described.

Subsequently, this theoretical assessment framework was applied in combination with the results obtained during the field trip to map the system in São Tomé, in relation to coastal flood events (i.e. the 4th arrow in Figure 12.1). An overview of the barriers to the adaptive capacity of São Tomé, in relation to coastal flood events, was obtained (i.e. the 6th dot in Figure 12.1). This system description and overview of factors inhibiting the adaptive capacity of São Tomé can be found in Chapter 15.

Not all the barriers to adaptive capacity as described in the system description can be addressed by the development of a tool (based on the simple flood model). In the next research step, it is analysed which barriers could be addressed with such a tool. Also, a short literature search on user experience and the development of user stories was conducted (i.e the 5th and 6th arrow in Figure 12.1). Based on the results obtained during the field trip and the insights obtained from user experience literature, different user stories are developed (i.e. the 7th dot in Figure 12.1). These user stories summarize who the potential users of the tool could be, what they want to get out of the tool and how this would benefit them. The user stories are described in Chapter 16.

During the next research step, the user stories are used to come up with a final design for the tool interface (i.e. the 7th arrow in Figure 12.1). This final design is described in Chapter 17 (i.e. the 8th dot in Figure 12.1). Also, a reflection on what such a tool could change in São Tomé is given, and a discussion on which other measures could enhance the effect of the tool. These considerations are also given in Chapter 17.

Lastly, an attempt is made to generalize the results of this study (i.e. the 8th arrow in Figure 12.1). The way in which this research has contributed to the theory on adaptive capacity is discussed. As this generalization is not part of the research, it is described in the discussion in Chapter 19 and depicted with a dotted arrow in the roadmap. In Chapter 18, the conclusions of this research are described.

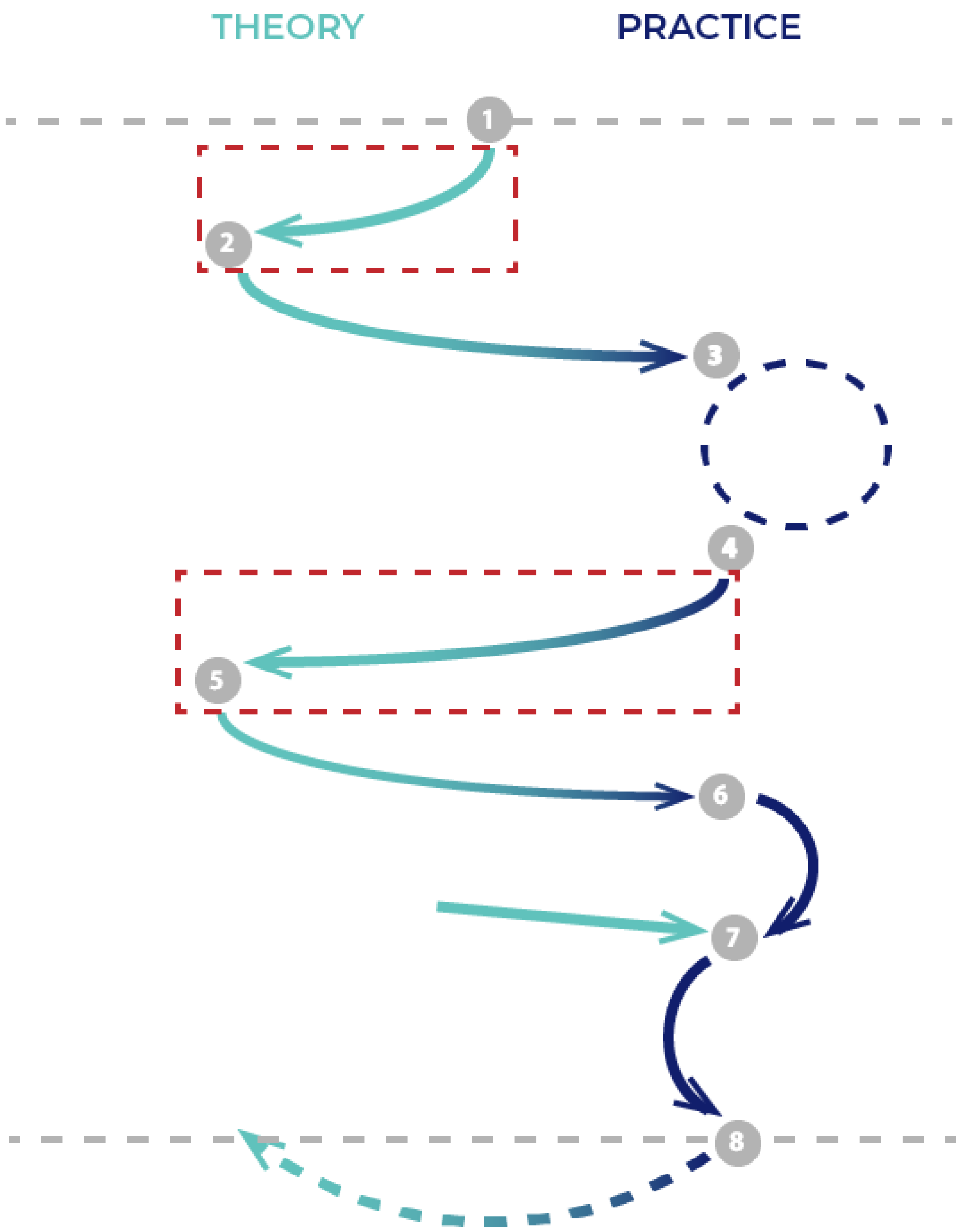


Figure 12.3: Theoretical framework in the roadmap

13

Theoretical framework

In this chapter, the development of the theoretical framework that is used in the remainder of this study is described. The methods that were used to conduct the literature research is described in Section 13.1. As can be seen in Figure 12.3, this theoretical framework was developed in two stages: one before the field trip to São Tomé and one after. Before the field trip, the literature study was focused on defining the term 'adaptive capacity' and studying different theoretical assessment frameworks for adaptive capacity, as found in literature. This is described in Section 13.2 and the first part of Section 13.3.

In Section 13.2, the concept of adaptive capacity is explored. A comparison is made between technical risk assessments and social vulnerability assessments. The differences and similarities between these two approaches are discussed. As we will see in this section, the main difference is the incooperation of adaptive capacity in social vulnerability assessments as compared to technical risk assessments. From this comparison, a definition for adaptive capacity was found.

Apart from a definition of adaptive capacity, we need a way to assess the adaptive capacity for a certain system and obtain an overview of the barriers to adaptive capacity experienced in the system. In Section 13.3, different theoretical assessment frameworks for adaptive capacity as found in literature are discussed.

During the field trip, many observations and insights were obtained. Using these practical insights to evaluate the assessment frameworks for adaptive capacity found during the literature research before the field trip, led to the conclusion that these existing frameworks could not be used to map the barriers to adaptive capacity for the island of São Tomé. The main problem with the existing frameworks is that they do not offer practical ways to map the adaptive capacity for a certain system; these frameworks are all very abstract. This is explained in Section 13.3. This conclusion led to a second literature research in order to develop a new theoretical assessment framework with the specific aim to provide practical guidance in determining the barriers to adaptive capacity for a certain system. This new theoretical framework is based on an existing system-based assessment framework, which is adjusted based on the insights obtained during the field trip. The existing assessment framework that forms the basis of the new theoretical framework and the adjustment that were made are described in Section 13.3.3. Lastly, a summary of the chapter is given in Section 13.4.

13.1. Literature review: methods

In order to develop the theoretical framework as described in this chapter, an exploratory literature review was conducted. In the first stage of the literature research, before the field trip to São Tomé, the focus was on finding a definition for the term 'adaptive capacity'.

As adaptive capacity is a term that is used in many different research fields, the search was confined to literature on adaptive capacity to climate change in SIDS specifically. Different search terms in different search engines were used. In order to determine whether the articles that came up were useful, first the title was examined. For the articles that seemed useful, the abstract and in some cases the conclusions were read. Based on this, the article was discarded or not. The main distinction that was applied here was the difference between theoretical and applied studies. Many studies on adaptive capacity to climate change in SIDS are applied studies that focus on building adaptive capacity in the context of a certain system (e.g. a village, island or country). Much fewer articles were found on the theoretical background of adaptive capacity. Especially in the starting phase of the literature search, these theoretical studies were used. For every useful article, the reference list was used to look for other relevant literature; in this way more useful articles were found.

The same approach was applied to find literature on assessment frameworks for adaptive capacity to climate change in SIDS. Again, the titles, abstracts and conclusions of the different studies were used to examine whether a certain study was useful or not. Regarding the assessment frameworks for adaptive capacity, both theoretical and more applied studies were found useful. As many theoretical studies were very abstract and generally did not offer much practical guidance in determining the adaptive capacity for a certain system, different applied studies were found useful as they gave insight into how adaptive capacity was determined in the context of the case study described in that study. Again, the so-called snow-balling approach was used by looking for useful articles in the reference list of the found articles.

After the field trip to São Tomé, an additional literature search was conducted, since insights from the field trip led to the conclusion that the different assessment frameworks for adaptive capacity as found in literature before the field trip could not be used to map the adaptive capacity in the context of São Tomé. This literature search was confined to assessment frameworks for adaptive capacity to climate change in SIDS that took a system approach. Eventually, this additional literature search led to one study that served as a basis for the development of the theoretical framework used in the remainder of this study.

13.2. Defining adaptive capacity

In order to understand the term 'adaptive capacity', we first have to understand coastal flood risk assessments from a technical perspective. Therefore, a general explanation of technical risk assessments and the main criticism to this approach are described in Section 13.2.1. In Section 13.2.2, the general approach taken in social vulnerability assessments is explained and compared to technical risk assessments. The similarities and differences between the two assessment methods are discussed. We will see that the main difference between these two assessment approaches is the introduction of adaptive capacity in social vulnerability assessments in comparison with technical risk assessments. Adaptive capacity represents a feedback loop in the social vulnerability assessments; this feedback loop will be elaborated in Section 13.2.3. Lastly, adaptive capacity is linked to a certain system. However, the system for which the adaptive capacity should be examined, can be defined at different scales (e.g. a household, a village or an entire country) which are not independent of each other. The implications of these interdependent system scales on the definition of adaptive capacity are discussed in Section 13.2.4.

13.2.1. Technical risk assessments

The method that is used in technical assessments is illustrated in Figure 13.1 below. The final goal in these assessments is to calculate the risk (often expressed in monetary terms, e.g. dollars) for a certain location related to a certain natural hazard (in this case to coastal flooding) or combination of natural hazards. In order to do this, 3 main elements are needed in the calculation: hazard, exposure and vulnerability. These elements will be explained below.

The first part is the hazard part. This is related to the consequences of the natural hazard with a certain return period. For example, in a coastal flood risk assessment the first step is to calculate the water depths due to a coastal flood event with a certain return period, for example a return period of 100 years.

These water depths are subsequently compared with exposure maps for the specific area. These exposure maps indicate the location of for example buildings, infrastructure and agricultural areas. In essence, these exposure maps contain objects and/or areas that can be damaged by the consequences of a certain natural hazard. After this step, we know for example that building A is exposed to water depths of 2 m during a coastal flood event with a 100 year return period.

The last step is then to calculate the damage in monetary terms. This is where the vulnerability comes in. For coastal flood risk assessments, this can be done using a so-called depth-damage curve. This curve links the water depth to damage expressed in monetary terms. Different depth-damage curves can be used, depending on for example the building type (e.g. concrete or wooden house) or crop type of the field (e.g. potatoes or tomatoes). After this step, we know that the 2 m water depth at building A during a coastal flood event with a 100 year return period, leads to a damage of for example 2 million dollar.

This calculation can be repeated for the same natural hazard, but with different return periods. A coastal

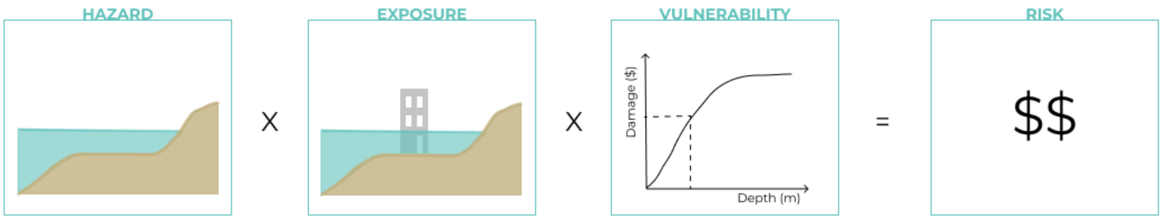


Figure 13.1: Approach to technical risk assessments

flood event with a return period of 1 year will lead to less damage than a coastal flood event with a 100 year return period. The damages linked to different return periods can be summarized in a graph, as illustrated in Figure 13.2. The total coastal flood risk for a certain place equals the integrated area under this graph.

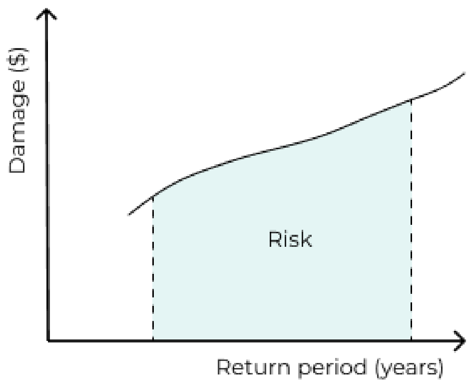


Figure 13.2: Calculation of risk

The approach described above is the general approach taken in technical assessments of risk in different fields (e.g. for assessments of coastal flood risk or risk to earthquakes). This approach to risk has also been applied to quantify the risk to different natural hazards in many SIDS. Different authors have criticised this approach as being to narrow, because the focus is mainly on environmental and economic vulnerability, while other aspects of vulnerability are not taken into account (e.g. social or institutional vulnerability) (Barnett and Waters, 2016) (Mossler, 1996) (Campling, 2006). Even though many SIDS are indeed vulnerable to economic and environmental factors, this is not the complete story. Different authors claim that not enough attention is given to the social and institutional challenges that these systems face, which are important to grab the total picture of the development challenges for these islands (Barnett and Waters, 2016) (Mossler, 1996) (Campling, 2006).

13.2.2. Expanding perspectives: including adaptive capacity

Based on this criticism, different studies have sought to expand the definition of risk by incorporating not only the economic and environmental, but also for example social and institutional perspectives. Different conceptual models of risk have emerged in the climate change scholarship. Consistent throughout this literature is the notion that vulnerability (an often-used synonym for risk in climate change literature) of any system, at any scale, is dependent on the exposure and sensitivity of that system to the hazardous condition under consideration and the ability or capacity of the system to cope, adapt or recover from the effects of that conditon (Barnett and Waters, 2016). This notion of risk is the basis of social vulnerability assessments and is visually depicted in a Venn diagram in Figure 13.3 and described in Formula 13.1 (Adger, 2003).

In this subsection, the general approach to social vulnerability assessments will be described in more detail and linked to the technical risk assessment as described in section 13.2.1. Here we will focus on the different components of vulnerability as defined in the Venn diagram: exposure, sensitivity and adaptive capacity (see

Figure 13.3). The distinction between local scale and broad scale determinants that is indicated in Figure 13.3 will be discussed in Section 13.2.4.

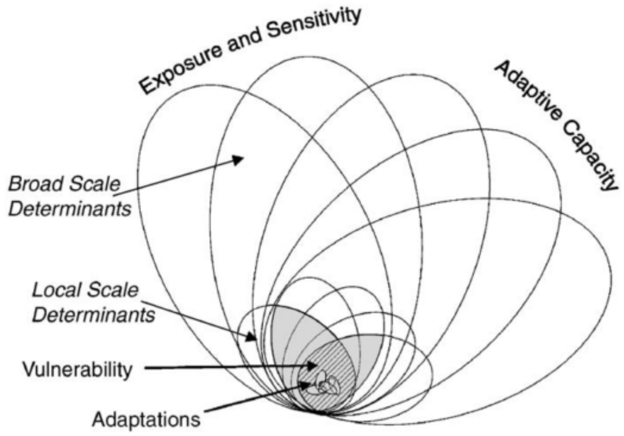


Figure 13.3: Nested hierarchy model of vulnerability (source: (Barnett and Waters, 2016))

$$\text{vulnerability} = f(\text{exposure, sensitivity, adaptive capacity}) \tag{13.1}$$

The first part, the exposure and sensitivity of the system to a certain hazardous condition (at the left part in Figure 13.3), reflects the biophysical component of the system and is a measure for the natural hazard. It can be related to the technical risk assessment as described in Section 13.2.1. However, the concepts used in technical and social assessments differ from each other. This is depicted in Figure 13.4.

In a technical assessment, the end goal is to determine the risk. In many social studies, the term 'vulnerability' is used instead of risk. Different studies have assessed in what aspects these concepts are similar and/or different from each other. Risk, as the outcome of technical assessments, is defined as 'the quantification of potential consequences of a hazardous event on a certain area and receptors (i.e. elements potentially at risk)' (Gallina et al., 2016). This is related to an impact assessment for a certain system; the starting point in these assessments is the stimulus (e.g. a storm leading to coastal flooding). The term 'vulnerability', as used in many social studies, is a property of the system relative to a specified stimulus. This is related to vulnerability assessments, where the system is the starting point. It can be concluded that the concepts of 'risk' and 'vulnerability' are similar in the sense that both concepts assess the consequences of hazardous situations, however they express these consequences in a different way. Technical risk assessments aim to express these consequences quantitatively, while social vulnerality assessments describe them qualitatively. Also, these concepts differ from each other because their respective perspectives and starting points are different (Smit and Pilifosova, 2003).

The concepts of hazard and exposure in technical risk assessments and the concept of exposure in social vulnerability assessments (see the Venn diagram in Figure 13.3) are related. In the different studies that describe vulnerability models, many different definitions for the terms 'exposure' and 'sensitivity' can be found. In this research, the definitions as given in (Smith and Klein, 2019) are used. Exposure is here defined as 'the change in climate and what is affected, e.g., how many people are living in an area that could be inundated by sea level rise or affected by change in coastal storms'. Exposure, as defined in technical risk assessments, is defined as 'the presence of people, livelihoods, environmental services and resources, infrastructure, or economic, social or cultural assets in places that could be adversely affected' (Gallina et al., 2016). Hazard is defined as 'the physical phenomenon related to climate change (e.g. sea level rise, storm surge) that has the potential to cause damage and loss to property, infrastructure, livelihoods, service provision and environmental resources (Gallina et al., 2016). From these definitions, it can be concluded that 'exposure' as defined in the Venn diagram in Figure 13.3, corresponds to a combination of the 'hazard' and 'exposure' concepts in technical risk assessments.

The term sensitivity is related to the concept of vulnerability in the technical assessment. In (Smith and Klein, 2019), sensitivity is defined as 'the direct effect of climate change on systems'. The determination of

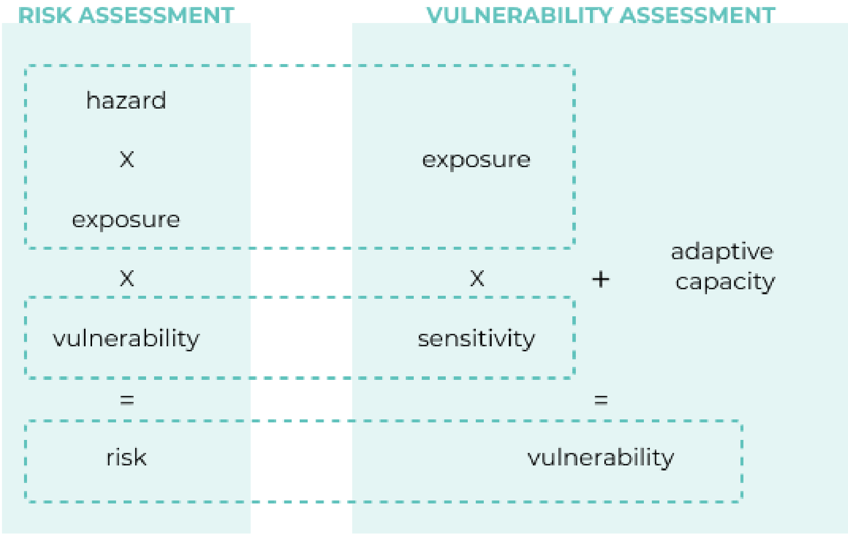


Figure 13.4: Linking risk and vulnerability assessment

these effects is preferably based on different perspectives of the system: economical and environmental, but also social, institutional, cultural etc. By contrast, the concept of vulnerability as used in technical risk assessments is defined as 'the propensity or predisposition of a community, system, or asset to be adversely affected by a certain hazard' (Gallina et al., 2016). In theory, this could encompass economic, environmental, social, institutional, political and social factors. However, in practice, often only economic factors, and sometimes environmental factors, are taken into account. From these definitions, it can be concluded that both concepts assess the occupance and characteristics of a certain system to a hazardous condition that determine the consequences. A difference between the concepts is in the emphasis on the type of consequences. In technical assessments, the emphasis is on negative consequences; it determines the adverse effects on a system. In social assessments, the type of consequences is less specified a priori. In the IPCC definition of sensitivity it is even explicitly stated that these consequences can also be beneficial: 'the degree to which a system will respond to a given change in climate, including beneficial and harmful effects' (McCarthy et al., 2001).

The second part of the notion of vulnerability, as used in social vulnerability assessments, is related to the social dimensions of the defined system. This part does not have a counterpart in technical risk assessments. In technical risk assessments, the process of calculating the final risk is quite linear, starting from the stimulus (e.g. an earhquake) and ending at the adverse effects on the system (often expressed in monetary terms). The starting point of these assessments is the natural hazard (Adger and Kelly, 1999). An important aspect of social vulnerability assessments is the recognition that there are feedback loops present in the system; the system is likely to respond in one way or the other to a stimulus and through this response the effects on the system are altered. The starting point of these assessments is not the natural hazard, but the system itself. Different authors claim that it is meaningless to study the consequences of natural hazards and climate change on the long term without considering these feedback loops and the resulting range of adaptive responses that will substantially alter any initial impacts (Adger and Kelly, 1999) (Smit and Pilifosova, 2001). In many studies, this is called the 'adaptive capacity' of the system. In (Smith and Klein, 2019), the term 'adaptive capacity' in relation to climate change is described as 'the ability of a system to adapt to climate change, reduce adverse effects or take advantage of beneficial effects'. This adaptive capacity is mostly related to long-term vulnerability assessments, because at this timescale the effects of adaptive capacity are expected to be more significant (compared to the short term). Long term is here related to a timescale of one year or several years (in which several hazard events occur) and the short term to the timescale of a few hours/days (in which one hazard event occurs).

13.2.3. Adaptive capacity: a feedback loop

As described in the previous section, adaptive capacity in social vulnerability assessments can be regarded as a feedback loop in the system. This will be elaborated in this section. It will be shown that adaptive capacity can lead to adaptation(s), which will influence the exposure and sensitivity of the system, thus eventually influencing the vulnerability of the system. First the link between adaptive capacity and different types of adaptation will be described. Subsequently, the link between adaptation(s) and a system's vulnerability will be shortly explained.

Adaptive capacity and adaptation

Adaptive capacity is not the same as adaptation. The role of adaptive capacity, as seen by the International Panel of Climate Change (IPCC), is visualized in Figure 13.5. In this model, it is assumed that in response to the effects of a certain stimulus on a system, the system will respond in accordance with its adaptive capacity (i.e. a system with a low adaptive capacity will have a weak response. A system with a large adaptive capacity, in contrast will have a stronger response). Take for example a community living in a village near the coastline. Due to a storm and associated coastal flooding part of the village is flooded, leading to damaged houses and loss of property. A possible response of the people living in this village might be that they decide to build their houses on poles. During the next coastal flood event, this will lead to lower adverse impacts. The vulnerability of the system is decreased. This is an example of the adaptive capacity of the community leading to an 'autonomous adaptation' of the system. It is called an autonomous adaptation because it is an adaptation initiated by the system itself; it is the outcome of the impacts on the system (the damages due to coastal flooding) and the adaptive capacity of that system (McCarthy et al., 2001)).

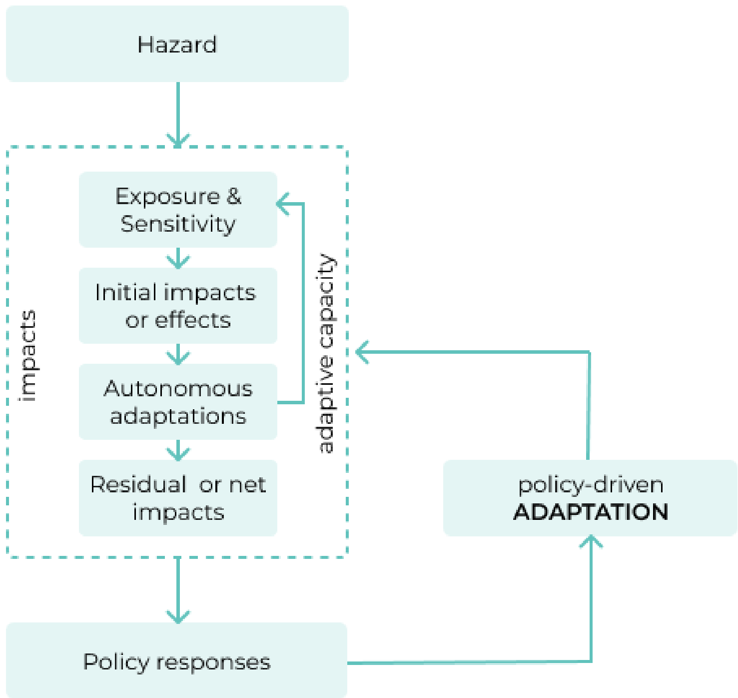


Figure 13.5: Adaptive capacity as part of the vulnerability assessment, IPCC model (adjusted from: (McCarthy et al., 2001))

The other type of adaptation that is often mentioned in literature is policy-driven adaptation. Here, the adaptation is initiated from outside the system; often based on policy. This adaptation is not a direct outcome of the adaptive capacity of the system. Rather it depends on the adaptive capacity on the level at which the policies are created. If, in the context of the example, the government would enforce a policy which states that no houses can be build in vulnerable areas along the coast, this would be policy-driven adaptation. These policies and policy-based adaptations are often a response to the net impacts of a certain natural hazard on a system (McCarthy et al., 2001)). If the consequences of a certain natural hazard are already sufficiently adressed by the autonomous adaptations by a system itself (related to the adaptive capacity of that system), there is no need for further policies and policy-based adaptations. As can be derived from these definitions, the dividing line between autonomous and policy-driven adaptation is highly dependent on the definition of the system. This will be discussed in more detail in Section 13.2.4.

Adaptations and a system's vulnerability

Adaptations can be directed at influencing the exposure and/or the sensitivity of a system (or a combination), as defined in social vulnerability assessments (Engle, 2011). This is depicted in Figure 13.6. In the example mentioned above, the adaptation is directed at decreasing the sensitivity of the system; the system still floods, but the consequences are decreased because the houses are built on poles and therefore less sensitive to damage from flooding. The people living in the community can also decide to build a dyke along the coastline to protect their houses. This adaptation is directed at decreasing the exposure in social vulnerability assessments (and to the hazard in technical risk assessments); due to the dyke, less area will be flooded.

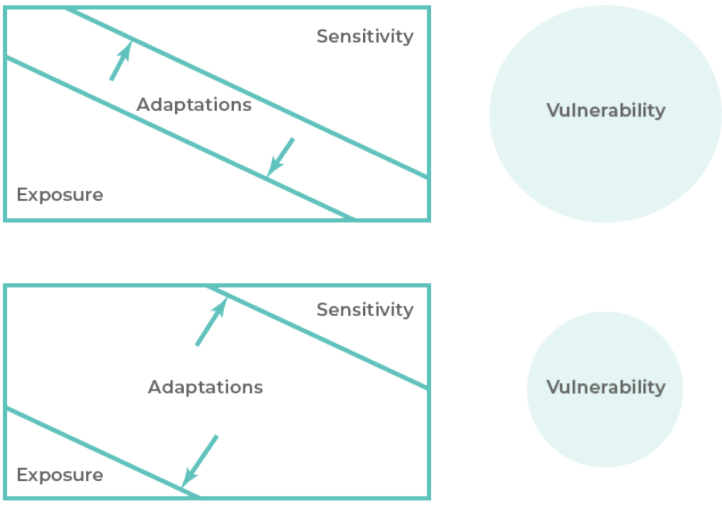


Figure 13.6: Influence of adaptations on exposure and/or sensitivity and eventuel effect on the vulnerability of the system (figure adjusted from (Engle, 2011))

In the context of the example, the response of the village will lead to lower damages during the next coastal flood event. The vulnerability of the system to coastal flood events is thus reduced. This notion is also emphasized by the IPCC, which states that neglecting the adaptive capacity of a system will likely lead to overestimations of the costs of climatic impacts (McCarthy et al., 2001). However, recent studies also note that a high adaptive capacity does not necessarily lead to reduced costs, because it can also lead to maladaptions, particularly when information to the system is flawed (Sem, 2007). For example, the people in the coastal communities might decide to move their houses to the areas that remained dry during the last flood events. However, during a stronger storm event, these areas might get flooded as well. In that case, the adaptive capacity of the community led to a maladaptation, caused by a lack of information (i.e. information on which areas are susceptible to flooding). In both cases, the inclusion of adaptive capacity in the analysis is expected to lead to a more realistic assessment of the vulnerability of a system. Another advantage of inclusion of adaptive capacity is put forward in (Adger and Kelly, 1999). In this study it is stated that an analysis of the different processes in 'a social system promoting or inhibiting adaptive responses (i.e. drivers and barriers to adaptive capacity) will lead to a focus on the structural causes of risk, rather than on the impact alone.

Despite these advantages of including the adaptive capacity of the system, to date there are not many studies that actually include it. There is still a clear division between quantitative technical risk assessments and more qualitative vulnerability assessments. The reason for this is mainly practical; although considerable literature on the determinants of adaptive capacity (see Section 13.3) is available, to date there is little agreement on a general theoretical framework for these determinants. Also, as we will see in Section 13.3, there is no consensus on criteria or variables by which adaptive capacity can be measured and by which the adaptive capacity of different regions can be quantitatively compared or combined with quantitative technical risk assessments (Smit and Pilifosova, 2001). There are different studies that tried to develop a composite proxy for adaptive capacity, but there is no agreement on a general accepted method to obtain such a proxy yet (Brooks et al., 2005) (Yohe and Tol, 2002).

13.2.4. Definition of the system and its boundaries

In the description and discussion of social vulnerability assessments above, the system for which these assessments are carried out is not further specified. Such assessments can be carried out for different systems that can be characterized by different scales, ranging from the individual to the global level. It is important to properly define the system boundaries of the assessment (e.g. a household, village or an entire country) so that the exposure, sensitivity and adaptive capacity can be assessed for the specified system. This was also indicated in the Venn diagram in Figure 13.3.

However, it is important to recognize that the different scales at which a system can be defined are not independent of each other. For example, the capacity of a household to cope with climate risks depends to some degree on the enabling environment of the community, and the adaptive capacity of the community is reflective of the resources and processes of the region (Smit and Pilifosova, 2003) (Yohe and Tol, 2002). This means that, although we can assess the exposure and sensitivity of a system within the specified boundaries, we cannot assess the system's ability to adapt without the role of obstacles or driving forces to adaptation that might by determined by processes operating outside of the specified system (Brooks, 2003). This is linked to Figure 13.3, where a distinction between broad scale and local scale determinants of adaptive capacity is made. The local scale determinants in this figure relate to the defined system. The broad scale determinants relate to the obstacles and/or driving forces to adaptation outside of the specified system (Smit and Wandel, 2006).

This recognition has led to different definitions of the term 'adaptive capacity'. In the first definition, the adaptive capacity of a certain system is defined based on the endogeneous factors of that system only. This is called the 'inherent' adaptive capacity of the system. (Brooks, 2003) argues that this definition might be too narrow and can lead to an emphasis on processes operating at the system and sub-system scale and a neglect of larger-scale processes. When applied in a capacity building context, this definition may lead to the false conviction that the vulnerability of a certain system can be decreased by adressing the characteristics and behaviour within that system only. The second definition of adaptive capacity entails both endogeneous and exogeneous factors of adaptive capacity. This definition thus encompasses all the processes that determine whether or not adaptation takes place, including those associated with different scales and systems, representing not only the characteristics of the system of interest, but also the context in which this system is embedded. Although this definition will lead to a better understanding of the true adaptive capacity of the system of interest, it is also more difficult to put into practice since it is much broader and requires not only an understanding of the system of interest, but also of the wider context influencing this system.

Not only the system (level), but also the hazard (or combination of hazards) to which the system is exposed should be specified. The exposure, sensitivity and adaptive capacity of a certain system will differ for different natural hazards. For example, houses that are build on poles may be less sensitive to damages due to coastal flooding, but more sensitive to damages caused by strong winds (Smit and Wandel, 2006).

In summary, in order to carry out a vulnerability assessment for a certain system, we must always ask the question "vulnerability of who (i.e. the system definition) to what (i.e. definition of the hazard)?" Furthermore, with regard to the assessment of the adaptive capacity of the system, it is important to realize that this is determined by processes at a range of scales, and some of these will be different from the scale at which the system of interest is defined (Brooks, 2003).

13.3. Assessing adaptive capacity

In the sections above, the concept of adaptive capacity was introduced. However, until now, the concept has been adressed in very broad and abstract terms. The definition of adaptive capacity as given above, 'the ability or capacity of the system to cope, adapt or recover from the effects of a specified hazard', is not a very practical one in terms of determining the adaptive capacity for a certain system. In order to assess the adaptive capacity for a certain system, the concept needs to be defined in a more practical way. This requires a more in-depth research on the different factors or determinants that make up adaptive capacity. Such analyses have been the topic of many studies that tried to establish an assessment method for adaptive capacity (Yohe and Tol, 2002) (Jones et al., 2010) (Brooks et al., 2005). Since the concept of adaptive capacity is quite abstract and its translation to practice very context- and scale dependent, it has proven difficult to come up with a general framework or overview of its determinants. Until now, there is no concensus in literature on this matter.

Therefore, in Section 13.3.1 first an overview of different studies into the determinants of adaptive capacity is given. We will see that the approaches to the assessment of adaptive capacity, as found in literature, can be subdivided into different categories. These different categories are introduced and further elaborated. For each catogory, a short description of the approach, a few examples and the criticism found in literature on this approach are described. This part of the literature research was conducted before the field trip to São Tomé.

Subsequently, in Section 13.3.2 some insights obtained during the field trip to São Tomé are described. Based on these insights, it is explained why the assessment frameworks as described in the previous sections cannot be used to map the adaptive capacity for São Tomé and obtain an overview of the barriers to adaptive capacity.

Therefore, additional literature research was carried out. The most important insight from the field trip was that the adaptive capacity for a certain system cannot be mapped by adding up different determinants; rather, it is very much dependent on the interactions within the system. Therefore, it seemed more logical to try to map the adaptive capacity starting from the system itself. The additional literature research was therefore focused on finding a system-based assessment framework for adaptive capacity. This is described in Section 13.3.3.

Based on the insights obtained during the field trip, this system-based approach was adjusted to develop a new theoretical framework, that is used in the remainder of this study. The adjusted framework is also described in Section 13.3.3. Finally, this new theoretical framework is used to reflect on the diversity in assessment frameworks for adaptive capacity as described in Section 13.3.1.

13.3.1. Different approaches to assessing adaptive capacity

As was stated above, there have been different studies that tried to come up with a framework for the assessment of adaptive capacity. Among these different studies, we can recognize different approaches; an overview of these approaches is given in Figure 13.7. A first division can be made between quantitative and qualitative approaches. The qualitative approaches can subsequently be subdivided in approaches that focus on the manifestations of adaptive capacity and approaches that focus on the determinants of adaptive capacity. These different approaches will be described in the subsequent sections.

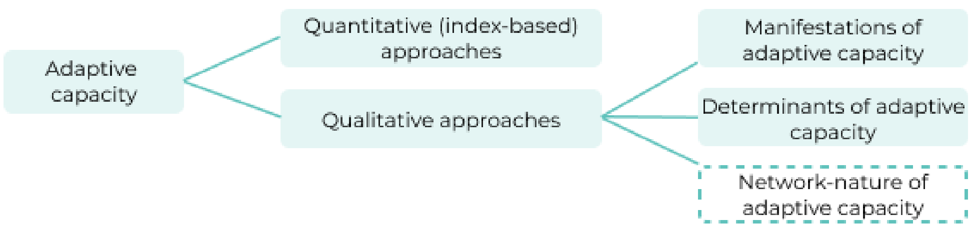


Figure 13.7: Different approaches to the assessment of adaptive capacity, as found in literature

Quantitative (index-based) approaches

Among the first to establish a framework for the assessment of adaptive capacity were (Yohe and Tol, 2002). Their approach was an index-based one; they tried to select indicators of adaptive capacity, quantify them and then produce an overall index that could be used in comparisons. Another example of such an index-based approach is the National Adaptive Capacity Index (NACI) developed by (Vincent, 2007), which was developed for the comparison of adaptive capacity among different African countries. As an example, the composition of this index is depicted in Figure 13.8.

The index-based approaches to adaptive capacity can be used to identify 'hotspots' for supporting prioritization of international assistance. In that sense, they are useful in the comparison of adaptive capacity between different systems (Jones et al., 2010). However, they are also critiziced for their data-driven nature and the lack of a sound theoretical basis.

Different studies have elaborated the problems related to this index-approach. The critism on this approach can be summarized in two main arguments. Firstly, in (Yohe and Tol, 2002) it is mentioned that 'many of the variables [of adaptive capacity] cannot be quantified, and many of the component functions can only be qualitatively described'. For example, Figure 13.8 shows that the national adaptive capacity index depends

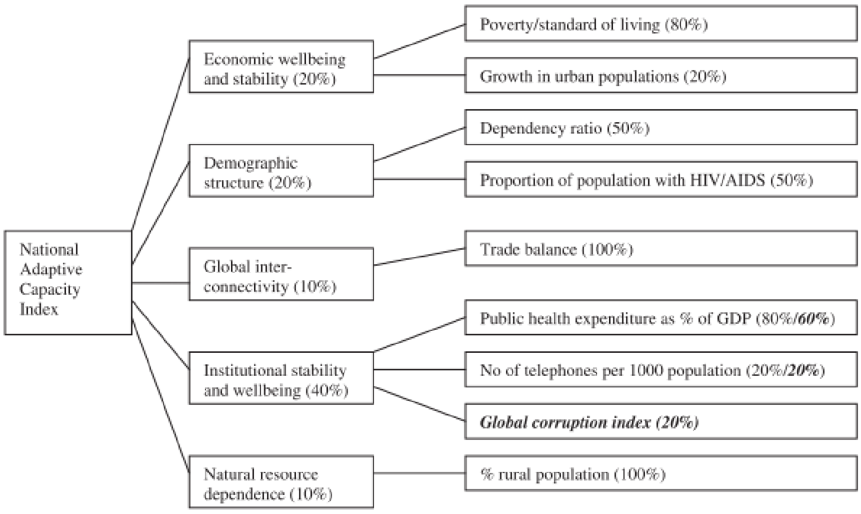


Figure 13.8: Structure of the National Adaptive Index (NACI) (obtained from (Vincent, 2007))

for 20 % on 'economic wellbeing and stability', but the justification for this 20 % is not clear. (The World Resources Institute, 2009) argues that therefore index-based methods do not properly include the multi-faceted nature of adaptive capacity; they focus on assets and physical resources (by trying to find proxies for these factors, e.g. the percentage of people living below a certain poverty standard is an indication for the financial resources of a system) while they miss social and institutional factors. Although these social and institutional factors are much more difficult to incorporate in an indicator, they are also important to understand the adaptive capacity for a certain system. The consequence of this asset-orientated focus is that determining the adaptive capacity of a system becomes a matter of answering the question "What resources are available that can help the sytem to adapt?". However, (The World Resources Institute, 2009) argues that this is not enough to obtain a complete picture of adaptive capacity; the question "What are the different actors within the system able to do to adapt?" is equally important. They conclude that these indices are therefore of limited value for country planning and capacity building processes, where it is important to define the adaptive capacity for a certain system (and it is not so much about the comparison between different systems).

Furthermore, (Vincent, 2007) states that 'the precise composition [of the determinants of adaptive capacity] may vary depending on the scale of analysis', indicating that the scale at which the system of interest is defined is another complicating factor in establishing the precise determinants of adaptive capacity. This complication is not adressed in index-based approaches, where the adaptive capacity is assumed to depend on a constant set of indicators.

Qualitative approaches

Recognizing the multi-faceted nature of the adaptive capacity of a system, many studies have investigated the psychological, social and institutional aspects of adaptive capacity. For example, (Pelling and High, 2005) investigate the use of theories of social capital for adaptive capacity framing and assessment. (Sjöstedt and Povitkina, 2017) investigate the role of institutional factors in the adaptive capacity of a system. These studies do not so much provide a framework for the assessment of adaptive capacity, but rather investigate the different determininants in more detail.

Based on this research on the (role of) different determinants of adaptive capacity, several authors, both from within the research community and development organisations, have developed different frameworks for the qualitative assessment of adaptive capacity. The aim of these frameworks is to 'better handle the multifarious nature of the adaptive capacity concept, comparing to the traditional indexing approach' (Phi, 2011). Although these different framework all try to assess the concept of adaptive capacity in a more qualitative way, they differ from each other in approach because they look at the concept from different perspectives. As can be seen in Figure 13.7, we can distinguish between qualitative approaches that focus on the manifestations of adaptive capacity and approaches that focus on the determinants of adaptive capacity.

The difference between these approaches can be understood as a difference between bottom-up and top-down approaches to assessing adaptive capacity. The qualitative approaches that focus on the manifestations of adaptive capacity, focus on the results of the adaptive capacity of a system; the extent to which the system is able to fulfill certain functions. This is a top-down approach. Qualitatitive approaches that focus on the determinants of adaptive capacity, focus on the causes of adaptive capacity; this is a bottom-up approach.

An example of a qualitative assessment framework that starts from the manifestations of adaptive capacity is the National Adaptive Capacity (NAC) framework. This framework was developed by the World Resources Institute (WRI) in 2009 and identifies the different functions that should be fulfilled in a system in order to adapt (The World Resources Institute, 2009). The 5 core fuctions identified within this assessment framework are:

1. Assessment of relevant information for climate change adaptiation decision making
2. Prioritization of adaptation among issues, areas, sectors or populations
3. Coordination of adaptation processes among actors and across levels
4. Collecting, analyzing and disseminating knowledge in support of adaptive activities
5. Reduction of climate related risks

The adaptive capacity of a system can be assessed by investigating how well the system is able to fulfill these functions. Within this framework however, the drivers and/or barriers that determine how well a system is able to fulfill these functions are not specifically adressed. The perspective to adaptive capacity taken in this framework is based on the outcome of the system: what are the functions that the system can carry out and to what extent? This could be seen as the manifestations of adaptive capacity in the system.

In contrast, the Overseas Development Institute (ODI) developed a framework for assessing the local adaptive capacity which is based on the drivers and barriers that determine how well a system is able to carry out the functions needed to adapt (Jones et al., 2010). This framework is therefore an example of a qualitative assessment that focuses on the determinants of adaptive capacity. In this framework, 5 fundamental features of local adaptive capacity are identified, which are depicted in Figure 13.9.

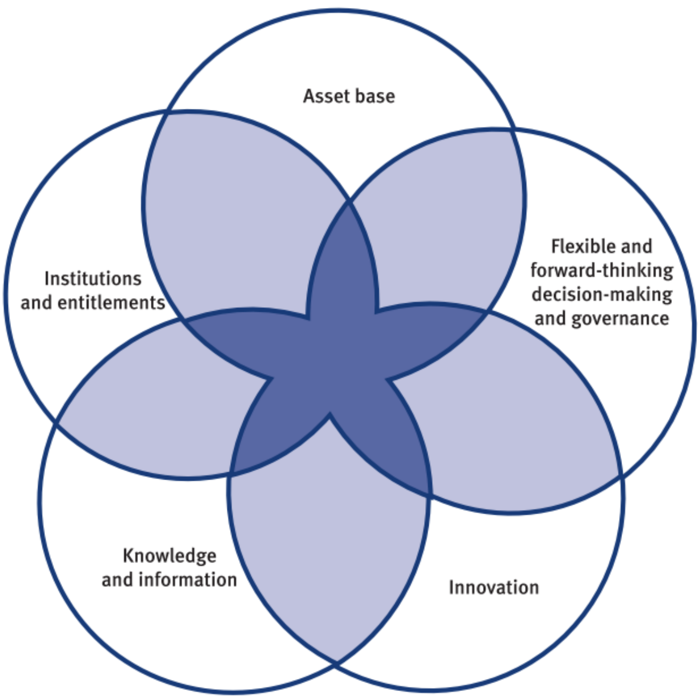


Figure 13.9: Local Adaptive Capacity's five characteristics (obtained from (Jones et al., 2010))

As opposed to the WRI framework, this framework does not focus on the outcomes, the functions that the system can carry out. Rather, the focus is on the different features that cause the system to be able to carry out these functions to a certain extent.

Although these qualitative assessments do provide a more broad assessment of adaptive capacity compared to the index-based methods described above, there are still some points of criticism which can again be summarized in two main arguments. First, there have been many different studies that focused on this perspective (Smit and Wandel, 2006) (Jones et al., 2010) (Vincent, 2007) (Wesche and Armitage, 2010) and tried to identify the different determinants of adaptive capacity. Although some determinants are often mentioned, there is no general concensus on the determinants that make up the adaptive capacity of a certain system. In (Jones et al., 2010), it is stated that "Although we presently agree that direct assessments of adaptive capacity are not feasible, the identification of the characteristics or features that influence it is hampered by our limited understandings of adaptive capacity.... the understandings of adaptive capacity is still very much in their infancy". This lack of understanding inhibits the development of a general qualitative framework that gives a complete description of adaptive capacity for all systems.

Secondly, as described in (The World Resources Institute, 2009), the different components of adaptive capacity are interrelated. Although many of these studies acknowledge this interdependence and many visual models of the different frameworks show overlap between the different determinants, these relations are not (explicitly) adressed in the qualitative approaches to adaptive capacity described above.

13.3.2. Insights from the field trip

During the field trip to São Tomé, I spoke to many different people, both people working at the central institutions of this island and people living in the different coastal communities. The results of this field trip are described in detail in Chapter 15.

One of the most important insights from this field trip was that the adaptive capacity for a certain system cannot be defined by simply adding up the different determinants of adaptive capacity. Rather, the different determinants are interdependent and their interaction is very important for the adaptive capacity of the entire system. This can be explained with an example from the context of São Tomé.

In São Tomé, an important institution is the National Institute of Meteorology (INM). This institute is a.o. responsible for the weather forecast. The general director of the INM explained that they are limited in their activities (i.e. in their institutional effectiveness) because of a lack of educated people and a lack of money. He explained that there are currently only four meteorologists working for the institute, but they would need at least eight to carry out their activities in a proper way. They are trying to educate more people, but this is a slow and difficult process, especially because people have to travel abroad to receive training at the required educational institutions (these are not present at the island). Also, a lack of money is an important factor determining the activities of the institute. The institute used to have a green line for fishermen (i.e. a telephone line that the fishermen in the different coastal communities could use for free to call the institute and ask for the weather forecast), which was used often and very useful to the fishermen. However, the green line was shut down a few years ago because the institute no longer had the financial resources to maintain the line.

In this specific example, it can be concluded that the effectiveness of the institute of meteorology is seriously hampered by a lack of educated meteorologists (i.e. knowledge) and a lack of financial resources. According to the ODI assessment framework, effective institutions, financial resources and knowlegde are three determinants of adaptive capacity. However, in this example we see that these three determinants are interdependent. In the context of this example, it would not be fair to conclude that the ineffectiveness of the meteorological institute is a barrier to the adaptive capacity, because this ineffectiveness is caused by a lack of other resources (in this case financial resources and expert knowledge).

In the example above, the different determinants of adaptive capacity, as defined in the ODI assessment framework, influenced each other in a negative way. However, during the field trip also examples of situations where the determinants compensated for each other were found. One of these examples was the coastal community of Praia Abade. In this community, they decided to have somebody standing watch during the rainy season (when most storm events occur) during the night. They take turns to do this: every night, somebody else stands watch. In case of a storm, this person wakes the rest of the community, so that everybody can help to secure the boats at the beach and to evacuate the people and their animals if needed. In this example, the lack of information (on when a storm will hit the community) in the community is compensated by a strong social system.

Based on these observations, it can be concluded that the interactions between the different determinants in a certain system are very important for the adaptive capacity of that system. These interactions are very system-dependent. These interactions are only indirectly adressed in the different qualitative assessment frameworks for adaptive capacity as found in literature and not at all in the quantitative assessment frameworks. This means that these assessment frameworks do not provide a useful tool to map the adaptive capacity of São Tomé. Therefore, an additional literature research was carried out. Since the interactions between the different determinants is very system-dependent, it seemed logical to focus in the literature research on finding a system-based assessment framework for adaptive capacity. This will be described in the next section.

13.3.3. Towards a new framework

As was described in the previous section, based on the insights obtained during the field trip it can be concluded that the theoretical assessment frameworks for adaptive capacity as described in Section 13.3.1 cannot be used in order to map the adaptive capacity in São Tomé. Therefore, some additional literature research was done after the field trip. The focus of this literature research was on a system-based approach to adaptive capacity. In this section, first a system-based approach that was found in literature is discussed. Subsequently, the adjustments to this approach are explained and a reflection on the other assessment frameworks (as described in Section 13.3.1) is given.

Literature: system-approach

(Phi, 2011) states that adaptive capacity is a system property and therefore, if you want to define adaptive capacity, you should start from the system. He furthermore states that the systems that are relevant in vulnerability assessments can be classified as socio-ecological systesm. These socio-ecological systems have a few general properties (Cumming, 2011):

1. A socio-ecological system consists of different components (sometimes also called building blocks), including elements of the social and ecological subsystems.
2. The different components of the socio-ecological system interact with each other. These interactions link all components together in a structured way.
3. A socio-ecological system is often situated within a wider context, which is often called the external environment of the system.
4. Socio-ecological systems exhibit certain behaviors, which are driven by the system components and their interactions.

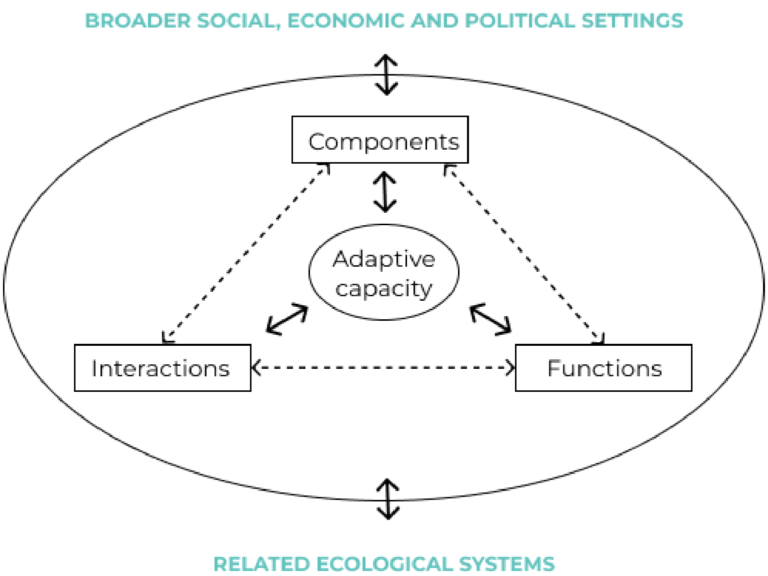


Figure 13.10: Configuration of the three elements defining adaptive capacity (adjusted from (Phi, 2011))

As was stated above, (Phi, 2011) states that adaptive capacity is a system property. Furthermore he states that for the socio-ecological systems that are of interest in vulnerability assessments, this property can be characterized by the integration of the system components, functions and interactions. This is illustrated in Figure 13.10. From this figure, it can be seen that adaptive capacity is an emergent property of the socio-ecological system under interest. Furthermore, it can be seen that the external environment, consisting of the broader social, economic and political setting and related ecological systems, does not directly influence a system's adaptive capacity. This influence is indirect, because the external environment can influence the system's components, the interactions between these components and a system's functions.

(Phi, 2011) distinguishes between three main system components, namely: resources, actors and the governing structure. Considering the system's resources, he puts the main focus on natural resources, human-made capital, financial capital and technology. The second component, the actors, deals with the relevant human actors and their role in shaping a system's adaptive capacity. Important factors here are the different actors, human capital (e.g. education level) and human cognition (e.g. perception about climate related risks). The third component, the governing structure, logically relates to the structure of the system's governing body/bodies.

Both for the functions and the interactions of the system, (Phi, 2011) states that there exist various ways to define these, depending on the system and the considered hazard. The classification of functions as described in for example the NAC framework (see Section 13.3.1) can be used. In his theoretical framework, (Phi, 2011) defines the following functions:

1. Natural capital provision (i.e. the components of nature that can be linked directly or indirectly with human welfare, for example timber, water and energy reserves)
2. Human made capital provision (i.e. produces assets that are used to produce other goods and services, for example machines, tools and infrastructure)
3. Social capital provision (i.e. social capital refers to those stocks of social trust, norms and networks that people can draw upon to solve common problemes and create social cohesion)
4. Human capital provision (i.e. Types of human capital include mental and physical health, education and work skills)

The functions of the system provide a measure for adaptive capacity; how well certain functions can be fulfilled is an indicator of the adaptive capacity of the system. For a more elaborate description of the different components, the reader is referred to (Phi, 2011).

Adjustment of the system-based approach

As stated above, the general definition of adaptive capacity is 'the ability or capacity of a system to cope, adapt or recover from a certain hazard or combination of hazards". In order to come to a more practical definition, (Phi, 2011) starts from the socio-ecological system for which we want to define adaptive capacity. For the development of the theoretical framework for this study, the system-based approach developed by (Phi, 2011) was used as a basis. However, the system is defined somewhat differently.

(Walker et al., 2004) states that the dynamics of socio-ecological systems are mainly shaped by individual human actors and that therefore socio-ecological systems are often dominated by human actions. This means that the adaptive capacity of a system is mainly a function of the social component - the individuals and groups acting to manage the system. This was also observed during the field trip to São Tomé.

Taking this perspective on the nature of and dynamics in socio-ecological systems, the system could also be defined as a network of actors. These actors can both be individuals or groups of people (e.g. an institution), depending on the scale of the considered system. These actors interact with each other in certain ways, which provides the links between the different actors. These interactions can differ both in intensity and nature. Furthermore, in every system certain resources are available, both physical (e.g. financial assets, natural resources) and non-physical (e.g. human capital). These resources are usually not freely available in the system, but are linked to certain actors or group of actors. Not only the presence of these resources in a system, but also the allocation/division over different (groups of) actors is highly relevant for the adaptive capacity of the entire system. An unequal division of resources generally leads to less efficient use and therefore inhibits the adaptive capacity of a system (Baland and Platteau, 1999). This system description is depicted visually in Figure 13.11. The interactions between the different actors and their resources lead to certain behaviours of the system as a whole. Depending on this, the system is more or less able to fulfill certain functions needed for adaptation. The adaptive capacity of a system with respect to a certain hazard or combination of hazards depends on the actors, interactions and resources of the system, and the interplay among these elements.

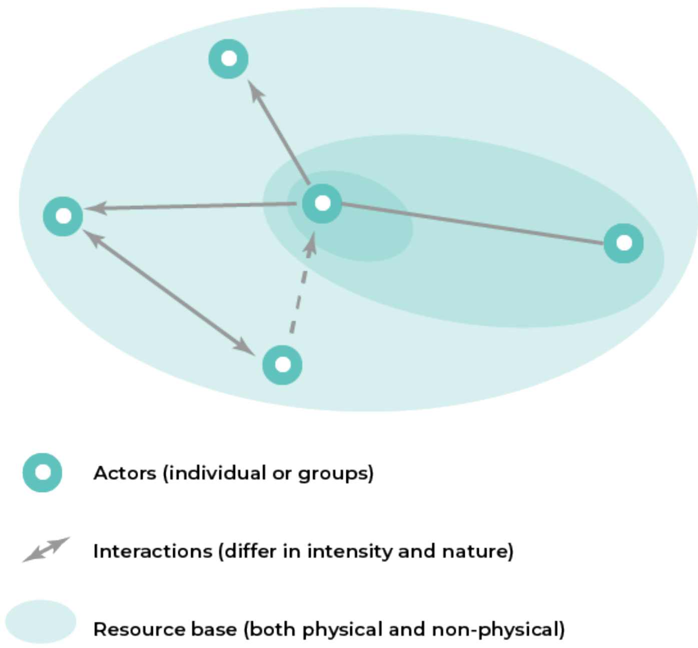


Figure 13.11: Adaptive capacity as a network property

This leads to certain behaviours of the system as a whole that are relevant in decreasing the vulnerability to the hazard or combination of hazards. The broader social, economic and political settings (i.e. broader than the boundaries of the defined system) can influence the actors, resources and interactions and the interplay among these elements and can in this way influence the system's adaptive capacity.

Similar to the approach taken by (Phi, 2011), this theoretical framework for adaptive capacity starts from the system for which the adaptive capacity should be defined. However, the system is defined somewhat differently (i.e. as a network of actors instead of a socio-ecological system), which leads to a different theoretical framework in the end. There are two main differences between the theoretical framework developed by (Phi, 2011) and the one described in this section.

Firstly, the system components as described by (Phi, 2011) consist of the system actors, resources and governing structure. Within the adjusted system-based approach, the actors and resources are explicitly split into two categories, while still acknowledging the fact that these are not independent, since resources are often linked to an actor or group of actors. The governing structure is not explicitly mentioned in the adjusted framework. The rationale behind this is that it is not so much the governing structure itself, but rather the effect of this structure on the different actors, their interactions and available resources that is important for the assessment of adaptive capacity. The governing structure (partly) determines the configuration of actors, the type and intensity of their interactions and which resources are available to whom.

Furthermore, the role of the functions-element is different in the two frameworks. In the theoretical framework developed by (Phi, 2011), adaptive capacity is seen as a property emerging from the interplay between a system's components, interactions and functions. Within the adjusted framework described in this section, the interplay between a system's components, interactions and resources is assumed to lead to certain behaviours of the system as a whole. This determines how well a system is able to fulfill certain functions that are relevant to decrease the vulnerability of the system to certain hazards or combinations of hazards. This corresponds to a certain amount of adaptive capacity within the system. In the adjusted theoretical framework, the functions do therefore not contribute to the adaptive behaviour of a system; rather the extent to which the system can fulfill certain functions is an indicator of the adaptive capacity of a system.

This is an important distinction to keep in mind related to the goal of the study. If the goal is to obtain a (qualitative) measure of adaptive capacity for a certain system (for example in order to compare it to other systems), these functions form an important part of the analysis. However, if the goal is to increase the adaptive capacity of a certain system, it might not be very relevant to have a measure of the adaptive capacity in that system. You are probably more interested in the factors that inhibit the adaptive capacity in the system. These inhibiting factors or barriers can be derived from a system analysis incorporating the actors, interactions and resources that are relevant in the context of a certain system to a specified hazard. It is assumed that by identifying the actors that are missing or not functioning well, and the interactions and resources that are lacking, an overview of the barriers to adaptive capacity to a specified hazard can be obtained for a certain system. In such an analysis, it might not be necessary to define the functions of the system in order to obtain a measure of its adaptive capacity.

Relation to the other qualitative approaches to adaptive capacity

Starting from the adjusted system-based theoretical framework as described above, it is now easier to explain the diversity in qualitative assessment framework for adaptive capacity present in the literature on adaptive capacity of SIDS to climate change. As was described in Section 13.3.1, a distinction can be made between assessment frameworks that focus on the manifestations of adaptive capacity and assessment frameworks that focus on the determinants of adaptive capacity. These approaches are very much linked to each other, but have different starting points.

Furthermore, as was described above, there is no consensus in literature on a general qualitative model for the determinants of adaptive capacity that is applicable to all systems. In literature, many different studies can be found that all give a slightly different list of determinants or features of adaptive capacity. Considering again the system-based framework as described above, it can be concluded that the approach taken to come to these assessment frameworks might be inherently flawed. By trying to come up with a list of a few determinants/features to describe adaptive capacity, the network-character of this concept is completely ignored. By ignoring its network-character and strong dynamics and interdependencies between the different elements, it will never be possible to come up with a complete description of the adaptive capacity of a certain system.

13.4. Chapter summary

The first sub-question of this part of the thesis was: 'What is adaptive capacity and how can it be defined for a certain system?'. As a result of the literature study and theoretical framework described in this chapter, this question can now be answered.

Regarding the first part of the subquestion 'What is adaptive capacity?', we can conclude that adaptive capacity represents a feedback loop in social vulnerability assessments, which is not present in technical risk assessments. The approach taken in technical risk assessments is quite linear, starting from the stimulus (e.g. a coastal flood event) and ending at the adverse effects on the system, often expressed in monetary terms. Many studies have criticised this approach, claiming that its focus is too narrow and that, especially in the long term, it is meaningless to analyse the vulnerability of a system without incorporating the response of the system to (the effects of) the hazard it is vulnerable to. This feedback loop within the system is dependent on the adaptive capacity of the system. The general definition of adaptive capacity is therefore 'the ability or capacity of a system to cope, adapt or recover from a certain hazard or combination of hazards'.

Although this definition of adaptive capacity is insightful, it is not a very practical one in terms of determining the adaptive capacity for a certain system or comparing adaptive capacity between different systems. In order to answer the second part of the first sub-question 'How can we define adaptive capacity for a certain system?', different assessment frameworks found in literature were studied. Among these different studies, we can distinguish between quantitative (index-based) and qualitative approaches.

Quantitative (index-based) approaches try to select indicators of adaptive capacity, quantify them and combine these to produce an overal index. Although quantitative approaches can be useful in the comparison of adaptive capacity between different systems, these approaches are also criticised. Many studies claim that these index-based methods do not properly include the multi-faceted nature of adaptive capacity (since it is very difficult to quantify e.g. social and institutional factors). Also, these approaches assume adaptive capacity to depend on a constant set of indicators. However, many studies state that the precise composition of the determinants of adaptive capacity is context and scale specific.

Qualitative approaches try to handle the multi-faceted nature of adaptive capacity. Among these approaches, we can distinguish between assessment frameworks that focus on the manifestations of adaptive capacity within a system and frameworks that try to identify the different determinants of adaptive capacity. Although these studies have led to more insight in the concept of adaptive capacity, to date there is no consensus on a general theoretical framework that gives a complete description of adaptive capacity for all systems. Also, these studies focus on the different determinants of adaptive capacity, but the relations between these determinants are not explicitly adressed.

One of the most important insights obtained during the field trip to São Tomé was that the adaptive capacity of a system cannot be mapped by simply adding up different determinents. The interaction between the different determinants are essential to the adaptive capacity of the system. Since none of the assessment frameworks found in literature directly adresses these interactions, these frameworks cannot be used to map the adaptive capacity for the system of São Tomé.

Therefore, additional literature research was carried out that focused on finding a system-based assessment framework to adaptive capacity. (Phi, 2011) described such a system-based approach to the determination of adaptive capacity. He states that the system relevant in vulnerability assessments can be defined as a socio-ecological system and assumes that adaptive capacity is an emergent property of the system that is linked to the interplay between a system's compontents, interactions and functions.

Based on this system-based approach, a theoretical framework for the assessment of adaptive capacity is described. Where (Phi, 2011) described the system as a socio-ecological system, in this framework the system is defined as a network of actors, which are linked to each other via various interactions. Each of these actors draws on a resource base, which entails both physical (e.g. natural resources) and non-physical resources (e.g. human capital). The interplay between a systems actors, interactions and resources determine a system's adaptive capacity.

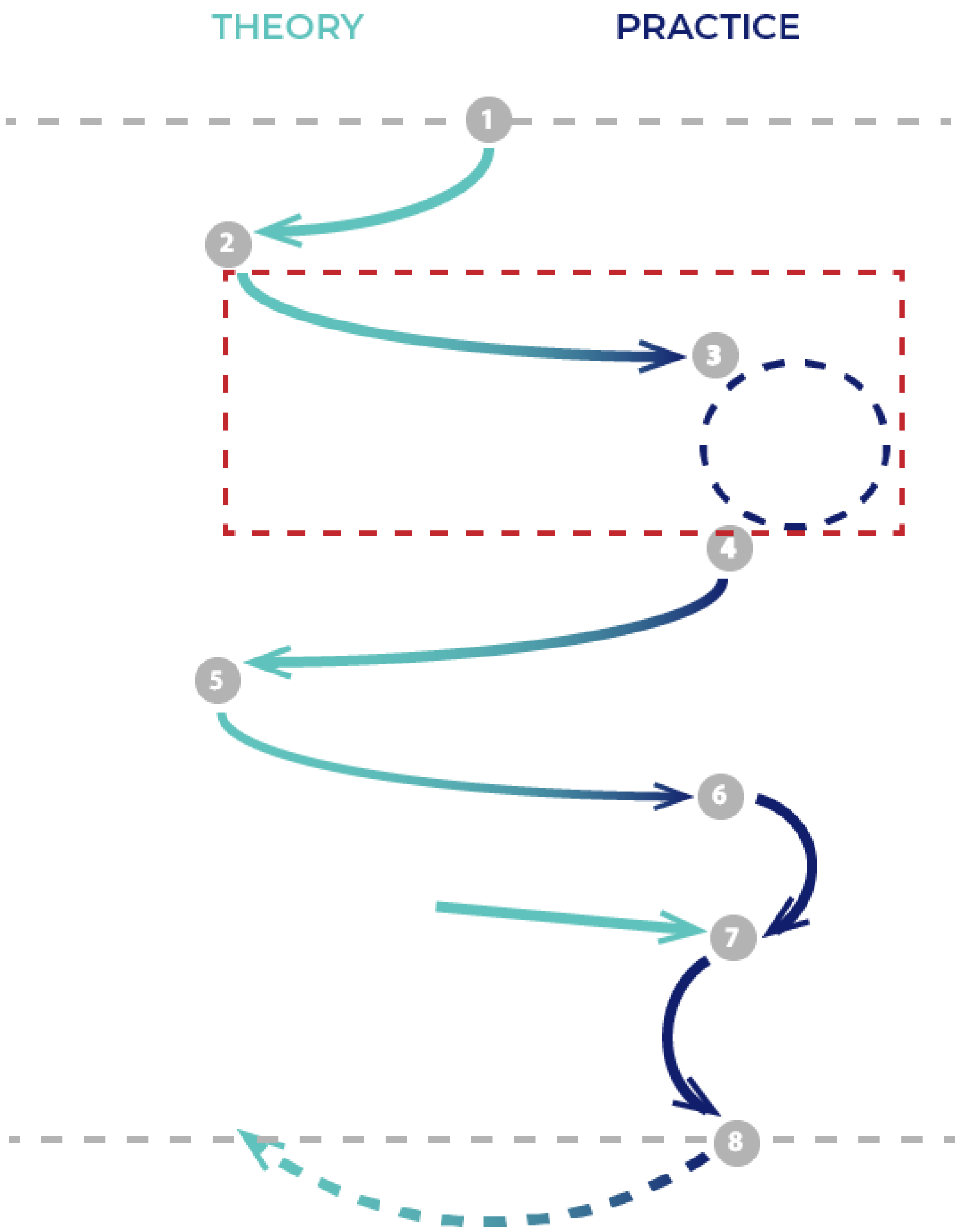


Figure 13.12: Preparation of the field trip in the roadmap

14

Preparation field trip

This chapter focuses on the second research step as indicated in the roadmap (see Figure 13.12); the preparation for the field trip to Sao Tome. The preparation entailed three different elements: the development of an initial design for the tool interface, a questionnaire and an interview protocol. These three different elements were developed in parallel and will be discussed in seperate sections in this chapter.

In Section 14.1, the different steps leading to an initial design for the tool interface will be described. In Section 14.2, the development of the interview protocol will be explained. Next in Section 14.3, the development of the questionnaire will be explained. Lastly, in Section 14.4 a summary of the chapter is given.

14.1. Initial design of the tool: approach and methods

An initial design of tool interface was made prior to the field trip to São Tomé. The choice to make an initial design for the tool interface was mainly based on practical considerations and marked the starting point for the design process (i.e. the dot with number 0 in Figure 14.1); this is explained in Section 14.1.1.

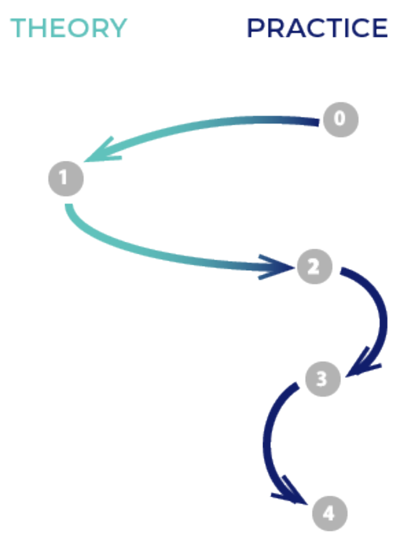


Figure 14.1: Design process initial tool design

Following the choice to make a design for the tool interface prior to the field trip, different steps were made to come up with an initial design. The first step was a short literature research (represented by the 1st arrow in Figure 14.1) to identify the different factors determining the effective use of support tools in general (i.e. the dot with number 1 in Figure 14.1); this is described in Section 14.1.2. For the initial design, it was decided to focus on one of these factors: user friendliness (i.e. the dot with number 2 in Figure 14.1). Therefore Alienor de Haan was contacted. Alienor is a graduated industrial designer who specializes in the design of tools, apps and websites. During an interactive session (the 3rd arrow in Figure 14.13), we discussed the concept of user friendliness extensively and came up with a first draft for the tool interface (the dot with number 3 in Figure 14.1). This interactive session is described in Section 14.1.2. After this meeting, I worked out the draft and organized a feedback session with two participants with a water background; this is visualized by the 4th arrow in Figure 14.13. Based on the feedback and suggestions that I received during this feedback session, the initial design for the tool interface was finalized (the dot with number 4 in Figure 14.1). This final step is described in Section 14.1.2.

14.1.1. The choice for an initial design of the tool

In the context of this thesis, an initial design of the tool interface was made prior to the field trip and used during the interviews in Sao Tome. There are different advantages and disadvantages to this approach, which will be elaborated on below.

An important advantage, especially in the context of São Tomé (and possibly other developing countries as well) is that such an initial design helps to make the project and its aim more tangible for local people. This advantage was pointed out both by Deltares members who visited São Tomé and Principe a few months before and by others with project experience in other developing countries. When the project and its aim are more clear to the local people, they are probably more interested and are also better able to give useful information and feedback. This aids the system analysis, the problem identification and the design of the final tool interface.

A disadvantage of using an initial design is that the local people will already be guided by this initial design, so you might limit the space for improvement. This disadvantage was also pointed out later by Alienor (see Appendix G). Taking both advantages and disadvantages into account, the choice was made to make an inital design for the tool interface and use this during the interviews in São Tomé. This choice indicates the first stage in the roadmap visualizing the development process of the initial tool interface. In order to address the risk that the local people will be guided too much by this initial design, the interviews were split in two parts; this will be explained in Section 14.2.

14.1.2. Development of the inital tool design

Literature research

Support systems can be found in many different fields. Studies that investigate the different factors influencing the effective uptake and use of (decision) support systems can be found for example in the fields of agriculture, health care, ICT and disaster prediction (Venkatesh et al., 2003) (Shibl et al., 2013) (Rose et al., 2016). In order to investigate the different factors influencing the effective use of (decision) support systems, studies from different fields were used during the exploratory literature research. The choice to include studies from different fields instead of only the field of disaster prediction was made deliberately, to obtain as broad an overview as possible.

Central in all these studies is the distinction between behavioral intention and use behavior. This distinction recognizes the fact that behavior intention and use behavior are not always linked. For example, in the context of support systems in disaster prediction, it is possible that a country wants to use an early warning system, but does not have the financial resources to buy the system. In this example, a lack of financial resources is the inhibiting factor to the actual use of a system, but other elements (e.g. a lack of trained people or a lacking integration system) could play an important role as well. Within many models, these different elements are summarized under the category 'facilitating conditions'(Venkatesh et al., 2003). These facilitating conditions are an important determinant in the translation from behavioral intention to use behavior.

This distinction between behavioral intential and use behavior is well established in literature. However, regarding the different factors influencing the behavioral intention, there is no general consensus and there exist multiple models that try to explain this behavioral intention. (Venkatesh et al., 2003) investigated the differences between eight different information technology (IT) acceptance models and came up with a unified model that integrates elements across these eight models[1]. The result of this study is depicted in Figure 14.2 below. In this model, (Venkatesh et al., 2003) distinguishes between 3 direct determinants of behavioral intention: performance expectancy, effort expectance and social influence.

[1] In this study eight different models are reviewed: the theory of reasoned action, the technology acceptance model, the motivational model, the theory of planned behavior, the model of PC utilization, the innovation diffusion theory and the social cognitive theory

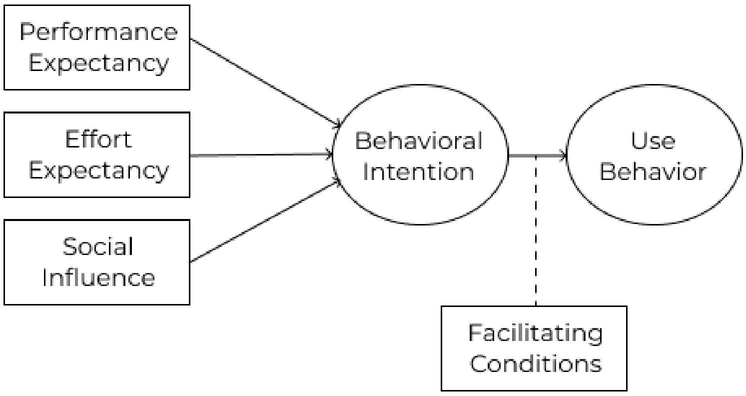


Figure 14.2: Unified technology information acceptance model (adjusted from (Venkatesh et al., 2003))

Performance expectancy is defined as the degree to which an individual believes that using the system will help him or her to attain gains in job performance (Venkatesh et al., 2003). Other studies further refined this determinant: (Shibl et al., 2013) mentions that the performance expectancy of a potential future user is determined by the relevance to the user and trust in the knowledge base. When a potential user trusts the knowledge base of a certain support tool, but he/she does not believe the outcomes of the tool are relevant, he/she won't be inclined to use the tool; this results in a low behavioral intention. Vice versa, when an individual beliefs the outcomes of the tool are highly relevant, but he/she has no thrust in the knowledge based, this also will not lead to a behavioral intention.

Effort expectancy is defined as the degree of ease associated with the use of the system. Different studies note that this is an important determinant both in voluntary and mandatory usage context. However, (Venkatesh et al., 2003) mentions that this determinants becomes less significant over time with extended and sustained use, because the user gets used to the system and learns to work with it. Therefore, this determinant is expected to be more salient in early stages of a new behavior.

Lastly, social influence is defined as the degree to which an individual perceives that important others believe he or she should use the new system. However, (Venkatesh et al., 2003) notes that this determinant is only significant in mandatory contexts. In voluntary contexts, the significance of this determinant is not established (Venkatesh et al., 2003) (Shibl et al., 2013). In voluntary contexts, the role of this determinant can be to introduce potential users with a system that they are not yet familiar with, but it will not further determine the behavioral intention (Rose et al., 2016).

An adjusted version of the model of (Venkatesh et al., 2003) is depicted in Figure 14.3. In this model, the determinant 'performance expectancy' is split in 'relevance to the user' and 'thrust in the knowledge base' as proposed by (Shibl et al., 2013). Furthermore, the social influence determinant is left out, since different studies concluded this determinant is not significant in voluntary contexts.

Not all the different determinants of behavioral intention as depicted in Figure 14.3 can be influenced via the design of the tool. Therefore, not all of these determinants are relevant to take into account in the inital design of the tool interface.

The facilitating conditions that influence whether a behavioral intention will result in actual use behavior, are a property of the context of the (potential) user and cannot be influenced directly by the design of the tool. Also, the determinant 'trust in the knowledge base' cannot be influenced directly via the tool design.

The determinants 'relevance to the user' and 'ease of use' however depend to a large extent on the tool design and are therefore important aspects to take into account during the initial design of the tool interface. In the context of this research, the determinant 'relevance to the user' is linked to the concept of adaptive capacity; the tool will be relevant to the potential user(s) if it can help to overcome (part of) the barriers to adaptive capacity that are experienced by these potential user(s). For the initial design of the tool however, the focus is mainly on the 'ease of use'. Since at this stage of the research little was known about the context of the potential users, it was not yet known what exact information would be relevant to the potential users.

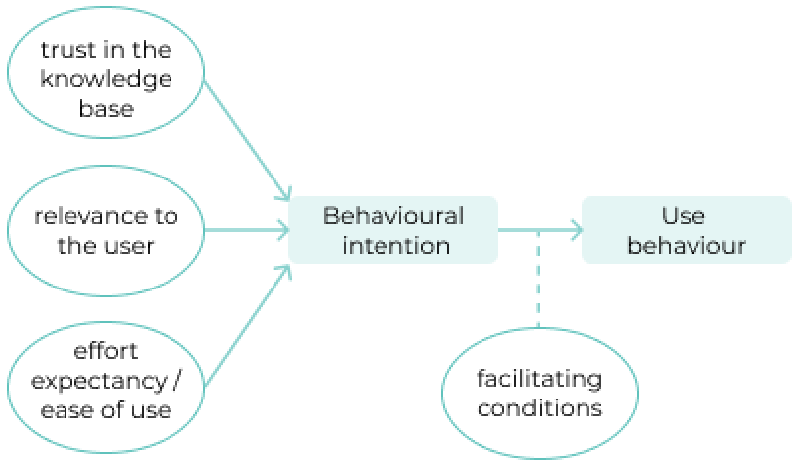


Figure 14.3: Factors influencing the effective use of support systems

Interactive session with Alienor de Haan

In order to come up with a first draft for the tool interface, an interactive session with Alienor de Haan was organized. Alienor graduated from industrial design about a year ago and is currently working for Codaisseur, where she designs websites, apps and tools (and teaches other people to do so)[2]. In her work, she focuses especially on user experience and user friendly design. Therefore, a meeting with her seemed like a good starting point to come up with a first draft for the tool interface.

During the interactive session, we first discussed the project in general and the aim of the session: to come up with a first draft for the initial tool design. We discussed the medium of the tool, the in- and output and the layout of the tool. A description of the interactive session is provided in Appendix G. The most important outcomes of the session will be discussed below.

Regarding the medium of the tool, there are different options ranging from an offline excel-based tool to an online web-based tool. Eventually we decided that a web-based tool would probably work best. A disadvantage of a web-based tool is that it requires an internet connection. However, in this way it is much easier to update the tool. Also, if the tool needs to function as an early warning system, it should be linked to online weather (and water level and waves) forecasts, which also requires an internet connection.

Secondly, we discussed the in- and output of the tool. In order to obtain results from the simple flood model, the model requires different input data: the topography and bathymetry, roughness values and hydrodynamic boundary conditions. Alienor advised me only to include those parameters that are understandable to the user and for which it is likely that he/she can give a realistic value. For example, the user will probably not understand what a Manning value (i.e. an indicator for bottom roughness) is, so it does not really make sense to include this in the tool. Eventually, we decided that the topography, bathymetry and roughness values would be fixed in the tool; the user is not able to adjust this. The user of the tool should choose a location (for which the topography, bathymetry and roughness values are set in the tool) and input the hydraulic boundary conditions (consisting of the water level with respect to MSL and the wave height). These hydraulic boundary conditions can either be entered manually or be obtained from global prediction models.

We also discussed the output of the tool. The simple flood model can be used to calculate the maximum water levels for a specified location given certain hydraulic boundary conditions. These maximum water levels can be visualized in different ways (e.g. flood maps, cross-sections) or they can be related to exposure maps to produce risk information (e.g. maps indicating which houses are most at risk). Lastly, actions that could be taken to prevent negative impacts could be included as well (e.g. evacuate the houses close to the beach). We concluded that in the initial design of the tool different visualisations of maximum water levels and an example of risk information should be included. Actions could be included later, based on information obtained during the field trip on which actions are useful.

Lastly, the layout of the tool interface was discussed. Alienor advised me to split the tool in multiple screens

[2](https://www.codaisseur.com)

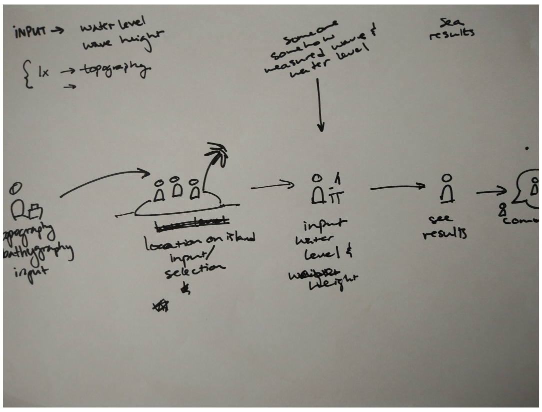


Figure 14.4: Visualisation of different steps in the tool

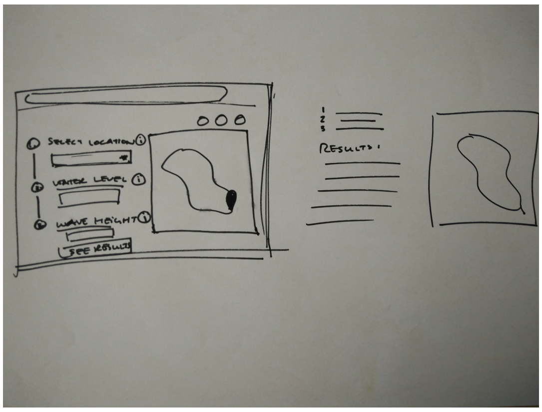


Figure 14.5: First design of the input screen in the tool

instead of one. In this way, the different steps in the tool are clear to the user. We discussed the different steps (see also Figure 14.4 below) and the corresponding screens. Eventually, we concluded that the first screen should give an introduction of the tool, in the second screen the user must fill in the input data and the last screen should give the output. It is possible to include different output screens, with different visualisation and output types. Furthermore, she gave me a lot of practical recommendations regarding the layout of the tool (see Appendix G).

Based on the ideas and input obtained during the interactive session with Alienor de Haan as described in the previous session, the first design of the tool interface was made. The different screens of the tool interface are depicted in Figure H.1 and H.2 (see Appendix H).

During the interactive session with Alienor, she advised me to use the (flooding) maps for a location in Sao Tome and Principe in the inital design of the tool interface (instead of some other island), in order to make it more recognizable for the local people. In order to do this, the simple model as described in Chapter 5 was applied to Praia Abade, a coastal community located at the island of Principe. This location was chosen because the results from the Deltares study showed that coastal flooding posed a significant threat to this community. The application of the simple flood model to Praia Abade, the results and the comparison to the Deltares model results are described in Appendix F.

Feedback session

When this first design of the tool interface was finished, a feedback session was organized to obtain feedback and make an iteration on the interface design. Since the first interactive session was with someone with an industrial design background, this second session was organized with participants with a water background. Eventually, two watermanagement graduates who just started working participated in the feedback session, Anna Waqué and Anna Goense. Both have a water background, are especially interested in the communication perspective of water projects and have experience with water-related projects in developing countries.

During the feedback session, first a short introduction into the project and the aim of the session was given. Subsequently, the different screens of the first interface design were shown. Then we thoroughly discussed the different screens and came up with ideas and suggestions to improve the design. Most suggestions that came up during this session were related to the graphical design of the interface and included suggestions to change the size and position of buttons, to add more explanation or to adjust the title of the screen. A summary of the session set-up and a graphical overview of the comments and suggestions per screen can be found in Appendix H.

The suggestions and comments obtained during this feedback session were used to finalize the initial design of the tool interface. The result is depicted below.

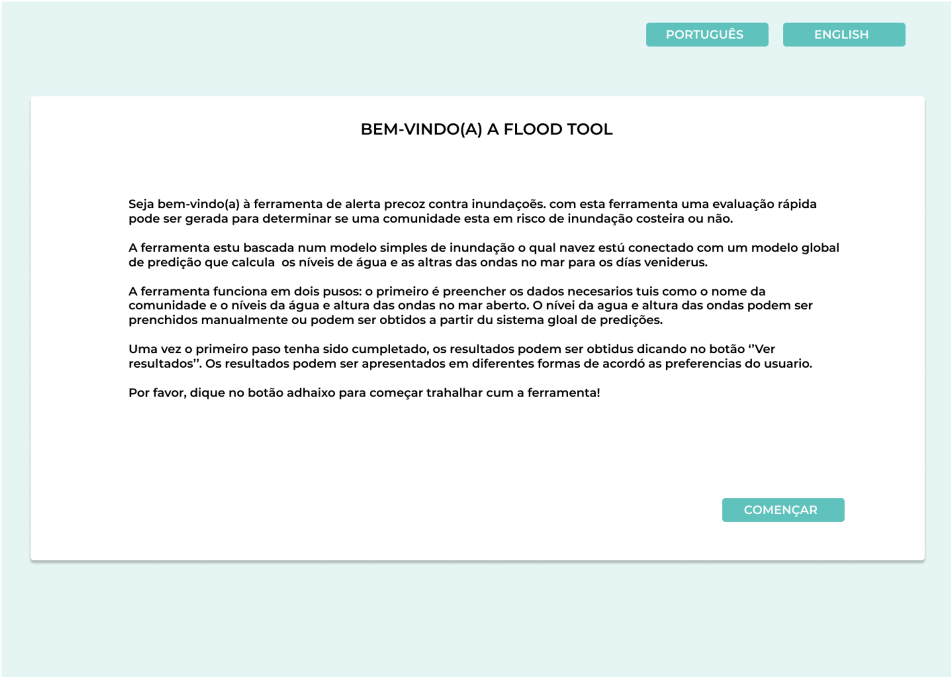


Figure 14.6: Start screen

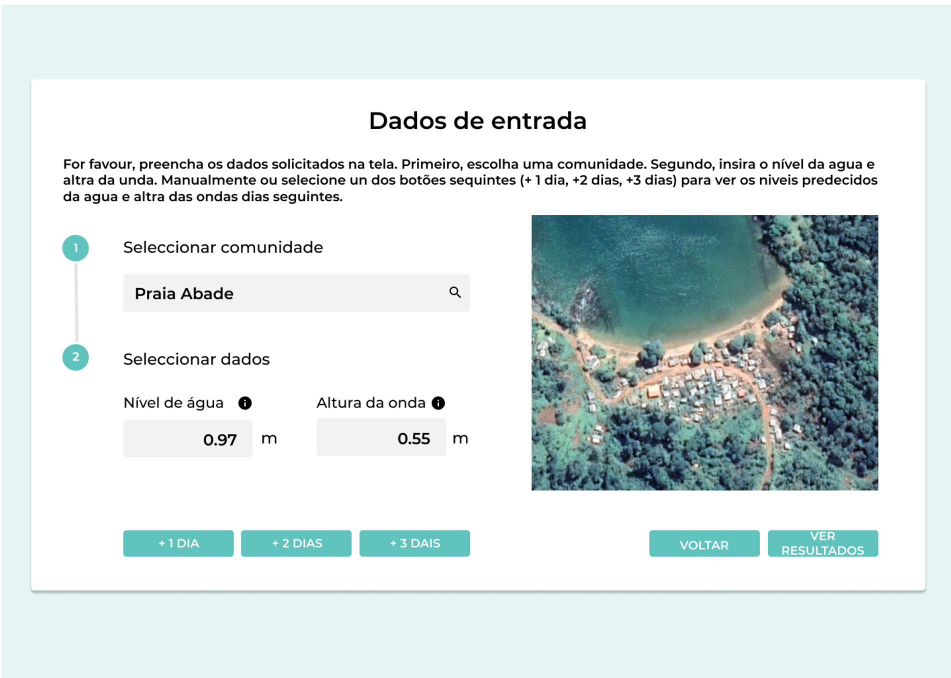


Figure 14.7: Input screen

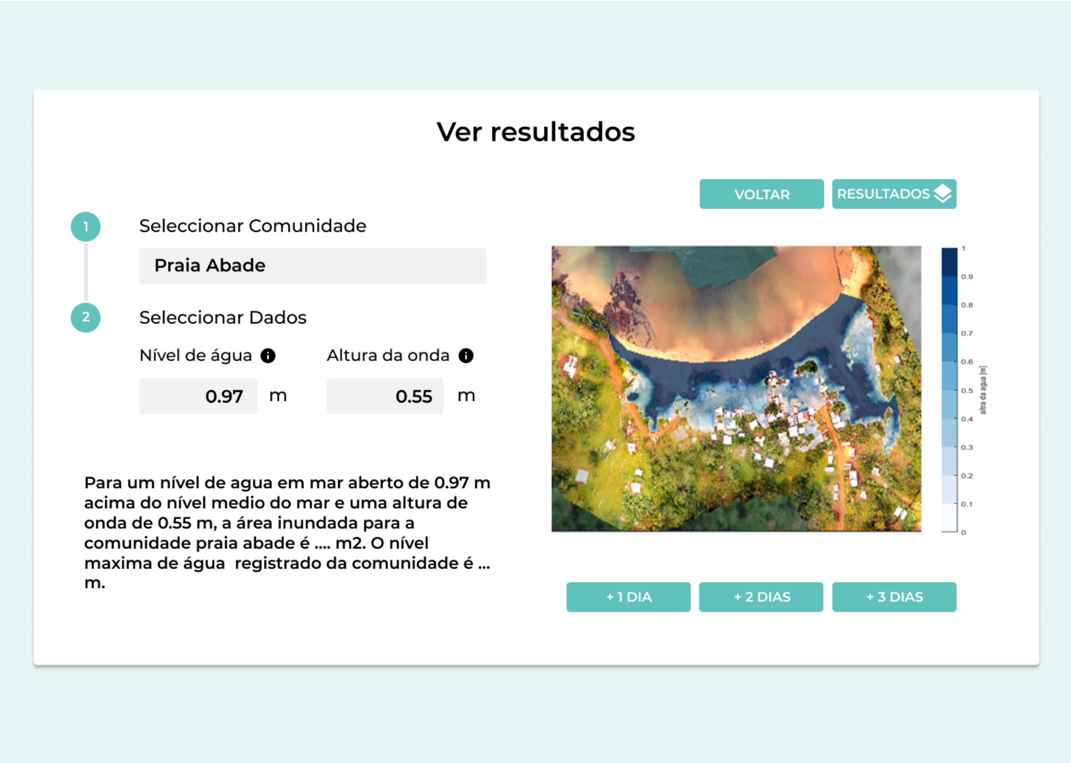


Figure 14.8: Output screen showing a flood map

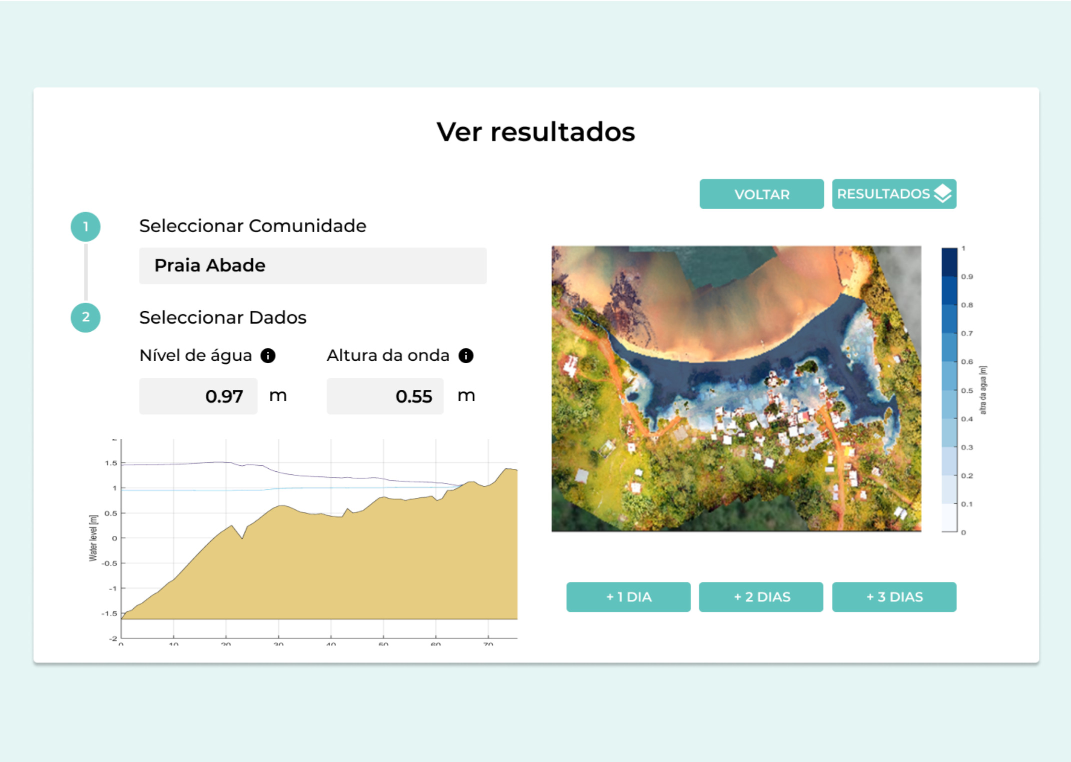


Figure 14.9: Output screen showing the water level in a cross-section

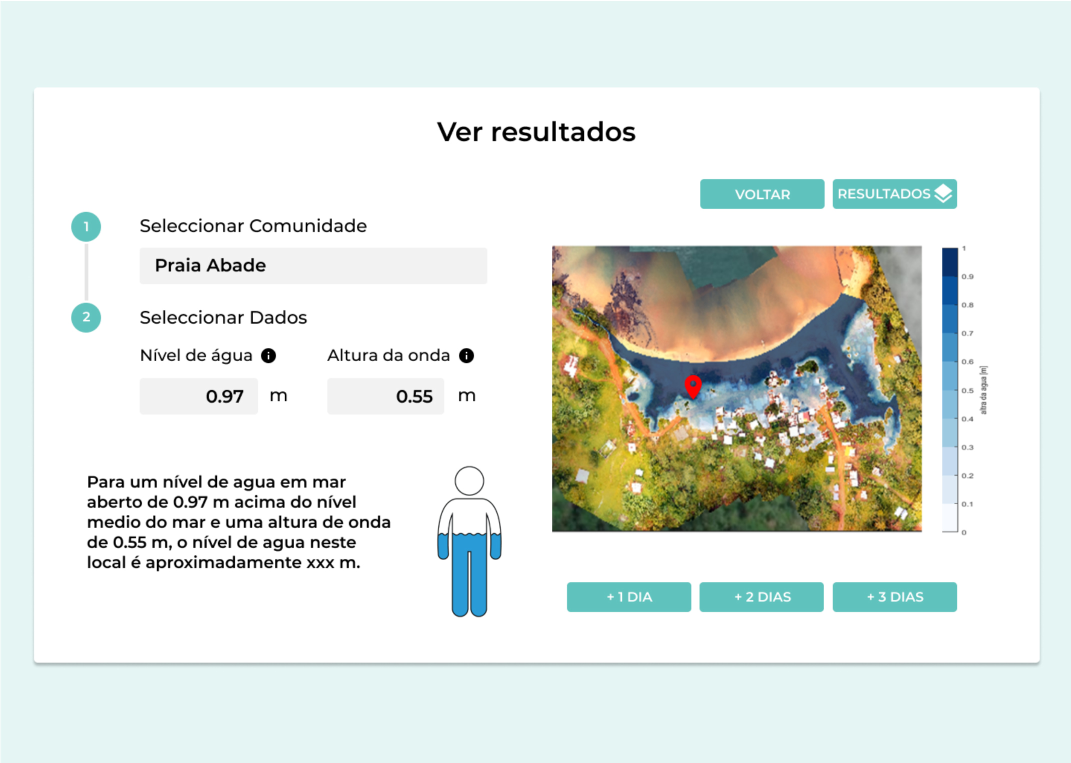


Figure 14.10: Output screen showing the water level at one location

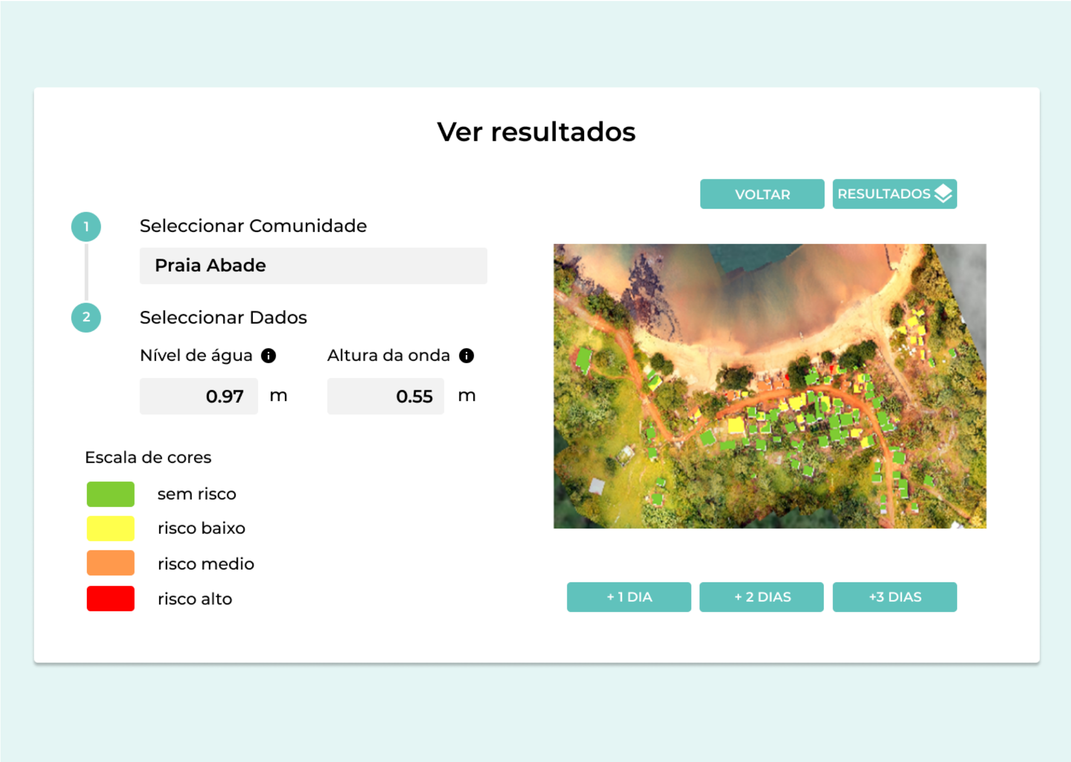


Figure 14.11: Output screen showing the risk to houses

14.2. Interview protocol

In this section, the process leading to the interview protocol for the interviews in São Tomé is described. First, the general aim of these interviews is described in Section 14.2.1. Subsequently, the process leading to the final interview protocol is described in Section 14.2.2. This process is depicted in a roadmap in Figure 14.12 and was already introduced in Chapter 12. In this section, the different steps will be explained in more detail.

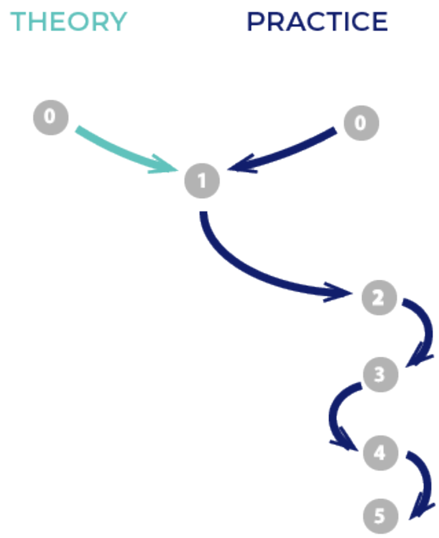


Figure 14.12: Design process interview protocol

14.2.1. Aim of the interviews

As was already described in Section 14.1.2, the relevance to the user is and important determinant influencing behavioral intention. In the context of this research, this determinant is strongly linked to the concept of adaptive capacity; the tool will be relevant to the potential user(s) if it helps the potential user(s) to overcome (part of) the barriers to adaptive capacity that they experience. Therefore, first the potential user(s) of the tool should be identified. This requires insight in the context of São Tomé.

A short analysis was done in order to get more insight into the system of São Tomé. The main information sources for this analysis were different reports and short interviews with Deltares employees who had joined the last field trip. This analysis led to the conclusion that in the context of São Tomé and Principe, there is a split user group for the tool. This user group can be split in direct users and indirect users of the tool.

São Tomé and Principe is governed by a central government. Different, central institutions are linked to this central government. Furthermore, the lowest administrative level in São Tomé are the so-called 'comunidades'. In terms of size, these comunidades are comparable to an average village in the Netherlands. Many of these comunidades are located at the east-side of the island of São Tomé. The people living in these comunidades are the once at risk from coastal flood events and are thus eventually the onces who should receive the information provided by the tool and act on it. These people can thus be seen as the indirect or end users of the tool.

However, most communities do not have access to electricity. The people living in these communities are very poor and do not own modern technical devices like a computer or a smartphone. Therefore, these people do not have the resources to use the tool directly. The direct users of the tool will be people working at central institutions (e.g. the central government). There should be communication between the direct users and the people in the coastal communities in order to get the information from the tool to the end users.

Since the tool will have a split user group in the context of São Tomé and Principe, it was important to incorporate both user groups in the research. The direct user group, consisting of people working at different central institutions in Sao Tome, was interviewed (this choice is represented by the dot numbered 1 in Figure 14.12). The aim of these interviews was to gain insight in the context of these institutions and what problems (i.e. barriers to adaptive capacity) they face that could be addressed with a tool based on the simple flood model. Since most people in São Tomé and Principe do not speak English, these interviews were held with the help of a translator. The indirect or end users, the people living in the coastal communities, were addressed with a questionnaire. This is described in Section 14.3.

14.2.2. Development of the interview protocol

The initial interview protocol was based on insights obtained from an interview with Ilse Nederlof. During an internship at HKV, she worked on the development of an online webportal for SIDS. The aim of this portal was to provide the different stakeholders in SIDS with information regarding different water-related problems. For this project, she interviewed different potential users of the portal, both in Curacao and Aruba. Although the project is different, the aim of her project was similar to the aim of this thesis. Therefore an interview was held to ask about her experiences and suggestions (this is represented by the 3rd arrow in Figure 14.12).

The most important insights from the interview were related to the set-up of the interviews. Ilse also developed an initial design of the portal to show during the interviews. She explained that initially, she showed this initial design at the beginning of the interviews. This helped to make the project more concrete. However, after a few interviews she decided to change her set-up and show the design only at the end of the interview, because she noted that the interviewees were very much guided by the initial design during the rest of the interview.

The final interview protocol (represented by the dot numbered 2 in Figure 14.12) was based on her suggestions and consists of several parts:

- **Context of the institution:** In this part the focus is on the institution, for which the interviewee works and its context. Important questions here are: 'What are the main tasks and responsibilities of the institution?', 'What are the main tasks and responsibilities of the institution in the context of coastal flooding?', and 'With whom does the institute cooperate and how does that work in practice?'
- **Problems hindering the tasks of the institution:** In this part, the focus shifts from the context of the institution to the problems that the institution faces in executing its tasks. Which problems do these institutions encounter and what causes these problems?
- **Introduction and discussion of the initial tool design:** In this final part of the interview, the tool is introduced. This is done by showing the interviewee a short movie that shows the different screens of the tool, supported by an spoken explanation in Portugues. Subsequently, the tool is discussed in relation to the problems mentioned earlier in the interview. The most important point here is to establish whether the tool could help to solve these problems. Lastly, the design of the tool is discussed. Important questions here are: 'What do you think of this tool design?', 'How can I make it (even) more useful?' and 'Is the tool understandable?'.

As can be seen in Figure 14.12, three short steps were taken at the end. These arrows indicate the short iterations on the interview protocol after every interview block. During the field trip, the interviews were clustered in three blocks, where each block consisted of two or three interviews. After every interview block, the interview protocol was reflected on and slightly adjusted.

14.3. Questionnaire

In this section, the process leading to the final version of the questionnaire is described. First, the rationale behind developing a questionnaire is explained. Subsequently, the development process is shortly described. This process is depicted in a roadmap in Figure 14.13. This roadmap was already introduced in Chapter 12, but the different steps will be explained in this section. For an elaborate description of this process and the final version of the questionnaire, the reader is referred to Appendix I.

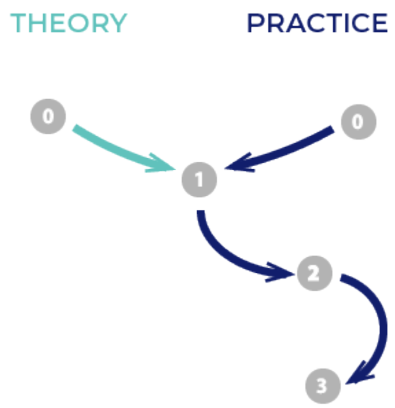


Figure 14.13: Design process questionnaire

14.3.1. Aim of the questionnaire

The first steps in Figure 14.13 correspond to the ones in the development process of the interview protocol. These steps were already explained in Section 14.2.1. In this section it is explained that from an analysis of the system of Sao Tome, it was concluded that a tool based on the simple flood model would have a split user group. The potential users connected to the central institutions in Sao Tome were interviewed. The indirect users, the people living in the different coastal communities, were addressed with a questionnaire. The choice for a questionnaire (instead of for example short interviews with the local people) was mainly a practical one, as the people living in these communities only speak Portugues and the translator was not able to come along during these visits. This choice is represented by the dot numbered 1 in Figure 14.13.

The goal of the questionnaire was to get more information on the perspective of the people living in the coastal communities of São Tomé on the requirements of an early warning system for coastal flood events. As they will be the final users of such an early warning system, their opinion on what information would be useful and when and how they want to receive such a warning, is important for the final design of the tool. Also, the questionnaire is used to gain more insight into the problems in the different coastal communities that are caused by coastal flood events and the actions that could be taken to adress these problems.

14.3.2. Development of the questionnaire

The questions incorporated in the questionnaire were iterated multiple times; this is described in Appendix I. A first version of the questions was made based on the goals set for the questionnaire. Special attention was paid to the fact that most people in these coastal communities did not receive a formal education. Also, most of the people living in these communities have to struggle every day to provide in their basic necessities; as a consequence, these people have a very practical attitute. I was warned in advance by different Deltares employees that visited the island before, that these people find it difficult to answer questions related to something that is abstract to them. Also, they are usually not involved in projects regarding their communities and are not used to give their opinion, so they might be a bit shy to do so. Therefore, it is expected that it is difficult for these people to answer general questions about an early warning system for coastal flood events. To address this difficulty, the questionnaire starts by asking about the last big flood event that the one filling in the questionnaire can recall. The rest of the questions are all related to this flood event. By linking the questions to a flood event that they experience, the aim is to make the questions more concrete and thus more easy to answer.

When a first version of the questionnaire was made, a short feedback session was held with Bram Peerlings,

Figure 14.14: People in different coastal communities filling in the questionnaire

who is also a science communication student. This is represented by the 4th arrow in Figure 14.13. During this feedback session, we discussed the different questions extensively and Bram came up with a lot of feedback and suggestions. Most of the suggestions concerned the reformulation of (parts of) questions. The changes that were made following this feedback session are explained in more detail in Appendix I.

Lastly, the questions were translated into Portugues. The Portuguese version of the questionnaire is also included in Appendix I. The questionnaire was printed and brought along during the different field visits to coastal communities. During the field visits, some of the questionnaires were filled in by the people in the coastal communities themselves. Others, who had difficulties with reading and writing, were read the questions and answered them orally. The people who read the questions to them also wrote down their answers in Portugues. After the fieldtrip, the answers to the questionnaires were translated from Portugues to English.

14.4. Chapter summary

The preparation for the field trip to São Tomé consisted of three different elements, that were developed in parallel: an initial design for the tool interface, an interview protocol and a questionnaire.

An initial design for the tool interface was made in order to make the project and its aim more concrete for the local people on the island during the field trip. The development of the initial tool interface followed different steps. First a short literature research was done to obtain an overview of the different factors influencing the effective use of support tools. Based on this theoretical analysis, 'user friendliness' and 'relevance to the user' were found to be important determinants. In the initial design of the tool interface, the focus was on 'user friendliness'. A first draft of the tool was developed in an interactive session with Alienor de Haan, an industrial designer specialized in user experience and user friendly design of tools and websites. This first draft was further developed and iterated on in a feedback session with two participants with a water background. The final version of the initial design is depicted in Figure 14.6 till 14.11.

In order to address the factor 'relevance to the user' in the design of the tool, it is necessary to understand the context of the potential user(s) of the tool. Therefore, the potential users of the tool must be identified. In the context of Sao Tome and Principe, the user group of the tool would be split in a group of direct and indirect users. The direct users of the tool are people at different central institutions linked to coastal flooding. The indirect users are the people living in the different coastal communities. Since these people do not have access to modern technical devices like a computer or a smartphone, they cannot use the tool themselves. However, they are the ones who should receive the information provided by the tool and act on it. Both user groups were addressed during the field trip.

The potential direct users of the tool are interviewed during the field trip. The aim of these interviews is to obtain insight in the context of the different central institutions related to coastal flooding in Sao Tome and what problems they face (that could be addressed with a tool based on the simple flood model). The interview protocol for these interviews is developed based on insights obtained during an interview with Ilse Nederlof, who did a similar project in Aruba and Curacao as part of her internship. The interview protocol was reflected on and adjusted after every two or three interviews.

The indirect users of the tool are addressed with a questionnaire. The aim of the questionnaire is to get more information about the perspective of the people living in the coastal communities of Sao Tome on the requirements of an early warning system for coastal flood events. The questions were developed with a special focus on the practical attitude of the people living in these communities. The final version of the questions was translated into Portugues, printed and brought along during the field trip. The questionnaire can be found in Appendix I.

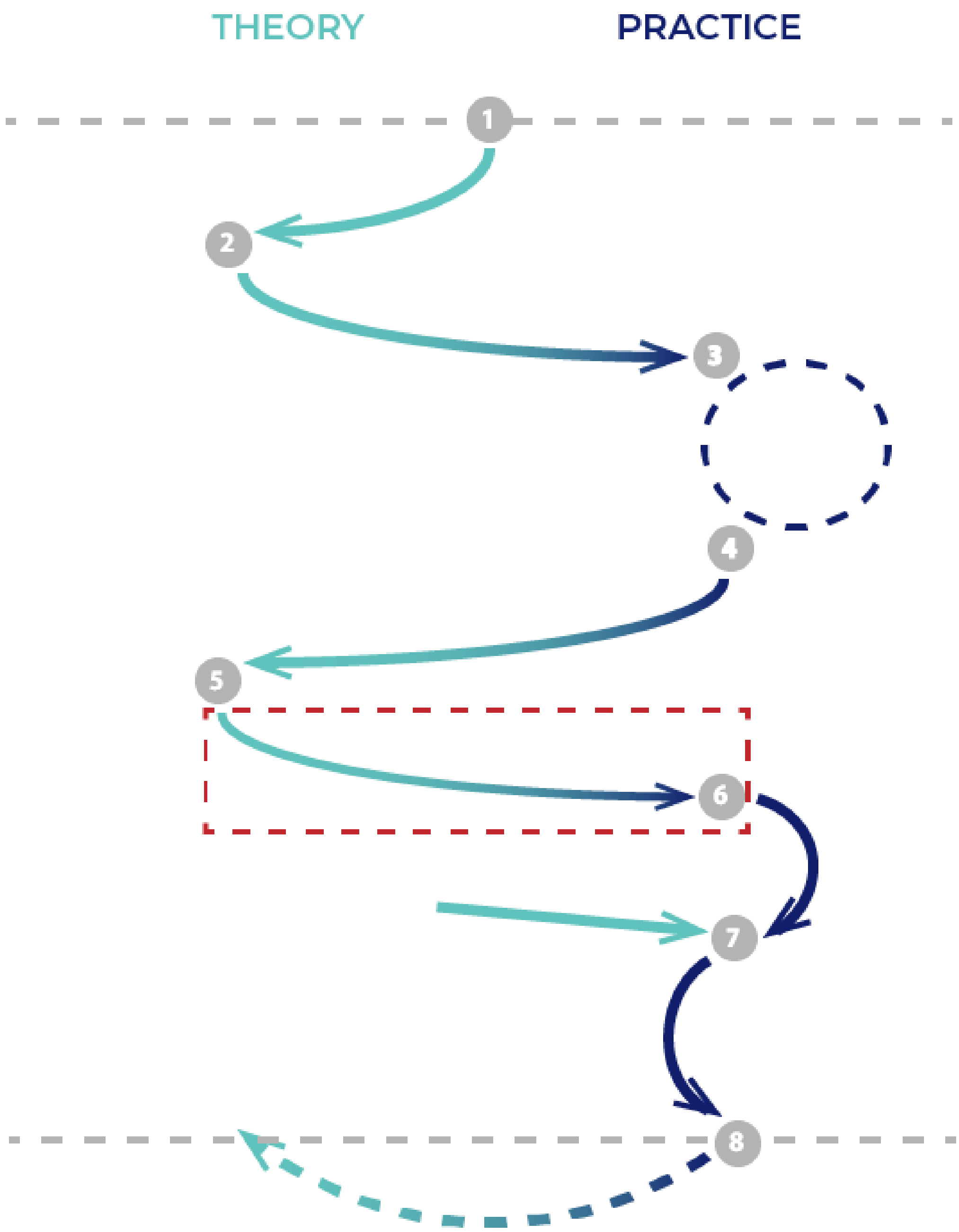


Figure 14.15: System description in the roadmap

15

System description

As indicated in the roadmap in Figure 14.15, in this chapter a description of the system related to coastal flooding in São Tomé is given. In the previous chapter, the preparation for the field trip was described. During the field trip to São Tomé, a lot of information was gathered trough the interviews, the questionnaire and own observations. The observations and insights obtained during the field trip further stirred the development of a theoretical assessment framework for adaptive capacity as described in Chapter 13. Based on all the information obtained during the field trip, the system of São Tomé related to coastal flooding was mapped using the newly developed theoretical framework. The results of this mapping exercise are presented and explained in this chapter.

In the first section, the approach and methods related to this system analysis are shortly described. In Section 15.2, a description of the most important actors related to coastal flood events and their context is given. The context of each of these actors is mapped using the theoretical assessment framework developed in Chapter 13. After these descriptions, the maps of the different actors are merged together to give an overview of the entire system related to coastal flooding in São Tomé. This is described in Section 15.3.

Subsequently, an overview of the barriers to adaptive capacity is given in Section 15.4. In Section 15.5, some observations from the mapping exercise are pointed out and used to reflect on the theoretical framework. Lastly, a summary of this chapter is given in Section 15.6.

15.1. Approach and methods

The system analysis for São Tomé is based both on semi-structured interviews with important actors in the system and on a questionnaire filled in by people living in different coastal communities. The development of the interview protocol and the questionnaire were described in the previous chapter. The inital list of important actors was made based on suggestions from Luisa, a Deltares employee who joined the previous field trip to the island. During the field trip some actors were added to this list. Eventually, 7 different actors were interviewed:

- **MIRNA:** the ministery of infrastructure, natural resources and environment
- **INM:** the national institute of meteorology
- **National institute of natural resources:** this institute is among others responsible for many river-related matters.
- **CONPREC:** a seperate part of the government which is responsible for disaster preparation and response, both in São Tomé and Principe.
- **MARAPA:** an NGO working with and for fishermen in different coastal communities both in São Tomé and Principe
- **PNUD:** the São Tomése department of the UNDP (i.e. Unitied Nations Development Program)
- **Observatoire:** a seperate department of the government responsible for the development of a national online information platform and a virtual library.

During the field trip, 20 people (living in 6 different coastal communities) filled in the questionnaire. The results of the questionnaire can be found in Appendix I. The interviews were all transcribed; as an example, the transcription of the interview with CONPREC is included in Appendix J.

The system analysis was done in 3 steps. In the first step, the context for the different actors was mapped for each actor seperately. In order to do this, the transcriptions of the different interviews were used to identify the actors that are relevant in the context of each actor, the interactions and the resources. In order to obtain this information from the different interviews, the method of concept coding was applied. According to (Saldana, 2016), this coding method can be applied to extract and label 'big picture' ideas or concepts suggested by the data. A concept is a word or phrase that symbolically represents a suggested meaning broader than a single item or action. The three concepts that were used are 'actors', 'interactions' and 'resources'; these concepts were taken from the theoretical framework described in Chapter 13. Also, the barriers that were mentioned during the interviews were listed. In Appendix J, an example of this analysis is included for CONPREC.

In the second step, the different individual actor maps were merged in order to obtain an overview of the entire system of São Tomé. This map is slightly simplified compared to the individual actor maps. The last step consisted of creating a barrier map; a map in which all barriers that were identified in the individual mapping exercises are combined in the map for São Tomé. In Figure 15.1, an overview of all actors included in the eventual map are depicted.

15.2. System description

In this section, the different actors that were interviewed during the field trip will first be discussed seperately. For each of these actors, their context will be mapped following the theoretical assessment framework described in Chapter 13. All actors that were interviewed are included in this analysis, except the national institute of natural resources. This actor is not included because during the interview they explained that they are only responsible for river-related flooding and are not working on coastal flooding.

For each of these actors, a visual schematization of their context is included. The different elements from these maps (i.e. actors, interactions and resources) will be discussed. For every actor, first the different actors in their network and the interactions with these actors will be described. Subsequently, the resources of this actor will be discussed. In the description of the actors, interactions and resources of each actor, the barriers that this actor experiences are also explained. At the end of each section, a short summary of these barriers is included.

In order to already get an idea of the actors that are related to coastal flood events in the system of São Tomé, an overview of these actors is depicted in Figure 15.1. The actors that were interviewed are indicated with a dotted circle. The subsequent sections will focus on these actors.

15.2.1. Ministério das Infraestruturas, Recursos Naturais e Ambiente - MIRNA

The Ministério das Infraestructuras, Recursos Naturais e Ambiente (Ministry of Infrastructure, Natural Resources and Environment) or MIRNA is divided in three departments: the department of infrastructure, the department of natural resources and the department of environment (see Figure 15.2). Of these three departments, the Direcção Geral do Ambiente (department of environment) or DGA is the most involved in coastal flood matters. According to Arlindo de Ceita Cavalho, the general director of the DGA, this department is not directly involved in coastal flood matters. The main function of the DGA (in relation to coastal flooding matters) is to supervise and coordinate the different projects and studies related to coastal flooding (and environment in general) that are carried out by different actors. In this context, the DGA communicates a.o. with CONPREC (see Section 15.2.4), MARAPA (see Section 15.2.5), the national institute of meteorology (INM, see Section 15.2.3), the Observatoire (see Section 15.2.2), the coast guard and different local governments. It is their task to have an overview of the things that are done in relation to coastal flooding, to make sure that the important matters are being addressed and that their is no unneeded overlap in the actions carried out by different actors. They are supported in this task by PNUD, who is also responsible for coordination between the different projects and studies (see Section 15.2.6).

Arlindo explained that most of these projects and studies are carried out within the framework of the WACA project [West African Coastal Areas] [1]. The WACA project is a project funded by the World Bank that aims to

[1]http://www.worldbank.org/en/programs/west-africa-coastal-areas-management-program

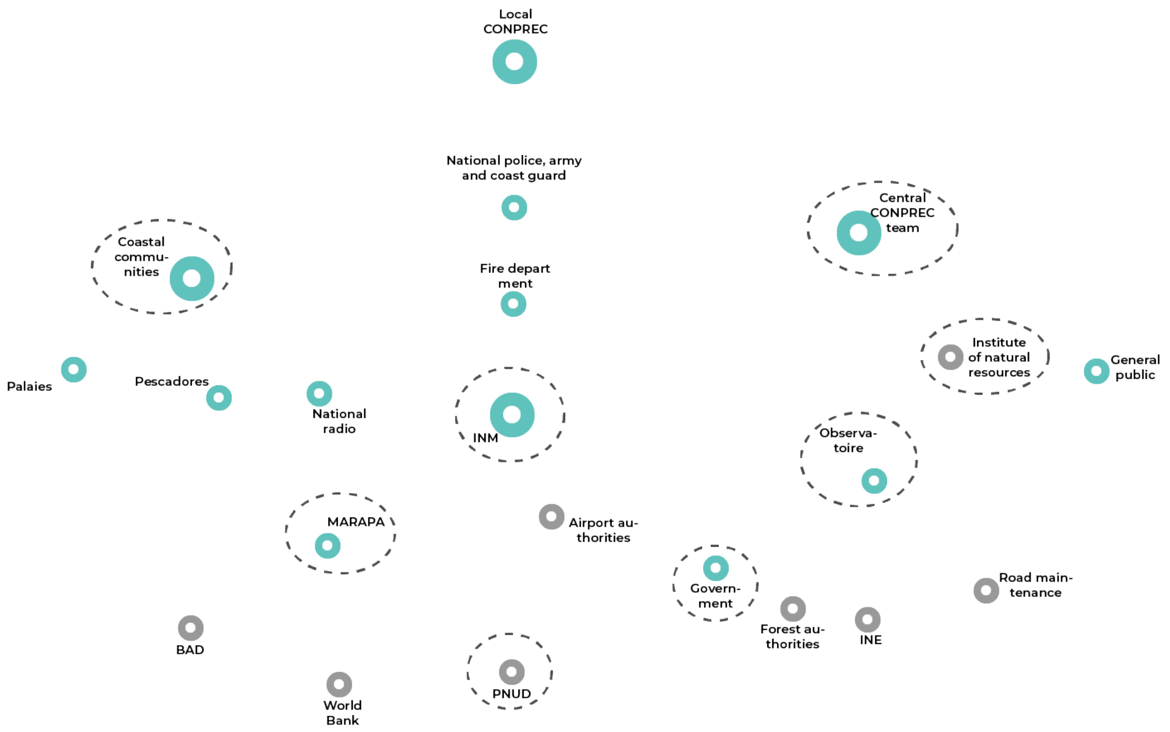


Figure 15.1: Overview of the actors

help West African countries to sustainably manage their coastal areas, especially considering the effects of climate change. They aim to help these countries in getting excess to the expertise and finance they need. A special focus of the project is the prevention and management of coastal erosion and flooding.

Since the DGA is not directly involved in the protection against and preparation for coastal flooding, I choose not to make a map for this actor. However in the other maps, this actor is incorporated.

15.2.2. Observatoire

Actors and interactions

In Section 15.2.1, the ministry of infrastructure, natural resources and environment was introduced. As described above, this ministry is subdivided in three departments: the department of infrastructure, the department of natural resources and the department of environment. Of these three departments, the department of environment (Direçao Geral do Ambiente, or DGA) is most involved in coastal flood matters. This department is again subdivided in three departments, among which the department of statistics and environmental education and communication (Direção de Estatística, Informação, Educação e Communicação Ambiental, or DEIECA). The observatoire is part of this department and is directly supervised by the DGA. It was founded in 2011, as part of the WACA project. According to Abnilde, who works at the observatoire, the main functions of the observatoire are to gather, analyse and store information related to climate change effects. They further aim to make this information available to everybody, by developing a virtual library [2] and an online information platform [3]. Abnilde is currently working at the

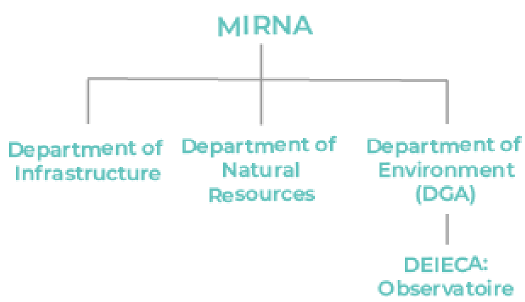


Figure 15.2: Observatoire in the organogram of MIRNA

[2] http://dga.st/pt/dga/work
[3] http://www.hudd.com.br:8080/

observatoire and is specialized in geographical information; a.o. he is responsible for updating the DEM of São Tomé and providing geographical information to others for specialized analyses (e.g. the calculation of river flows and water levels).

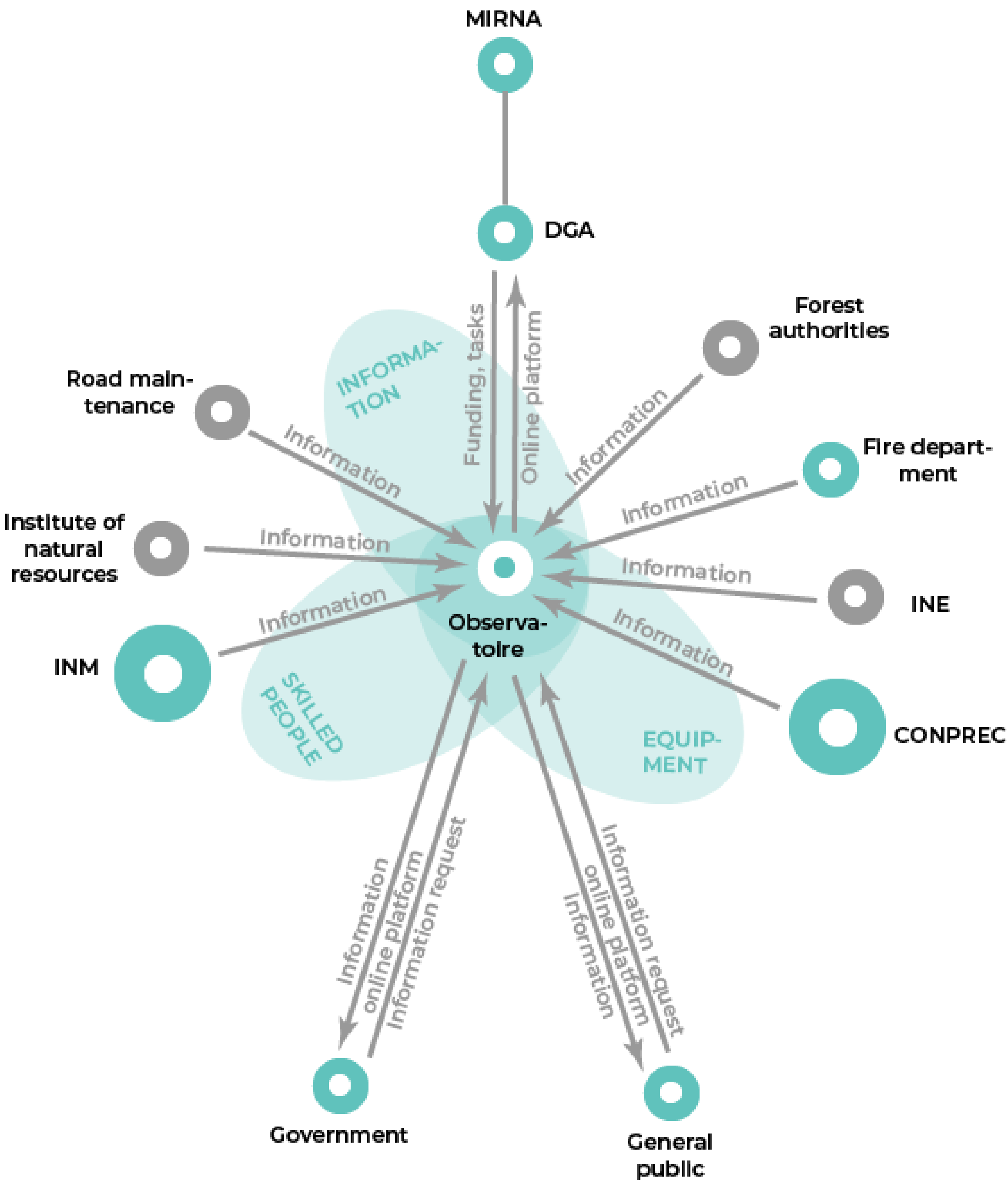


Figure 15.3: Observatoire (part of the department of environment)

During the interview, Abnilde explained that the observatoire was founded back in 2011 based on a need for a central information center. Abnilde: 'Back then, it was very difficult to get information. Many people went to the different institutions, but the institutions did not provide information. I myself was a victim of this. For my final project back in school, I wanted to write about São Tomé, but there was no information available'. Back then, the different institutions gathered their own data, but these data were not shared with others. This caused many problems, for example because local governments lacked essential information (e.g. information on which areas should not be build because there is large risk of flooding) and subsequently their actions did not always turn out to be effective. The observatoire tries to address this problem.

The team that works at the observatoire currently consists of 12 people. 3 of them are working full-time for the observatoire. The other members are working parttime and are also employed at different institutions in São Tomé. Abnilde explained that this works very well, because in that way it is much easier to gather the information from the different institutions; these parttime employees of the observatoire function as the contact points at the different institutions. He also explained that these members frequently work at the observatoire as well, but this is mostly project-related. For example, if the observatoire is working on an analysis of the rivers, the person working at the national institute of natural resources (this institute is responsible for measurements related to rivers) comes to the office and works on that.

The observatoire gathers data from different institutions in São Tomé and Principe. Abnilde explained that they receive information from the forest authorities, the fire department, the organization for road maintenance, the national institute of natural resources, the national institute of meteorology (INM), CONPREC and the national institute of statistics (Instituto Nacional de Estatística, or INE). This is depicted in Figure 15.3. We will see in the remainder of this chapter that the INM, CONPREC and the fire department are directly involved in coastal flood matters. The other institutions are not; therefore these actors are grey in the figure. The information that is gathered by the observatoire is made public in two ways: via a virtual library and via an online information platform. The aim of the virtual library is to create one (online) location where all reports and studies from the different institutions can be found. The online information platform focuses mainly on visualising disaster information. Currently, there are three main items on the platform:

- **A register that aims to incorporate all historic disaster events in São Tomé and Principe:** whenever a disaster event occurs, the local authorities report this to the observatoire and they include it in the database. In the database, the location and nature of the disaster (e.g. a fire or a flood event) are entered.
- **Exposure data:** the observatoire included different maps showing how the land occupation (i.e. builded area) changed over the last decades.
- **Maps that indicate which areas are vulnerable to river flood events:** the observatoire included maps that show the areas affected by river flood events in the past. They also included maps visualizing predictions for the future.

According to Abnilde, the main users of the virtual library and the online information platform are students and local authorities. He also explained that currently not all information is available via the library and/or the platform. Whenever people are trying to find something that is not yet available, they can send an information request to the observatoire. The team of the observatoire will then try to get this information and make it available.

Resources

During the interview, Abnilde mentioned three main types of resources that the observatoire needs in order to carry out their main functions: information, equipment and skilled people.

The observatoire gathers and combines information from many different institutions. Abnilde explained that the information that they gather is not always accurate or complete. For example, he thinks that the disaster information that they obtain from the local authorities (for the disaster event register on the online platform) is not always complete. Also, some information is lacking completely. Abnilde explained that they currently do not have any information on areas that are susceptible to flooding from the sea. They would like to have this information and include it in the online platform, but none of the institutions currently provides this information and they do not have a way to calculate it themselves.

Other important resources are equipment and skilled people. The equipment that they need mainly consists of computers; the observatoire does not have its own measurement equipment. According to Abnilde, there are no major problems regarding these two resources. He explained that it would be nice to have a bigger office with more working space, so that they could work there with more people at the same time. But the current resources are sufficient to carry out their tasks.

In contrast to the other actors described in this section, money is not a resource held by the observatoire. They receive their equipment and salaries directly from the DGA and in that sense do not have to manage their own budget.

In summary, we can conclude that for the observatoire the most important barrier is related to the resource 'information'. This is related both to the quality and quantity of information; the information that they receive is not always accurate and some information is completely lacking.

15.2.3. Instituto Nacional de Meteorologia

Actors and interactions

The main function of the Instituto Nacional de Meteorologia (INM), or national institute of meteorology, has shifted over the years. According to Aristómenes Nascimento, the general director of the institute, the main function of the institute used to be to provide weather information and forecasts to the public. Now their function is mainly to provide weather forecasts and information to the airport authorities. The institute is currently located next to the airport, and maintains close contact with the airport authorities to decide whether or not it is save for planes to land and/or depart. This is especially important during the rain seasons[4], when strong winds can occur. This interaction between INM and the airport authorities is depicted in Figure 15.5. Since the airport authorities are not involved in coastal flooding, this actor is grey in the figure.

Figure 15.4: Aristómenes Nascimento, general director of the INM

The communication of weather forecasts and information to the public happens now only indirectly, via national radio and via CONPREC. As we will see in Section 15.2.4, CONPREC is part of the government and is responsible for disaster preparation and response; this includes disasters caused by coastal flooding. INM maintains daily contact with the central organisation of CONPREC over email. This communication is usually one-sided: INM sends the weather forecast to CONPREC over email. CONPREC then puts this weather forecast on their central website, which can be accessed by everyone and thus provides weather information and forecasts to the public. These interactions are also depicted in Figure 15.5.

The meteorologists working at the meteorological institute also access whether a storm is coming up that might pose a risk. If this is the case, they tell CONPREC to send out a warning. The decision to send out a warning is thus usually made by the INM, not by CONPREC itself. CONPREC then further communicates this to the public (e.g. the people living in the coastal communities). This is further elaborated on in Section 15.2.4.

Since the weather in São Tomé and Principe can change very quickly, it happens sometimes that the weather forecast sent to CONPREC becomes outdated and a storm is coming up which was not predicted before. In that case, the INM of course notifies CONPREC, but they also communicate this to the national radio. The national radio then broadcasts a warning to notify the public on the upcoming storm. Normally, CONPREC would tell the national radio to broadcast a warning when a storm is predicted, but this procedure is shortcut

[4]Sao Tome and Principe have two rain periods per year: in March/April and October/November.

in case a storm is coming up which was not predicted before. According to Aristómenes, this procedure is quite effective, since many people in São Tomé and Principe listen to the radio. In the future, they want to broadcast these warnings via the national television (TVS) as well (depicted in Figure 15.5 by a dotted line). However, currently the amount of people listening to the radio strongly outnumbers the amount of people watching television. This is especially true for the people living in the different coastal communities, for whom the storm warnings are very important.

As was stated above, the main function of the INM used to be to provide weather information and forecasts to the public. Aristómenes became general director of the institute only a few months ago, but remembers that the institute used to have their own website on which they published the weather forecast. Also, the institute used to maintain a 'linha verde' (green line); a free telephone line that fishermen from all over the country could use to call the institute and ask for the weather forecast. Based on these predictions, the fishermen made their decision whether or not to go out to sea to go fishing. A few years ago, the budget of the institute was cut and this line was closed (indicated with a red line in Figure 15.5). The closure of the linha verde is considered a big problem by the INM. Aristómenes: 'The shut-down of the website is not so bad, because our website is replaced by CONPREC. But the closure of the green line is a problem, because there is no replacement'. Aristómenes is currently trying to negotiate extra budget from the government to open the line again.

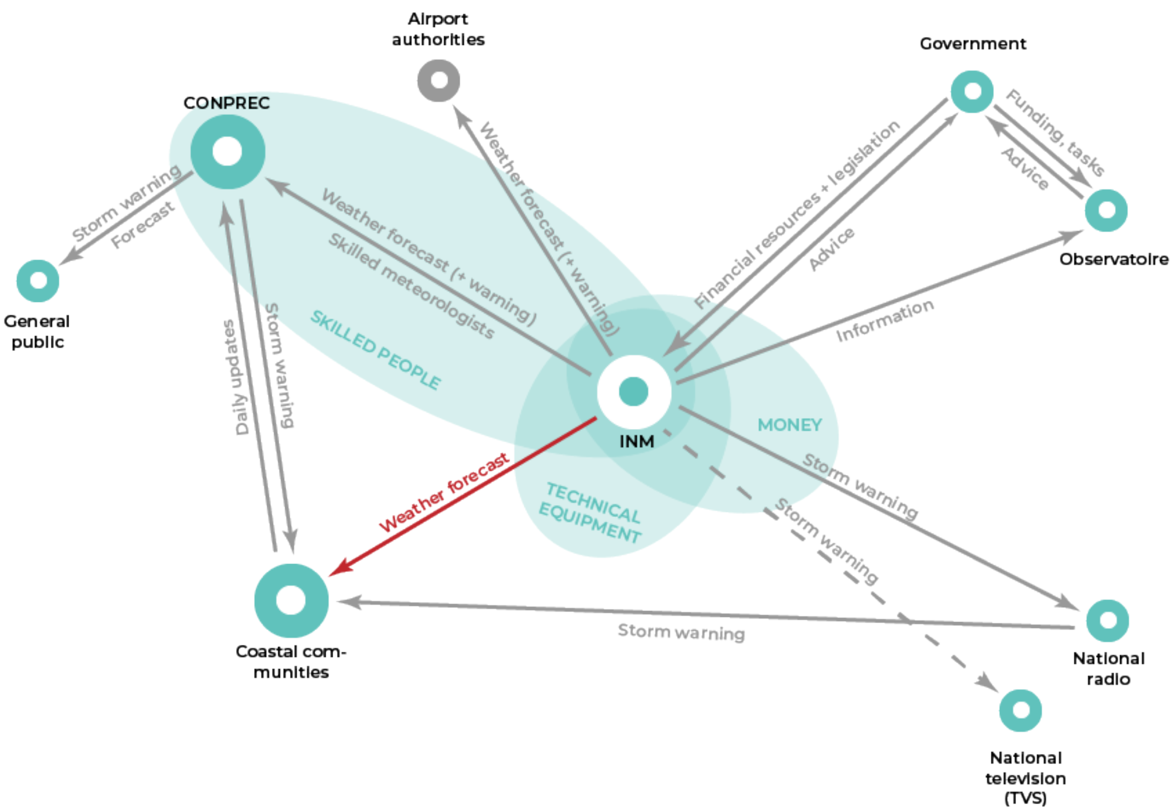


Figure 15.5: National institute of meteorology

According to Aristómenes, it is not so easy to secure enough financial resources for the activities that the institute wants to perform. Eventually, it is up to the government to decide on the tasks of the INM. The government decides on the legislation, in which it is stated what the tasks of the different institutions are, and needs to divide the available financial resources among the institutions. Aristómenes: 'We give advice on what would be useful, because we have more specific knowledge. But in the end, it is up to government to decide. Off course it also depends on the money that is available'. This is also depicted in Figure 15.5. In this figure, it can be seen that the interaction between the INM and the government is two-way. However, the arrow towards the government is smaller, since this interaction is less influential than the interaction in the other direction (i.e. from the government towards the INM). Lastly, the INM also provides a specific part of the government with information: the observatoire. As was described in Section 15.2.2, this department of the government is responsible for creating a national online information platform.

Resources

Financial resources are very important for the INM. During the interview, Aristómenes mentioned several times that some activities were stopped or hampered because of a lack of financial resources (e.g. closing down of the green line). A lack of financial resources can also cause a lack in other resource types. For the INM, two other important resources are technical equipment and skilled people.

Skilled people are an important resource for the INM. Currently, they have a shortage of skilled staff. There are 18 people working for the INM. Of these 18 people there are only 4 meteorologists and from those 4 meteorologists, there is only one specialist (Aristómenes himself). The other 3 meteorologists learned the basics in São Tomé, but to become a specialist you need to follow a course abroad. According to Aristómenes this shortage of skilled people has a large influence on the ability of the institute to provide accurate weather predictions. He explained that the measurements come in 24 hours per day, but these measurements need to be evaluated. This process is not automatic and requires skilled people (i.e. meteorologists). They do not have enough people to watch these measurements 24 hours a day, so this only happens when people are at the office. As the weather can change very quickly in São Tomé, this affects the accuracy of their weather forecast. In order to solve this issue, they would need at least 8 meteorologists at the institute. However, they do not have enough budget to hire and/or educate more people. Aristómenes explained that the education of a meteorologist is expensive, especially because they have to receive part of their training abroad.

Aristómenes explained that the shortage of people was also partly caused by the fact that some meteorologists started working somewhere else. For example, he mentioned that CONPREC has a fulltime meteorologist in their central team, who used to work at the INM. Also, the general director of CONPREC mentioned that in case of a big storm event coming up, sometimes one of the meteorologists working at the INM temporarily joins the CONPREC team.

The weather predictions done by the INM include information and predictions regarding the rainfall, the wind, the temperature and the water levels. In order to analyse these things, they make use of different measurement stations and models. There are automatic measurement stations scattered across the island, that measure every hour for 24 hours per day. Furthermore, there is one marine measurement station located close to the airport. With this measurement station they can normally measure the water levels and the waves, but currently the device measuring the waves is broken. But even when it was operational in the past, according to Aristómenes the device did not always give realistic values. They want to install more marine measurement stations in the future, but this is difficult because of a lack of financial resources and skilled people. Aristómenes explained that in case they want to install more measurement stations, they also need to hire and train more specialized technicians that can work with the equipment in these measurement stations. They hope they can realize this in the context of one of the WACA (West African Climate Adaptation) projects.

Furthermore, they currently use a global model to predict the weather forecast. According to Aristómenes, this global model is a good model, but it does not always provide accurate information for São Tomé, because it is such a small island. By combining information from the global model, local measurements and experience with the local climate of São Tomé and Principe, they come up with their weather forecasts. However, a more accurate local model would improve their predictions. Furthermore they currently do not have a coastal model to make predictions on water levels and waves, or to assess whether a certain area will be flooded or not.

These three resource types, financial resources, technical equipment and skilled people, are all included in Figure 15.5. The resource skilled people is shared with CONPREC.

In summary, we can conclude that the INM experiences multiple barriers that limit their functions in relation to coastal flood events:

- **No direct contact with the communities** - Currently, there is no direct contact between the INM and the coastal communities. There used to be a free telephone line for the fishermen to call to the INM, but due to a lack of financial resources, this line was shut down a few years ago.
- **Financial resources** - It is difficult to secure enough budget to carry out their tasks in a proper way.
- **Skilled people** - Currently, the INM does not have enough skilled people (i.e. meteorologists and technicians). It is difficult to hire and/or educate more people, a.o. because of a lack of financial resources.
- **Technical equipment** - The INM would like to have more marine measurement stations, but this is difficult to realize (a.o. due to a lack of financial resources and skilled people). Furthermore, they would like to have more accurate, local models for weather prediction. Lastly, they currently do not have a model to calculate coastal flooding.

15.2.4. Conselho Nacional de Preparação e Resposta às Catástofes - CONPREC

Actors and interactions

The Conselho Nacional de Preparação e Resposta às Catástofes, or CONPREC, is an organ from the government. According to Carlos Diaz, the national coordinator of CONPREC, the aim of the organisation is to organize the preparation and response to disasters in São Tomé and Principe. This entails a wide range of possible disasters, including both natural (e.g. flooding from the river or the sea) and social disasters (e.g. an outbreak of violence). According to Carlos Diaz, CONPREC deals with 'everything that changes the normal livelihoods in the communities'. Although the focus of CONPREC is wider than coastal flooding alone, the remainder of this section will focus on coastal flood events.

Figure 15.6: Carlos Diaz, national coordinator of CONPREC

The work of CONPREC started in 2009, when the organisation was set up with help from PNUD (see Section 15.2.6). In April 2010, the government of São Tomé and Principe established a preparatory committee for CONPREC with the task to develop a Disaster Contingency Plan and a National Disaster Strategy Plan. On 24 May 2012, CONPREC was officially established. The organisation has been growing ever since and currently entails about 280 people.

The organisation of CONPREC is split in a central team and local CONPREC members living in different communities (both coastal and inland). The central team consists of representatives from different ministries and organisations:

- Ministry of health
- Ministry of foreign affairs
- Ministry of spatial planning
- Ministry of defense and internal order
- Ministry of infrastructure, natural resources and environment (MIRNA)
- Ministry of agriculture

- Ministry of civil protection
- Fire department
- Coast guard
- Army
- National police
- National institute of meteorology (INM)

From each of these ministries and institutions a representative was chosen to join the central team. This is also indicated in Figure 15.7. Not all of these representatives are fully employed by CONPREC; most of them still work at their respective ministry or institution and are called upon when needed. However there are also fulltime members of the team, mostly technicians and coordinators. There is one meteorologist who is now working fulltime for CONPREC; he used to work for the INM (see Section 15.2.3).

In addition to this central team, CONPREC works with local people in 31 different communities (both in São Tomé and in Principe). In each of the communities where CONPREC is active they have 8 to 10 local members, depending on the size of the community. In total, there are currently 254 local CONPREC members, of whom 78 are women. In principle, these local CONPREC members are volunteers. However, sometimes they receive a small amount of money for the organizations of special activities (e.g. a sensitizing meeting for the entire community; this will be explained below). The local CONPREC members in these communities are chosen by the people in their respective communities, in cooperation with the central CONPREC team. Usually, members of the central CONPREC team visit a community to explain the aim of the organisation and ask the local people to become a member. Subsequently, from the group that would like to volunteer, 8 to 10 people are chosen by the local community. It is important that the local members are trusted by the rest of the community and have a certain authority. Therefore, these local CONPREC members are often people that also fulfill other important social roles in the community, for example the leader of the fishermen, the leader of the palaies (the women who sell the fish) or the leader of the community. Furthemore, it is important that the team of local CONPREC members is able to communicate information to a large part of the community quickly. Therefore, the group of local CONPREC members is often quite diverse, incorporating women, fishermen and youth leaders. For each community, two of the CONPREC members are chosen to be the local contact persons with CONPREC. There are two instead of one to make sure there is always someone available to get in contact with CONPREC.

When the local CONPREC members are chosen by the community, the team is taken to the main capital to receive a 3 days-training. This training is given by members from the central CONPREC team and consists of three different elements. The first part consists of an explanation of the risks to which the community can be exposed (e.g. coastal flooding, river flooding, strong winds, fire, social risks etc). In addition to this, it is explained which actions can increase these risks (e.g. building too close to the sea or river, extracting sand from the beach, building the kitchens too close to the houses etc). The idea is that the local CONPREC members pass this information on to the rest of the community, so that the people in the communities can change their practices if needed. Eventually, this should lead to safer conditions in the different communities. The second part of the training covers the response to disasters: what should be done in case of an emergency? In this part, the local CONPREC members must think about what to do in case of an emergency in their specific community and develop an emergency plan (e.g. which evacuation routes can be used?). An important part of this plan is the identification of vulnerable people in the community that should get extra attention in case of an emergency. Lastly, the local CONPREC members are trained in practical skills. They learn how to work with different communication devices (e.g. radio, telephone) and how they should get in contact with CONPREC or other institutions like the police or the coast guard. Lastly, they also learn how to rescue people from the water. The local CONPREC members receive this training every year; the emergency plan for the communities is also updated every year.

The central CONPREC team stays in close contact with the different coastal communities. This happens in two ways: via daily updates from the different communities and via sensitizing trainings in the different communities. The local CONPREC members are asked to provide the central CONPREC team with daily

Figure 15.7: CONPREC

updates on their communities. CONPREC subsequently communicates these daily updates to the coast guard and the fire department. Based on these daily updates, the central CONPREC team makes monthly reports for every community to keep track of the activities and problems in the different communities. Furthermore, in every community the central CONPREC team organizes sensitization trainings a few times a year. For these sensitization trainings, the local CONPREC members are asked to arrange a location and call upon the people in their community to attend the session. During these sessions, the central CONPREC team tries to build awareness on the different risks in the community and explain to them how these risks can be reduced (e.g. by planting trees on the beach and stop extracting sand from the beach).

Apart from the daily updates and sensitizing trainings, CONPREC is closely involved in case of a storm event or another emergency. As was explained in Section 15.2.3, the meteorological institute (INM) provides CONPREC with a weather forecast everyday. They also warn them in case a storm is coming and CONPREC should send out a warning. Apart from information from the INM, CONPREC also receives information from the institute of natural resources and environment. This institute is in charge of all information related to the different rivers in São Tomé and Principe. There are different hydrological measurement stations scattered over the different rivers. The data measured by these stations are send to the institute's data center. Based on these measurements and different models, the institute aims to monitor and predict the water levels in the rivers. In case these water levels are high and can lead to flooding, this information is sent to CONPREC. This usually occurs simultaneously with storm warnings from the INM. In case the INM sends out a storm warning to CONPREC or the institute of natural resources and environment warns CONPREC on high river levels, subsequently CONPREC sends out this warning to different actors via different communication channels (see Figure 15.7):

- **The general public:** CONPREC sends out warnings over the national radio to the general public. Also, people can indicate whether they want to receive a warning via SMS or email.
- **Local CONPREC members:** CONPREC communicates the warning to the communities for which the warning is relevant (and where CONPREC is active). They communicate this warning to the local contact persons, usually over telephone. These local CONPREC members subsequently communicate the information to the rest of the community. In order to do this quickly, each local CONPREC team received a megaphone from the central CONPREC team.
- **Coast guard and fishermen:** CONPREC sends out a warning over a special radio channel that is received both by the coast guard and by fishermen (i.e. by fishermen that own a special radio which can receive this channel. These radios are a.o. provided by MARAPA, see Section 15.2.5).
- **Coast guard, national police, army and fire department:** CONPREC also sends out a warning over another radio channel that is received by the coast guard, the national police, the army and the fire department. So, the coast guard receives a double warning.

It should be noted that although all these institutions receive a warning in case of an emergency, this first warning is mainly meant to alert them. In case action from one or more of these institutions is required, there will be additional communication between CONPREC and the institution(s) concerned. Whether additional help is required and from which institution(s), is based on communication between the local CONPREC members in the different communities and the central CONPREC team.

Sometimes, CONPREC is not able to send out a warning to the communities in time. This can have different reasons, which will be discussed below under resources. In that case, the local CONPREC members alert the central CONPREC team on the situation and can also ask for help directly to the different civil protection institutions (i.e. the national police, the fire department, the army and the coast guard). In order to do this, all local CONPREC teams have a communication radio (for communication with the central CONPEC team, the army, the fire department and the national police) and a marine telephone (for communication with the coast guard).

Resources

From an interview with Carlos Diaz, the national coordinator of CONPREC, the five most important resources for CONPREC were identified. These resources are technical equipment, authority, information, skilled people and financial resources. Each of these resources is indicated in Figure 15.7 and will be shortly discussed below.

As for most institutions in São Tomé and Principe, financial resources are very important. Carlos mentioned during the interview that it is difficult to secure enough money to carry out all the required activities. Furthermore, this lack of financial resources also influences other resources that are important to the organisation: skilled people and technical equipment. During the interview, Carlos explained that it is difficult to involve more communities in the organization, because they do not have enough money to hire or educate more people, to buy more communication devices, to train more local people etc.

The technical equipment that CONPREC needs consists mostly of communication devices and calculation models. The communication devices are very important to keep in contact with the different local CONPREC teams and civil protection institutions. Carlos mentioned that even though all local CONPREC teams receive communication radios and telephones, communication is not always possible, for example because of electricity problems (especially during storms, electricity is frequently down). Also, the batteries in the communication devices can be down; in that case they need to be recharged, which does not always happen immediately. These practical issues can hamper the communication with the communities. The communication devices are important both for the central CONPREC team and the local CONPREC teams; this is also indicated in Figure 15.7.

Apart from communication devices, CONPREC makes use of some simple calculation models to calculate the water levels in the rivers. Carlos explained that calculating these water levels is officially the task of the institute of natural resources and environment. The institute uses more advanced models in combination with rainfall and water level measurements. However, this is not an automatic process and requires skilled people. Because of a lack of skilled people at the institute, there is not always enough capacity to do these calculations. Therefore, CONPREC asked to send the rainfall and water level measurements directly to the operational centre of the central CONPREC team. Here, they use a less advanced (and less accurate) model to get an indication of the water levels in the rivers. This is not an ideal situation and they are currently trying to educate more people at the institute of natural resources and environment to improve this process. Furthermore, CONPREC does not have models to calculate the areas affected by coastal flooding. Also the INM, who is responsible for marine information, does not have these models.

Skilled people are also an important resource for CONPREC. This relates both to the people in the central CONPREC team and in the local CONPREC teams. Carlos mentioned that CONPREC would like to grow and involve other communities as well. However, currently the central CONPREC team does not have enough capacity to do that. Carlos: 'The problem is the support. How should we support that? We need more people'.

Another important resource for the central CONPREC team is information. In Section 15.2.3 it is described that the central CONPREC team receives the weather forecast and storm warnings from the INM. However, this information is not always accurate. The causes of this inaccuracy in the weather forecast are explained in Section 15.2.3. The central CONPREC team receives information on the rivers from the institute of natural resources and environment. As described above, this information is not always accurate and/or in time. Furhtermore, the central CONPREC team receives information on a daily basis from the different communities. This communication is usually very accurate. However, sometimes no daily updates are given because of problems with the communication devices from the local CONPREC teams.

Authority is also important for CONPREC. As was described above, it is important that local CONPREC members have a certain authority in their respective communities. People need to listen to them, especially in case of emergency. Authority is also important for the central CONPREC team. People (both the general public and the people in the different communities) need to listen to them when they send out a warning and act on this warning. Futhermore, it is important that people in the different communities listen to them during the sensitizing trainings and act on the information that they give. According to Carlos, this is especially difficult. It can be very difficult to convince the people in the communities to listen to them, especially if that means they have to change their daily practices. Carlos described an example of a sensitizing training where they were telling the people which areas are most at risk (i.e. the areas close to the river and the sea) and should thus not be build. Carlos: 'So, you are telling them that this is a risk area, but where will they go? There is no space. So, it means they are still building on this risk area. This is the challenge'.

In Figure 15.7, the different resources are mapped. The resources technical equipment and authority are important both for the central CONPREC team and the local CONPREC members.

In summary, we can conclude that CONPREC experiences multiple barriers that limit their functions in relation to coastal flood events:

- **Contact with the local CONPREC members** - It can be difficult to get in contact with the local CONPREC members in the different communities, due to practical issues with the communication devices.
- **Financial resources** - As for most organisations in São Tomé, it is difficult to secure enough budget to carry out their tasks in a proper way.
- **Skilled people** - CONPREC is currently active in 31 communities, but they would like to extent to other communities as well. However, they do not have enough skilled people to do this. This is partly caused by a lack of financial resources.
- **Technical equipment** - The most important equipment for CONPREC consists of communication devices. Currently they do not have enough budget to buy more equipment, which would be needed to extent the organisation to other communities.
- **Information** - The information that CONPREC receives from the INM and the institute of natural resources is not always accurate and/or timely. This seriously hampers CONPREC, because then they cannot provide the different communities with this information.
- **Authority** - It is often difficult for CONPREC to make the people in the coastal communities listen to them and act on the information that they give them. This does not only have to do with authority; this is further elaborated in Section 15.2.7.

15.2.5. MAR Ambiente e Pesca Artesanal - MARAPA

Actors and interactions

In Figure 15.9, the context of MARAPA is mapped. MAR Ambiente e Pesca Artesanal, or MARAPA, is a non-governmental organisation (NGO) in São Tomé and Principe. According to Manuel Jorge de Carvalho do Rio, the operational director of MARAPA, the aim of the organisation is to improve the living conditions in the country's coastal communities. Manuel explained that artisanal fisheries are very important to the country, since the fishing sector directly or indirectly provides a living for almost 25 % of the national population. Even though this sector is so omnipresent at the island, in general it is poorly organized. MARAPA was founded in March 1999 and the NGO is currently active in 23 fishing communities, both in São Tomé and Principe. The organisation currently has a staff of 18 permanent workers, including 6 technicians. They aim to support the fishing sector of the country. In order to do so, MARAPA focuses on two main objectives: environmental protection and support of artisanal fisheries. Both objectives entail a wide range of actions and projects.

Figure 15.8: Manuel Jorge de Carvalho do Rio, operational director of MARAPA

Regarding environmental protection, the main focus is on the protection of sea turtles. Manuel explained that São Tomé and Principe is an important breeding and feeding area for five of the seven species of sea turtles in the world. However, many fishermen on the islands used to hunt on the sea turtles for food and to make all kinds of objects from their shields. This unregulated capture has affected the populations of these endangered species. In order to protect the sea turtles, in 2003 MARAPA started 'Programa Tatô'. Over the years, this programme became so big that it grew into an independent NGO, of which MARAPA is a founding member [5]. The main focus of this progamme/NGO is to create awareness among the people on the island

[5] https://www.programatato.org

and commitment to the protection of the turtles. A few years ago, a law was created that prohibits the capture and hunting of turtles. Under Programa Tatô, a team was set-up that aims to develop awareness, mainly in the coastal communities, so that they will comply with these laws. The team organizes education activities and together with the people in the coastal communities try to generate alternative livelihoods. Also, they set up a network that monitores the female turtles that nest on the island and the turles that feed in the waters off the island. This network consists of people from the different coastal communities. During the breeding season, these people are paid a small fee to stand watch at night and make sure no one tries to capture the turtles. The team linked to this NGO, including all trainees, technicians and field guards (i.e. people from different coastal communities), currently consists of about 50 people. Since programa Tatô is not related to coastal flooding, this actor is not included in Figure 15.9. Apart from the protection of sea turtles, MARAPA also tries to educate the people in the coastal communities on for example the benefits of planting trees on the beach to counter beach erosion and on the risks associated with building close to the sea or the river.

The second objective of MARAPA is the support of artisanal fisheries. This support is mainly focused on the palaies and fishermen organisations in the different coastal communities. Palaies are the women who sell the fish on the market. MARAPA organizes trainings in salting and drying fish for these women. The projects to support the fishermen are aimed at increasing the safety of the fishermen at sea and to increase their production. In order to help the fishermen increase their production, MARAPA provides them with fish detection equipment and better fishing nets. Regarding the fishermen's safety, MARAPA provides support in different ways:

- **Providing fishermen with compasses and/or GPS devices:** especially fishermen who go further out to sea or who fish at night are at risk of loosing their way. MARAPA tries to address this problem by providing the fishermen with equipment to better orientate themselves.
- **Providing fishermen with lifevests, flares, marine radio and watertight mobile phone holders:** many fishermen do not have any safety equipment on board when they go out fishing. Also, they are often not able to ask for help when they get into trouble. With the water tight mobile phone holder, the fishermen can ask for help when they are in trouble. However, this is only possible if they are not too far from the coast because the mobile network does not extend to far seawards. If they cannot use their mobile phones anymore, they can use the marine radio that MARAPA provides the fishermen. With this radio, that is powered by solar energy, they can contact the coast guard and ask for help.
- **Providing better boats:** many fishermen have wooden boats and use a sail or peddle. Boats with an engine are very rare. MARAPA tries to provide fishermen with better boats (made out of polyester) and an engine to increase their safety (during a storm, it is much easier to get back to shore with an engine than by sail or peddle).
- **Make sure the fishermen have access to up-to-date meteorological information:** Manuel explained that the weather can change very quickly in São Tomé. This poses a problem to the fishermen, because if they are already out at sea they might not have enough time to get back to shore. Therefore it is important that the fishermen have access to up-to-date meteorological information. With the marine radio that the fishermen can use to contact the coast guard, they can also listen to the normal radio to listen to the storm warnings.
- **Training the fishermen:** MARAPA also provides trainings to fishermen to teach them what to do if they get in trouble in sea and how to use the safety equipment.

MARAPA is an NGO and therefore they do not receive any money from the government of São Tomé. They receive funding from different national and international organizations, among which the most important ones are the World Bank, the Banque Africaine de Developpement (BAD) and the European Union. Furthermore, MARAPA is also supported by PNUD (see Section 15.2.6). This funding is always related to a certain project or combination of projects. Although MARAPA does not receive money from the government, the NGO has good relationships with the government. The interaction between MARAPA and the government mainly concerns the mutual coordination of projects, as the government also coordinates several projects to support the national fishing sector.

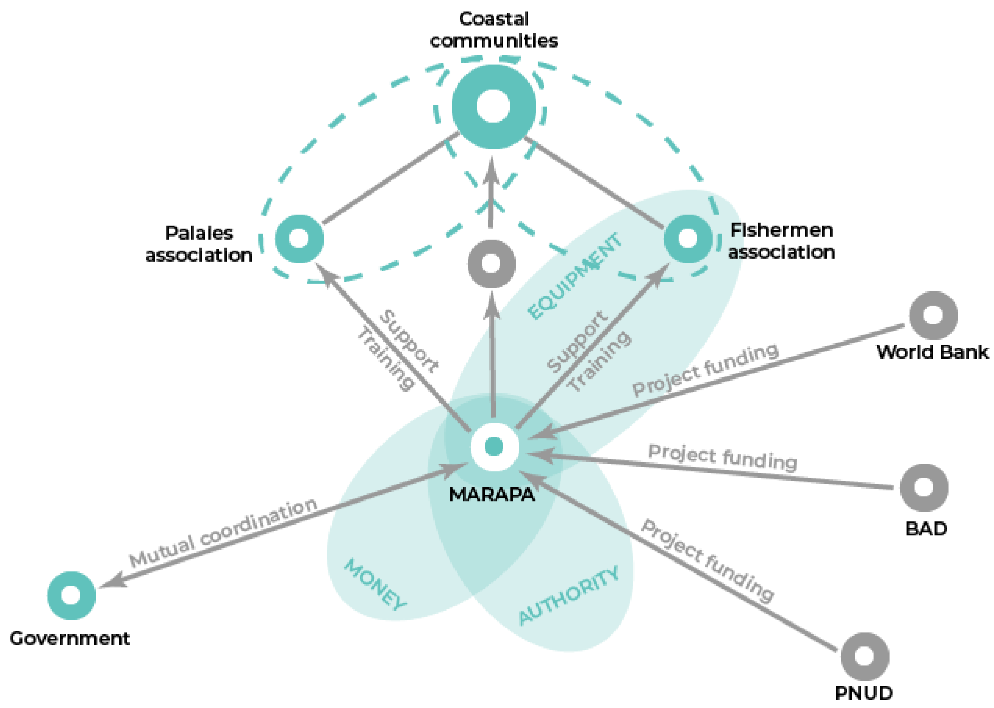


Figure 15.9: MARAPA

Resources

From the interview with Manuel, the three most important resources for MARAPA were identified. These resources are equipment, authority and financial resources. Manuel explained that the organisation is completely dependent on national and international institutions for their funding. This is a challenge, because it is not always easy to secure enough money for all the activities they would like to do. He further explained that all the funding they get is related to a project or combination of projects, which leads to certain challenges. For example, MARAPA has a team with 16 fulltime members that need to be paid. It is sometimes an administrative challenge to decide how the different project funds can be used to pay these fulltime members. Also, the different projects have a certain duration; usually a few years. However, some activities are not bound to this project duration and MARAPA would like to provide these activities on a continuous basis, like for example the safety trainings for fishermen.

Another important resource is equipment. As described above, a large part of the activities carried out by MARAPA consists of providing the fishermen and palaies with equipment needed to increase their productivity and/or secure their safety (e.g. fishing nets, fish detecting equipments, marine radios, lifevests, GPS, flares etc.). It is not always possible to secure enough equipment for all the fishermen and palaies; this is partly caused by a lack of financial resources. Manuel gave an example related to the marine radio that they hand out to the fishermen. They currently distributed about 400 of these radios and they still have about 400 to distribute. However, there are much more fishermen; they simply cannot help everyone.

Lastly, authority is an important resource. Manuel explained that it is not always easy to get the people in the different communities to listen to them. He mentioned an example of a community where they handed out a marine radio to several fishermen. During the next storm, one of these fishermen got lost at sea and was found eventually by the coast guard; however he did not contact the coast guard with the marine radio. When MARAPA asked him why he did not use it, they discovered that he had sold the radio. According to Manuel, these things happen quite often and are partly caused by the fact that these people are very poor. However, a large part is also that many fishermen are not convinced of the necessity of things like a marine radio. Manuel: 'They have fished all their life without a radio, so why would they need one now?'. He mentioned this difficulty also in relation to other projects, for example when they tried to teach the people in different communities on the benefits of planting trees to counter beach erosion.

In summary, we can conclude that MARAPA experiences multiple barriers that limit their functions in relation to coastal flood events:

- **Financial resources** For MARAPA it is difficult to secure enough budget for all the activities that they want to carry out, especially because they are dependent on international organisations that provide project-based support.
- **Technical equipment** It is not always possible to secure enough equipment for all the fishermen and palaies; this is partly caused by a lack of financial resources.
- **Authority** It is often difficult to get the fishermen and palaies to listen to them, especially if that means they have to change their daily practices.

15.2.6. Programa das Nações Unidas para o Desenvolvimento - PNUD

The Programa das Nações Unidas para o Desenvolvimento, or PNUD, is a part of the United Nations Development Programme (UNDP) which is located in São Tomé and Principe. It was established shortly after the independence of the country. PNUD aims to support the country in achieving the sustainable development goals. The scope of PNUD is therefore much broader than coastal flooding alone; they also focus on a.o. agriculture, health, education and agriculture. During an interview with Aderito Santana and Maria Teresa Mendizabal, both working at PNUD in São Tomé, they explained that PNUD is only indirectly involved in coastal flooding problems. They are more involved in the field of river flooding; last month they finished a project to install more and better measurement stations in the different rivers of São Tomé. The measurements coming from these stations are used by the institute of natural resources and environment. Furthermore, they explained that most projects related to the coastal area and coastal flooding are under the authority of the WACA (West African Coastal Areas) project (financed by the World Bank). The main task of PNUD regarding coastal flooding is to coordinate the different projects that are related to the coast. It is their job to know which institutions are working on what projects (not only in relation to coastal flooding, but in general), so that they can advice the government of São Tomé and Principe on the coordination of all these projects.

Figure 15.10: Aderito Santana and Maria Teresa Mendizabal, both working at PNUD

Since PNUD is not directly involved in the protection against and preparation for coastal flooding, I choose not to make a map for this actor. However in the other maps, the actor is incorporated.

15.2.7. Coastal communities

In Figure 15.11, the context of the coastal communities is mapped. In contrast to the other actors discussed above, the coastal communities are not an institution. Also, there are many different coastal communities, with different sizes and characteristics, which are grouped together as one actor in the figure. It is important to keep this in mind, because every community is different. The coastal communities may have some characteristics in common, but can differ completely in others. In the remainder of this section, it will be indicated when the results and observations from the field trip showed a difference between the coastal communities that were visited during the field trip.

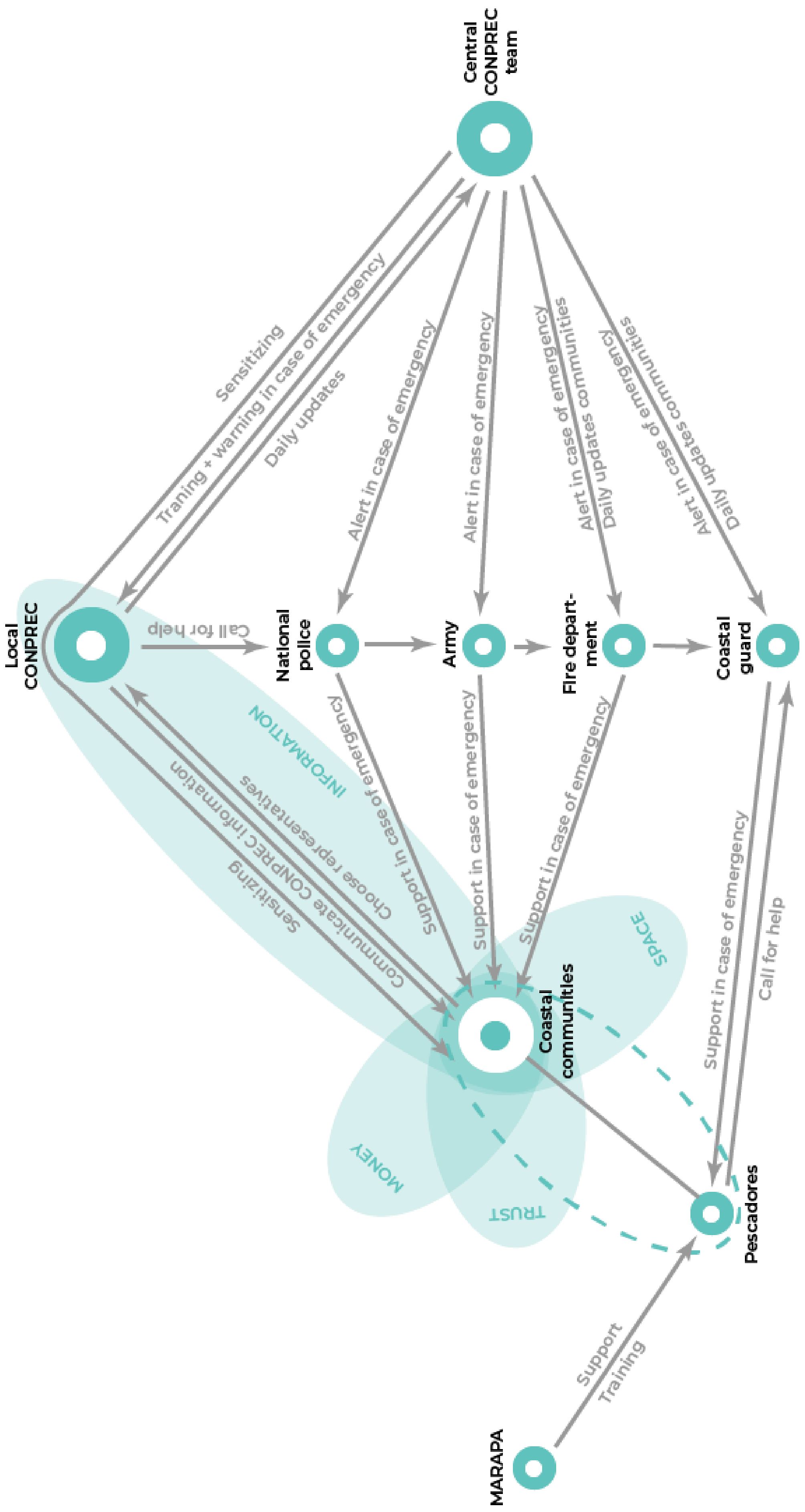


Figure 15.11: Coastal communities

The different actors and interactions mapped in Figure 15.11 will not be discussed here as these are already described in the sections above. It is important to remember that this schematization only applies to communities involved in the CONPREC organisation. Other communities are not in contact with CONPREC and only receive storm warnings over national radio. In many communities, especially the smaller ones, the people do not own a radio, which means that they have to trust on their own experience and knowledge of the local climate to know whether a storm is coming. In the remainder of this section, the different resources that are relevant for the coastal communities is relation to coastal flooding are discussed: financial resources, trust, space availability and information and skills.

First of all, financial resources are an important resource in the coastal communities. During different actor interviews, the interviewees mentioned that the people living in the coastal communities are very poor and have to struggle every day to provide in the basic necessities of their families. Because of this lack in financial resources, it is difficult for the people in these communities to construct solid, stable houses. Most houses in these communities are made of wood and are not always able to withstand the strong winds during a storm (see Figure 15.12a and 15.12b). In the questionnaires, people living in different communities mentioned that one of the problems during the last storm that they can recall was that the roofs of some houses flew off.

(a) Io Grande

(b) Praia Pantufo

Figure 15.12: Wooden houses in different coastal communities

During the interview with PNUD, Maria explained that these people live on a day-to-day basis; most people do not have any savings or reserves. That means that when the fishermen miss a day of fishing because of a storm, they will not have any fish to sell. This means they do not make money and are thus not able to buy food for their families. Therefore the fishermen will only stay ashore if they believe a dangerous storm is coming up. During the CONPREC interview, Carlos mentioned that this is a difficult factor in the warnings they give to the communities. Even though they send out a warning, sometimes fishermen still go out to fish. According to Carlos and Maria, this is largely motivated by a lack of financial resources.

Space is another important resource in many coastal communities. Most communities are very densely populated and available space is scarce. During the actor interviews different interviewees mentioned that this is big problem, because this drives the people in the communities to build their houses close to the river and the sea, even though organisations like CONPREC try to inform the people that it is dangerous to build in these areas. This is also caused by the preference of the fishermen in these communities to live close to the sea. These fishermen also put their boats on the beach; in that way it is very easy to go out fishing (see Figure 15.13a and 15.13b). This can cause damage and loss of boats during storms, which was also mentioned as a problem by many respondents of the questionnaire. However, in many communities there is no space to store the boats in another, safer location that is not too far from the beach. It should be noted that not every coastal community experiences a lack of available space. In the community of Io Grande for example, this is less of an issue. However, in most larger communities, this is a problem.

Information and skills are a third important resource for the coastal communities. First of all, the people in the communities do not always receive a warning for an upcoming storm event in time. In Section 15.2.3 and 15.2.4, the reasons for this were elaborated. In the questionnaires, the respondents were asked about the last big flood event that they could recall. Almost all respondents indicated that they did not receive a warning in advance to this storm event and that they did not know the storm was coming.

Even when the people receive a storm warning in advance, according to Carlos (national coordinator of CONPREC), many people in these communities lack information on what actions they should take to decrease the adverse consequences of a storm. He mentioned the example of a coastal community where the fishermen store their boats on the beach. In preparation to a storm event, they tie their boats to a fence along the beach, so that their boats will not be lost. However, because their boats are tied to the fence and very close together, the boats are slamped into each other during the storm which causes a lot of damage both to the boats and the fence. It is important to provide these people with information on what to do; this is also one of the aims of the sensitizing trainings carried out by CONPREC (see Section 15.2.4). However, it often proves difficult to change the behaviour of the people in these communities. In the specific example of the fishermen tying their boats to the fence, this is also caused by a lack of space to put their boats (see above). In the questionnaire, many respondents indicated that beside a storm warning, they would also like to receive information on what actions to take. This is true for all coastal communities that were visited during the field trip.

(a) Praia Melão

(b) Praia Pantufo

Figure 15.13: Fishing boats on the beach in Praia Pantufo

Apart from information, people in these communities also lack the skills to take certain actions. Maria (working at PNUD) mentioned that many people in these coastal communities understand that a stone house provides better protection against a storm than their wooden houses. However, these people do not know how to build a stone house and they often do not have the money to afford the materials (i.e. a lack of financial resources).

Lastly, trust is an important resource for the coastal communities. Regarding this resource, big differences were observed between the different coastal communities that were visited during the field trip. The people in some coastal communities indicated in the questionnaire that they would not evacuate from their houses during a storm or flood event, because they were afraid that people will steal from their houses while they are gone. This indicates a low level of trust. In the community of Praia Abade however, this is completely different. The people in this small community set up a system during the rain seasons where every night someone stands watch. If the weather changes and a storm is expected, this person wakes the others and together they prepare for the storm, a.o. by getting the boats of the beach. This indicates a high level of trust within the community, which leads to cooperation in order to decrease the adverse effects of a storm.

Trust is not only related to the trust people have in the other people living in their community, but also relates to the trust that the people living in the different coastal communities put in the different central institutions. As was already described in Section 15.2.4 and 15.2.5, for institutions like CONPREC and MARAPA authority is an important resource. It has often proven difficult for these institutions to get the people in the different communities to listen to them and act on the information they provide, especially if that means they have to change their daily practices. As described above, this is partly caused by a lack of resources like money, available space and information/skills in the communities. However, this can also be caused by a lack of trust in the central institutions. During one of the visits to the coastal communities, a fishermen explained that he does not always listen to what the people from the different central organisations tell them. When asked why he does not always listen, he answered that he first needs to be sure they give him accurate information. 'Ver para crer', first see then believe. He explained that this mentality is very normal among the people in

São Tomé and explained that the name of the country even warns for this. The name São Tomé is based on Saint Thomas, the apostel with the nickname doubting Thomas. During the interview with PNUD, Maria also mentioned this and explained that the people first need to trust you before they will listen to you. In order to win their trust, they need to know you are providing them with the correct information. Maria: 'If you warn them the first time for a storm, they will not listen. But when the storm actually comes, next time they will listen to you'.

In summary, we can conclude that the people in the different coastal communities experience different barriers to the adaptation to coastal flood events. It is important to note that these barriers can differ among the different communities.

- **Financial resources** - The people living in the coastal communities are very poor. Therefore, it is difficult to construct solid, stable houses. Also, since these people live on a day-to-day basis, they tend to go out fishing even when a storm warning is given; they need to earn money to provide food to their families.
- **Available space** - Most coastal communities are very densily populated. There is very limited free space available. This causes the people living here to build in areas close to the sea and river (that are suscept to flooding). Also, there is no space available for the fishermen to safely put away their boats.
- **Information** - The people in the coastal communities often do not receive a storm warning, or they receive a warning only 10 to 15 minutes in advance. Also, the people in these communities do not always know what actions to take in case of a storm event.
- **Trust** - In some communities (especially the larger ones), different people indicated that they would not evacuate their house in case of a storm event, out of fear of getting robbed. Also, the people in these communities do not always trust the central institutions; they first want to be sure that they can trust the information that they get from these institutions ('ver para crer', first see then believe).

15.3. Overview of the system in São Tomé

In Figure 15.14, the maps linked to the different actors as described above are merged in order to obtain an overview of the total system in São Tomé. In this total overview of the system in São Tomé, some actors are grouped to keep the figure clear. In this figure, the different ministries and departments of the government, that were mapped seperately in the maps of the individual actors, are grouped under one actor 'government'. Only the central team of CONPREC and the observatoire, which are also part of the government, are mapped seperately. Furthermore the civil protection organisations consisting of the national police, the army and the coast guard are mapped as one actor. The fire department is still mapped seperately, since this institution also provides the observatoire with information, while the other civil protection organisations do not have this interaction with the observatoire.

15.4. Overview of barriers to adaptive capacity for São Tomé

In Figure 15.15, the barriers that were experienced by the different actors are indicated in the map of São Tomé. In this way, a complete overview of the barriers to adaptive capacity in relation to coastal flood events is obtained.

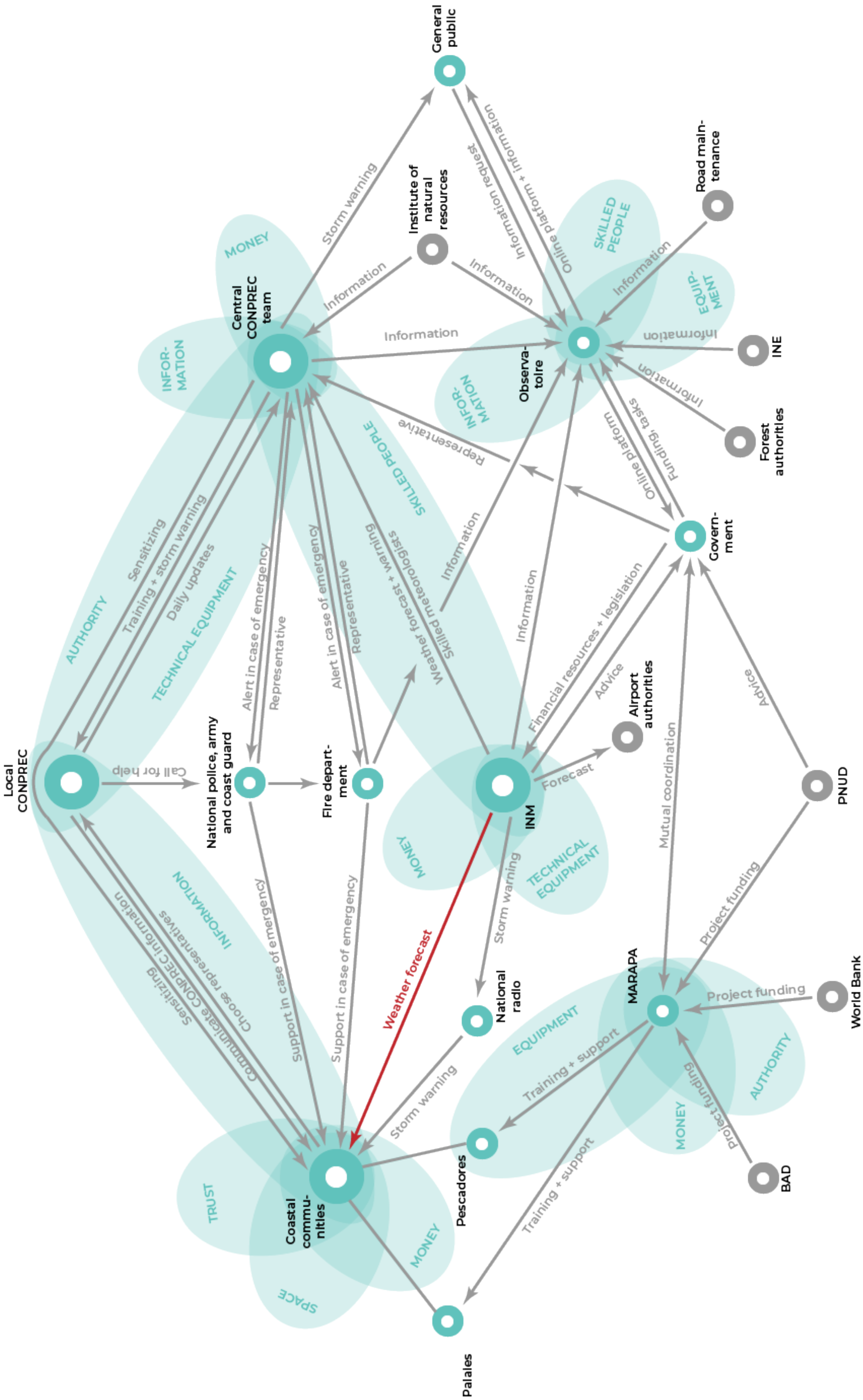


Figure 15.14: São Tomé and Principe

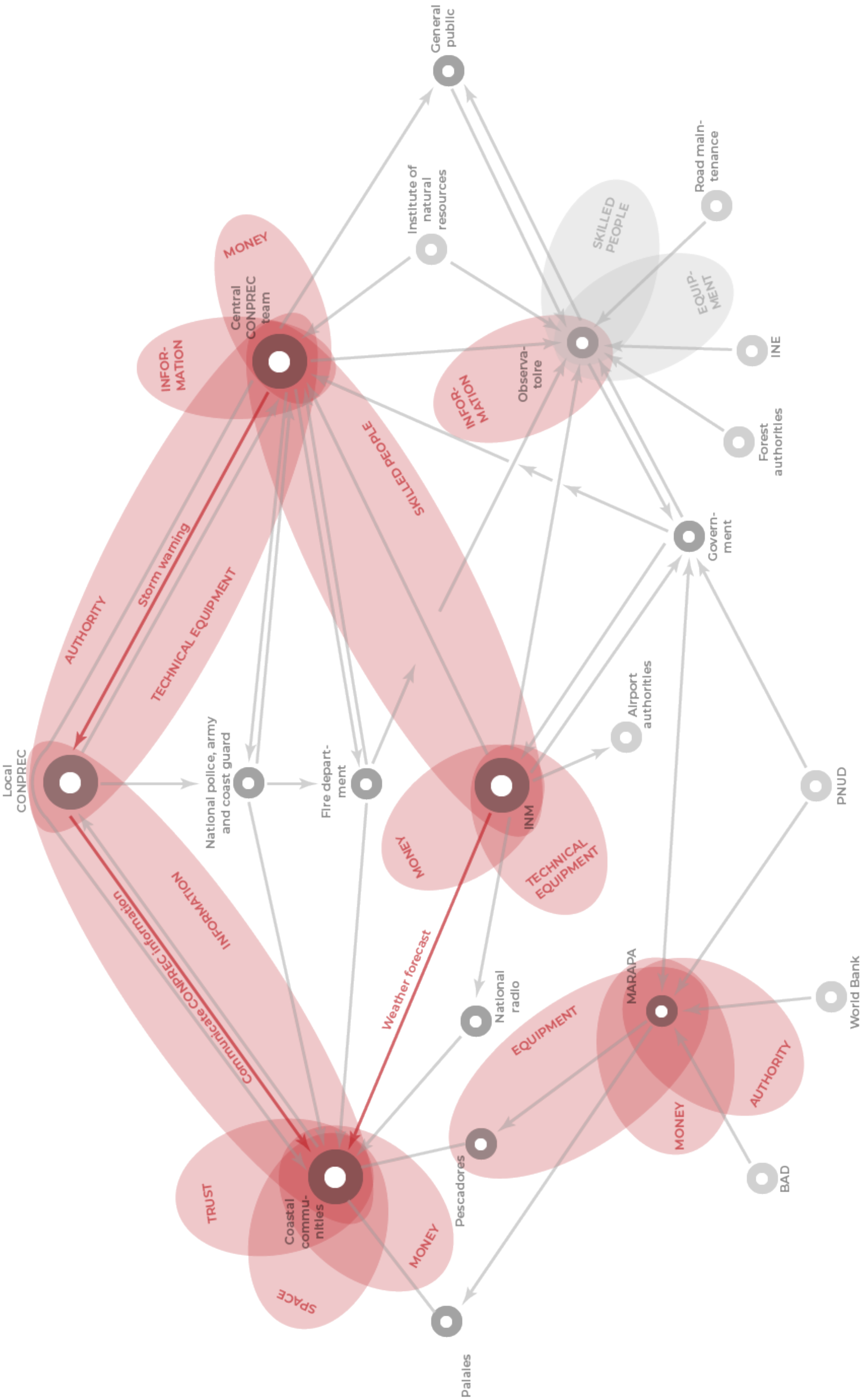


Figure 15.15: Overview of the barriers experienced by the different actors

15.5. Reflection

In this section, some general observations from the system analysis described in this chapter are pointed out. These observations are linked to the newly developed theoretical framework (see Chapter 13), to draw conclusions on the validity of this framework.

We have seen that the barriers to adaptive capacity in the system of São Tomé are all related to interactions and (a lack of) resources in the system. An example of a barrier that is linked to an interaction is the communication between the central CONPREC team and the local CONPREC members in the different communities. During the interview with the national coordinator of CONPREC, he explained that this communication is sometimes difficult, because of problems with the communication devices that they use. Also, the interaction between the meteorological institute and the coastal communities is very difficult, because the green line does not exist anymore.

Eventually, the barriers related to these interactions can be traced back to a lack of resources of the different actors. The communication between the central CONPREC team and the local CONPREC members would be less problematic if they had more and better communication devices available; this relates to the technical equipment resource. The green line was shut down due to a lack of financial resources of the INM; if they could secure enough budget, they would be able to open this line again. In the context of São Tomé, it can therefore be concluded that the barriers to adaptive capacity that are present in the system are all directly or indirectly related to the resources that are present throughout the system.

Regarding the resources present in the system, we have seen that the different resources linked to a certain actor are interdependent and can influence each other. In the context of São Tomé we can observe this for example for the INM. During the interview, the general director of the INM mentioned that they are limited in their financial resources. Apart from the fact that their limited budget directly affects the execution of their tasks (e.g. the shutdown of the green line for fishermen), it also influences other important resources for the institute. For example, the lack of financial resources (partly) causes a lack in skilled people, because they do not have enough money to hire or educate new people. This is further enhanced by the fact that the education institutions present at the island are not always sufficient; especially not for specialisations like meteorology. In order to obtain the right education and training, people need to go abroard, which makes it even more expensive to educate people.

Furthermore, the lack of financial resources and skilled people that the INM experiences (partly) causes a lack in technical equipment. The INM needs measurement stations to gather data, both related to the weather and to the sea. Currently they only have one marine measurement station and therefore would like to install more stations. However, they do not have enough money to do this. Also, they would need more technicians that can work with these measurement devices. In this case, a lack of financial resources and a lack of skilled people both influence the resource 'technical equipment'. This example shows that the different resources related to a certain actor are interdependent and can influence each other.

We can further conclude that the resources related to a certain actor can also influence the resources of other actors in the network. This can again be explained using an example from the context of São Tomé. As described in Section 15.2.3 and 15.2.4, the central CONPREC team receives the weather forecast and storm warnings from the INM. This information is an important resource for the central CONPREC team; they need this information in order to carry out their functions (e.g. warn the coastal communities for storm events). So, if the information that they receive from the INM is not timely and/or accurate, because of lacking resources at the INM, this influences an important resource for the central CONPREC team.

Although the resources of a certain actor can negatively influence the resources of other actors in the network, this can be (partly) compensated. In the context of São Tomé, we saw that the central CONPREC team is informed by the institute of natural resources in case a flooding from a river is expected. However, the institute of natural resources does not have enough capacity (i.e. they do not have enough skilled people) to provide this information on a continuous basis. Therefore, the central CONPREC team currently applies its own, simple model to calculate river water levels. In this example, a lack of resources of the institute of natural resources (i.e. skilled people) is compensated by a resource of the central CONPREC team (i.e. technical equipment; a model to calculate river water levels).

These conclusions confirm the initial assumption that led to the development of the theoretical framework used in this study: that adaptive capacity cannot be mapped by simply adding up different determinants; these determinants are interdependent and these interdependencies are crucial to take into account. Furthermore, it can be concluded that the newly developed theoretical framework can indeed be used to directly assess these interdependencies. In this way, an overview of the barriers to adaptive capacities and how these are related to each other can be obtained for a certain system. Such an overview can serve as a basis to access which measure or combination of measures will be helpfull in a certain situation and where in the network this measure will be most effective. This will be further elaborated in the next chapter.

Lastly, a methodological observation has led to a slight adjustment of the theoretical framework. During the interviews with the different actors, the interview always started by asking the interviewee about the functions, related to coastal flooding, of the institution where they worked. The rest of the interview was related to the functions they mentioned in the beginning and whether it is always possible to fulfill these functions. All interviewees answered that this was not always the case; during the interview the different causes for this were discussed. It can be concluded that during the interviews, the different interactions, resources and barriers that the different institutions face were discussed in relation to the function(s) of these institutions. In general, it would not work to try to identify the relevant actors in the context of a certain actor, the interactions and resources if the function of this actor is not clear. It could be stated that this function is implicit in the identification of the actors. However, since the identification of the actor's function(s) was observed to be quite important for the whole mapping exercise, it is included in the theoretical framework. This is depicted in Figure 15.16. When applying this general theoretical framework to a specific context, it might not be necessary to include these functions in the map (as that might lead to a chaotic figure), but it is important to make these functions explicit in order to be able to map the relevant actors, the interactions between them and their resources.

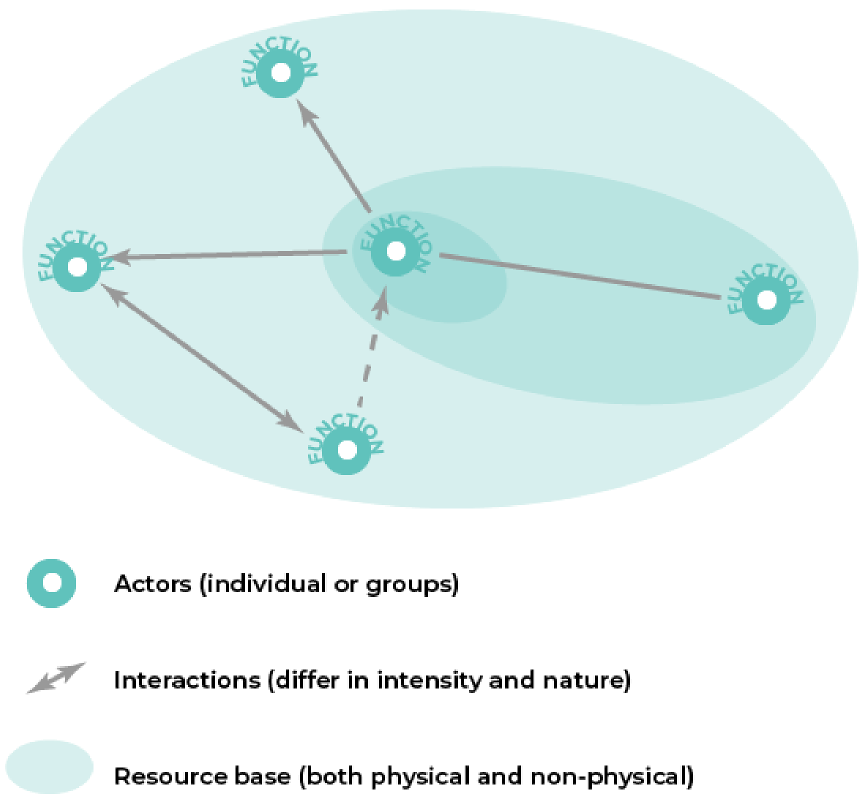


Figure 15.16: Adjusted theoretical framework

15.6. Chapter summary

In order to analyse the system related to coastal flood events in São Tomé, different interviews were conducted with important actors in the system. Furthermore, a questionnaire was used to incorporate the people living in the different coastal communities (the development of the interview protocol and questionnaire is elaborated in the previous chapter). The results of these interviews and the questionnaires were used in combination with the theoretical framework as described in Chapter 13 to map the system of São Tomé and obtain an overview of the barriers to adaptive capacity related to coastal floodings that are present in the system.

This mapping exercise consisted of three steps. First, the theoretical framework was applied to each actor seperately, to map the context of that actor. Therefore, the different actors that are relevant in the context of this actor are listed. Next, the interactions with these actors are specified. Lastly, the resources that the actor needs are added to the map. For each actor, the barriers to adaptive capacity are explained. In the next step, the maps of the different actors were merged in order to obtain an overview of the entire system of São Tomé. Lastly, the map of the entire system of São Tomé was used to indicate all the barriers to adaptive capacity that were identified during the individual analyses of the different actors. The end result is depicted in Figure 15.15.

From this mapping exercise we can conclude that the barriers to adaptive capacity that are present in the system of São Tomé are all related to interactions and (a lack of) resources in the system. Eventually, the barriers related to interactions in the system can be traced back to a lack of resources of the different actors. Therefore, we can conclude that the barriers to adaptive capacity in the system of São Tomé are all directly or indirectly related to (a lack of) resources in the system. Regarding these resources, the mapping exercise described in this chapter indicated that the different resources linked to a certain actor are interdependent and can influence each other. Furthermore, it was observed that the resources related to a certain actor can also influence the resources of other actors in the network.

These observations confirmed the initial assumption that led to the development of the theoretical framework: that adaptive capacity cannot be mapped by simply adding up different determinants; the interdependencies between these determinants are crucial to take into account. Furthermore, this mapping exercise showed that the newly developed theoretical framework can be used to directly adress these interdependencies. In this way, an overview of the barriers to adaptive capacity and how these are related to each other can be obtained for a certain system.

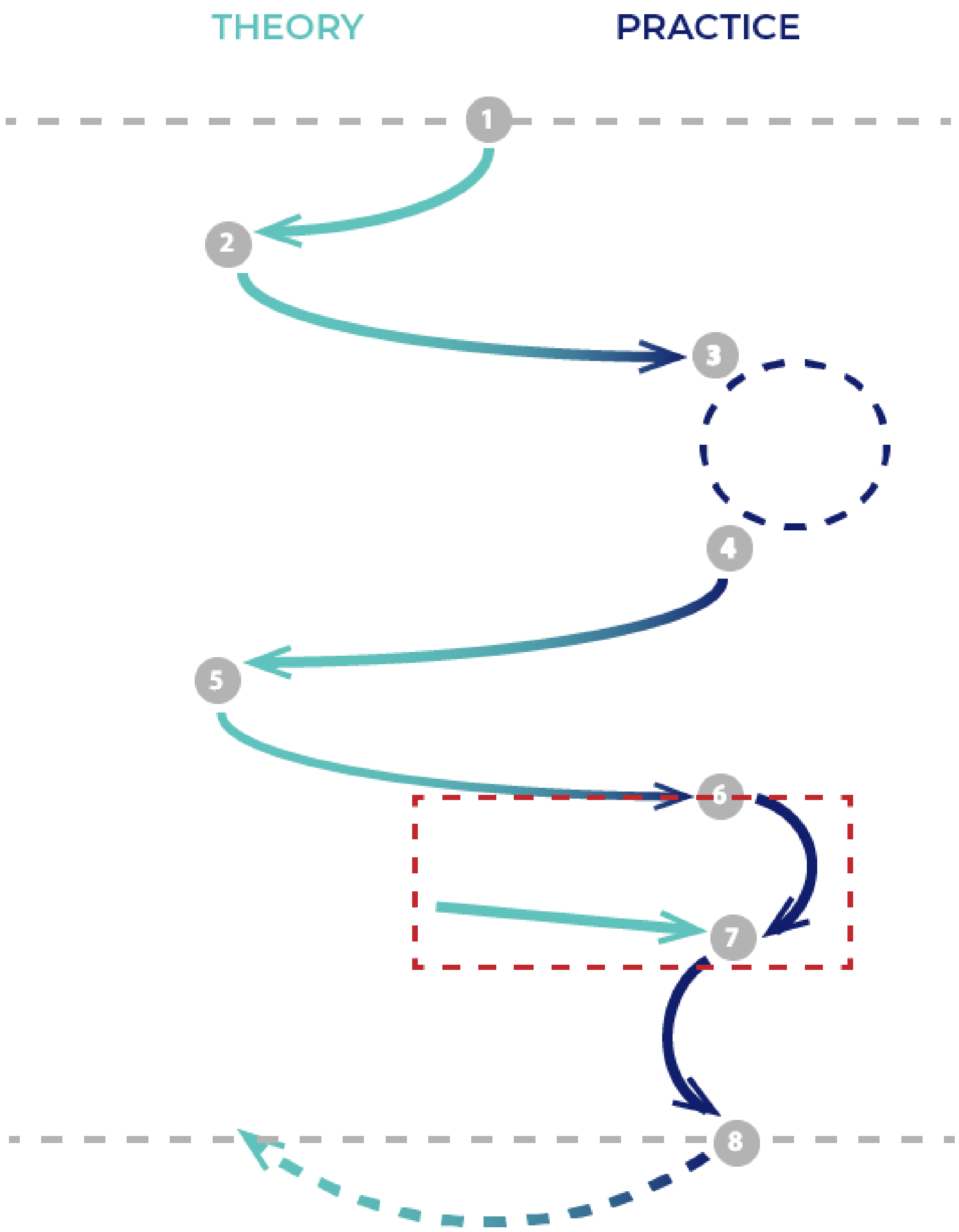


Figure 15.17: User stories in the roadmap

16

User stories

In the previous chapter, we have obtained an overview of the different barriers to adaptive capacity and their interdependencies that are present in the system of São Tomé, in the context of coastal flooding. This overview was the result of an elaborate analysis, starting from a system's perspective. Not all the barriers that were identified in this chapter can be addressed with a tool based on the simple flood model as developed in the first part of this thesis. Therefore, in this chapter the barriers to adaptive capacity in the system of São Tomé are analysed from the tool's perspective. The aim of this analysis is to identify the barriers that can be addressed with a tool based on the simple flood model. This is described in Section 16.1.

Based on the identification of the barriers that can be addressed with the tool, different user stories are developed that serve as input for the final design of the tool interface. In Section 16.2, first a short introduction to user stories is given. Next, the user stories in the context of São Tomé for the development of the tool interface are described. Lastly, in Section 16.3, a short summary of the chapter is given.

16.1. Barriers addressed by the tool

In Figure 15.15, the different barriers to adaptive capacity related to coastal flooding that are experienced by the different actors were indicated. Not all of these barriers can be addressed by the tool. In Figure 16.1, the barriers that can be adressed with the tool are indicated with green. The barriers that cannot be addressed by the tool, but that are important for the final design are indicated with a dotted stroke.

The tool can be used to address the barrier related to the 'technical equipment' resource experienced by the INM. As explained in the previous chapter, the INM currently has very limited marine information as they only have one marine measurement station and do not have a way to determine or predict coastal flooding. The tool could provide them with a way to predict coastal flooding. However, more marine measurement stations would still be required to gather more information on the local water levels and waves. During the interview with the INM, the general director indicated that they have a shortage of educated people at their institute. This is not something that can be addressed with the tool, but it does provide an important requirement on the design of the tool; the simpler the tool, the better. This is indicated in Figure 16.1 by a dotted stroke around the 'skilled people' resource of the INM.

Furthermore, the tool (partly) addresses the 'information' resource from the central CONPREC team. As explained in the previous chapter, the central CONPREC team obtains information regarding the weather forecast and storm events from the INM. Therefore, if the INM has a tool to predict coastal flooding, this additional information can be communicated to the central CONPREC team. The information regarding coastal flooding that is useful for the central CONPREC team is largely determined by the limitations related to the interaction between the central CONPREC team and the local CONPREC members and coastal communities in general. As is also indicated in Figure 16.1, there are two main types of interaction. The first type of interaction is related to storm warnings; this interaction between the central CONPREC team and the local CONPREC members happens over radio or telephone. That means that only spoken information can be communicated; it is not possible to communicate a map or a figure. Furthermore, since the final goal is to provide warnings and information in the different coastal communities (i.e. to address the 'information' barrier experiences by the people in the coastal communities), which information is useful is also determined by the information that is understandable and relevant to the people in these communities. The second type of interaction is related to sensitizing of the different coastal communities; this interaction happens face-to-face, when members of the central CONPREC team visit the communities. The information that is useful in this context is also determined by the information that is understandable and relevant to the people in these communities, but in contrast to the storm warnings, visual information can also be used.

For the observatoire, the resource 'information' can be (partly) addressed. As was described in the previous chapter, the information that the observatoire receives from the different institutions is not always accurate or complete. According to Abnilde, who works at the observatoire, the disaster information that they receive is not always complete. Currently, they do not receive any information on coastal flooding. The information that the observatoire would like to receive is partly determined by their interaction with the government. In the design of the tool, it is important to consider which information regarding coastal flooding is useful for the government and is thus helpful for the observatoire. For example, the local governments need information on what areas are suspectible to coastal flooding in order to take effective action.

As indicated above, the goal of the tool is eventually to provide the people in the different coastal communities (including the local CONPREC members) with useful information in relation to coastal flooding. However, they can only receive information and storm warnings over radio/telephone or in face-to-face meetings. These people do not own a computer and can therefore not use the tool. Based on the above analysis, it can be concluded that the INM, the central CONPREC team and the observatoire are the potential users of the tool. This is indicated in Figure 16.1 as well; the dark green actors are the potential users of the tool. Therefore, different user stories will be developed for these actors in the next sections. First, a short introduction in the theoretical background of user stories is given. Subsequently, the user stories for the different actors will be described.

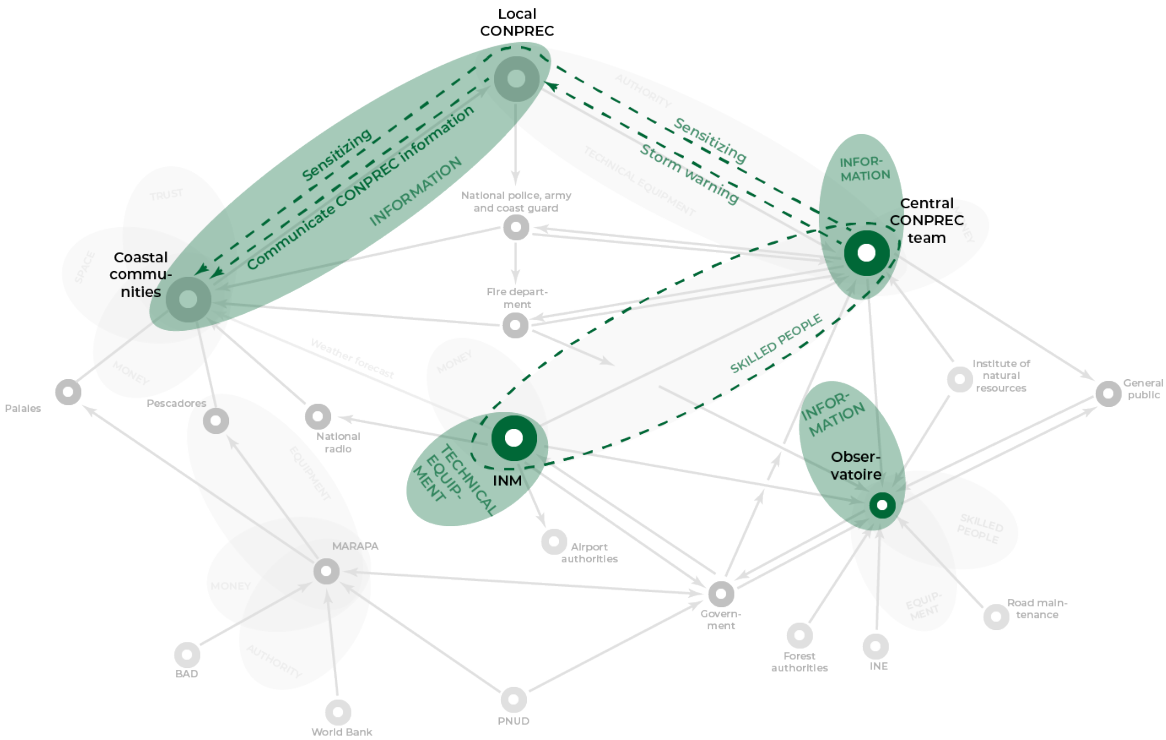


Figure 16.1: Barriers to adaptive capacity that can be addressed by the tool.

16.2. User stories for São Tomé

The use of user stories as input for design originates from the field of software development. The main advantage of the use of user stories is that they keep the focus on the user. A user story for a certain design describes the functionality that will be valuable to the user of that design (Cohn, 2004). In short, a user story only captures the essential elements of a requirement: who is it for, what is expected from the design and why is it important. The most well-known format is: 'As a <type of user>, I want <goal>, so that <some reasons>' (Lucassen et al., 2015). This translates to finding the who, what and why: who is the user, what does he/she wants to do with the tool and why is that important to the user? This format was also used in the context of this thesis. This will be elaborated for the different potential users of the simple flood tool.

16.2.1. INM

The first user story is related to the INM. In the context of coastal flooding, the main goal of the INM is to provide the central CONPREC team with accurate and timely predictions on coastal flood events. Considering the fact that in an early warning context detailed flood maps cannot be communicated to the different coastal communities, the main focus is to determine whether or not coastal flooding will occur in the different coastal communities. In order to do this, they need a tool to predict coastal flooding. Ideally the tool is easy to use such that it does not require skilled meteorologists to work with it, as the INM experiences a lack of skilled people.

WHO? - The INM

WHAT? - The INM wants a simple tool that can predict coastal flooding; the focus is on determining whether or not a certain coastal community will experience coastal flooding during a predicted storm event

WHY? - To provide this information to the central CONPREC team, so that they can use it to warn the people in the different coastal communities if needed.

16.2.2. CONPREC

The second user story is related to the central CONPREC team. For this actor, two different user stories were developed, as the team communicates with the coastal communities in two different ways.

First, the central CONPREC team communicates with the communities in an (early) warning context, to warn the communities in case a storm is predicted. The main goal of this interaction is to provide the people in the coastal communities with accurate and timely information so that they can take measures and in that way decrease the negative consequences of the coastal flooding event. Since the communication to the communities happens over telephone or radio, for the central CONPREC team it is most important to know whether or not a certain commmunity will experience coastal flooding. This information can then subsequently be communicated to the relevant coastal communities.

WHO? - The central CONPREC team

WHAT? - The central CONPREC team wants to know whether the different coastal communities will experience coastal flooding or not

WHY? - To be able to provide the local CONPREC members with information regarding coastal flooding, so that the people in the coastal communities can take measures and in that way decrease the negative consequences of a coastal flooding event.

Secondly, the central CONPREC team communicates with the communities in a training context; this entails both the training of the local CONPREC members and the sensitization sessions held with the entire community. These interactions with the communities are characterized by face-to-face contact. The main goal of both the trainings and the sensitization sessions is to create awareness regarding the different risks that these communities are exposed to and teach the people which actions they can take to decrease these risks. In order to make people aware of risks related to coastal flooding, the central CONPREC team needs visual content related to coastal flooding that is understandable to the people in the coastal communities.

WHO? - The central CONPREC team

WHAT? - The central CONPREC team wants visual content related to coastal flooding that is understandable to the people in the coastal communities

WHY? - To use this visual content during the training of the local CONPREC members and the sensitization sessions of the different coastal communities. The goal of these trainings and sensitization sessions is to create awareness of the risks related to coastal flooding and teach the people in the coastal communities on which actions to take to decrease these risks. In this way, the central CONPREC team hopes to improve the disaster adaptation in the coastal communities.

16.2.3. Observatoire

The last user story is related to the observatoire. The main goal of the observatoire is to make information from different institutions in São Tomé publicly available and in this way aid decision-making by the central and local government(s). In the context of coastal flooding, maps that indicate which areas are vulnerable to coastal flooding are most useful for the central and local government(s), especially in combination with maps indicating the builded area.

WHO? - The observatoire

WHAT? - The observatoire wants information regarding coastal flooding that is relevant to the government and local governments. This information consists of the location of coastal flood events and the areas that are susceptible to coastal flooding

WHY? - To aid the decision-process of the government and local governments.

16.3. Chapter summary

In the previous chapter, the different barriers to adaptive capacity related to coastal flooding were identified for the system of São Tomé. In this chapter, the barriers that can be addressed with a tool based on the simple flood model were identified. This led to the conclusion that the INM, the central CONPREC team and the observatoire are potential users for the tool.

Subsequently, different user stories for these potential users were developed. A user story generally has the form: ”As a [persona], I [want to], [so that]”. In other words, it is important to determine the who, what and why. This was elaborated for the different potential users. In the next chapter, these user stories will be used to iterate on the design of the tool interface.

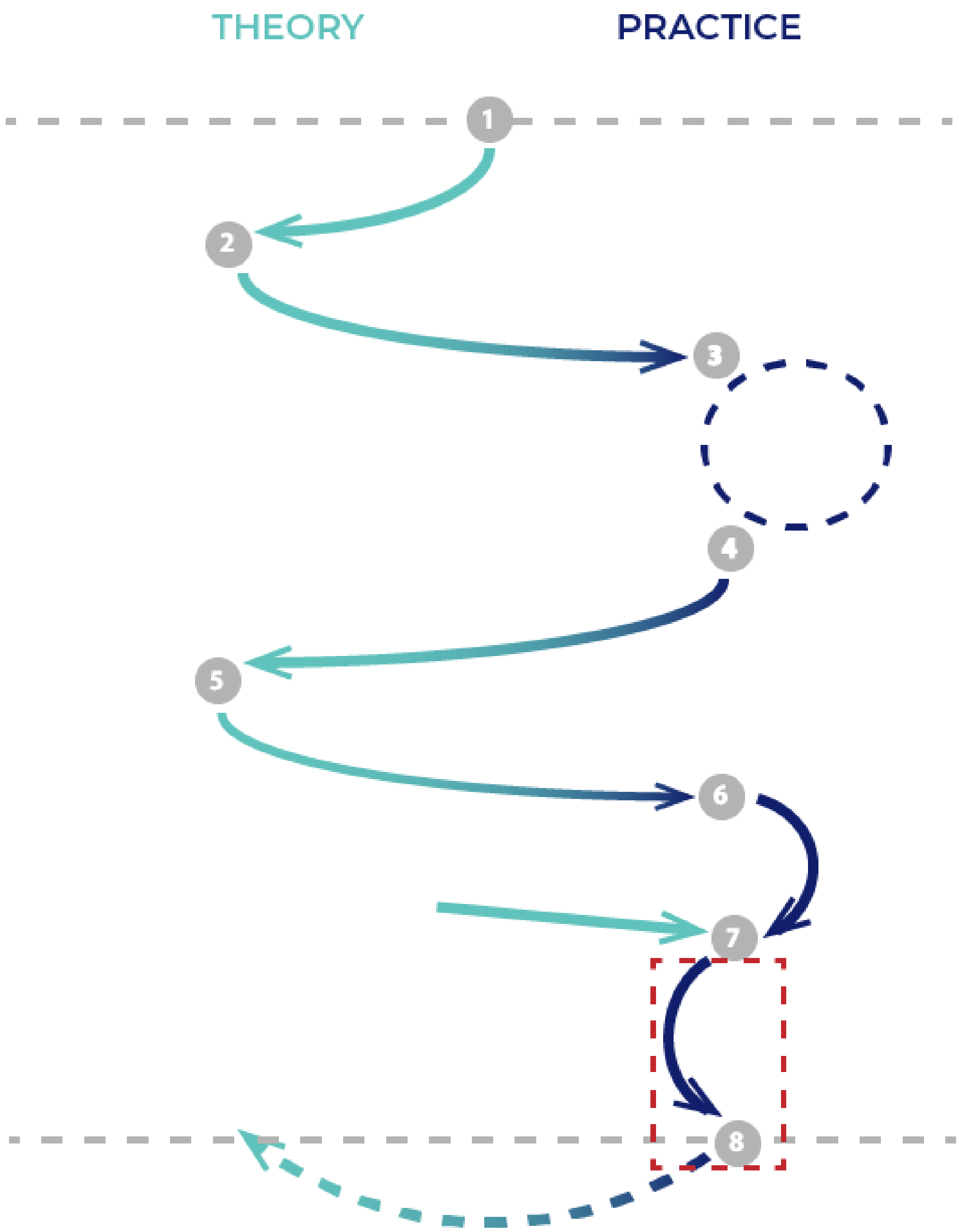


Figure 16.2: Final design in the roadmap

17

Iteration of the tool interface design

In this chapter, the iterated design of the tool interface is described. This interface design is based on the user stories as formulated in the previous chapter. In Section 17.1, the final design is depicted and explained. Next, different ways to improve the tool and increase its effects in the context of São Tomé are discussed in Section 17.2. Lastly, a short chapter summary is given in Section 17.3.

17.1. Iteration of the design

As described in the previous chapter, different user stories were developed for the tool in the context of São Tomé. Although there are multiple user stories (related to the different potential users), eventually one tool interface was developed. As in the initial design of the tool interface, the results can be visualized in different ways; in that way the requirements related to the different user stories can all be incorporated. An advantage of creating one tool that can be used in different ways by the different potential users, is that each of the potential users has the same information and knows what the other ones are talking about when interacting with them. The second iteration of the tool interface is depicted in Figure 17.1 till 17.6. In the different subsections below, the translation of the different user stories into a graphical interface will be explained for the different users.

17.1.1. INM

The INM wants a simple tool that can predict coastal flooding; the focus here is on the determination whether or not a certain coastal community will experience coastal flooding. For this goal, a simple flood map as incorporated in the first iteration (see Figure 14.8) is sufficient. However, the more detailed information regarding the inundated area and the maximum water levels is not included, since both the 1D and 2D tests in the previous part indicated that the accuracy of the simple flood model is not good enough to predict exact values of the maximum water levels. Instead, a message is shown that warns the user that the values in the flood map are an estimation. Furthermore, the location of the houses is indicated on top of the flood map with black lines. In this way, it can be quickly assessed whether a flood event will affect the houses in a certain area. Also, the the part of the beach where the fishermen store their boats is indicated with a black line. From the interviews and observations during the field trip, it became clear that in most coastal communities, the fisherman store their boats on the beach. In case of a high water event, they need to secure their boats, for example by tying them up or by storing them somewhere else. The combination of the flood map with the information on the location of the houses and the boats allows for an easy, quick assessment on whether a certain community should be warned or not. The INM can subsequently use this information, in combination with other information related to the weather (i.e. the wind speed, the rainfall) and communicate this to the central CONPREC team.

17.1.2. CONPREC

As explained in Chapter 16, CONPREC has two user stories related to the tool. Related to the storm warnings, they want to know whether a certain coastal community will experience coastal flooding or not, so they can warn the coastal communities if needed. For this goal, the information provided by the INM is in principle sufficient. However, since the communication between the central CONPREC team and the different coastal communities in a storm warning context happens over telephone and/or radio, the information that can be communicated to the different communities is very limited.

In order to provide the people in the communities with a bit more information, the following is suggested. During the training of the local CONPREC members, an addition to the program could be to pinpoint different locations in the community that often flood in case of high water. These locations should be clearly recognizable for the people living in the community (e.g. the front door of Jose's house). Furthermore, there should be just a few of these locations (e.g. 2 or 3). The amount of locations depends a bit on the size of the community under consideration. For some, smaller communities, one location may be sufficient, because everybody knows 'the front door of Jose's house'. However, in larger communities multiple locations may be needed. These locations can be indicated in the flood tool (e.g. using stars, see Figure 17.5). In case of an upcoming storm event that will lead to coastal flooding in a certain community, these points can be used to provide the people in the community with some additional information. Instead of only being able to inform them that there will probably be a flood event, the central CONPREC team can use these points to give an indication of the severity of the event as well (e.g. we expect that the maximum water level at the front door of Jose's house will be at knee-height). Considering the accuracy of the simple flood model, it is probably best to give an approximate indication of the maximum water level, for example related to body parts, instead of an exact value in meters. Also, this may be better understandable to the people in the coastal communities. Such a system is also useful for feedback to the central CONPREC team. After the storm event, the local CONPREC members can report the maximum water levels that actually occured at these points back to the central CONPREC team. This information can be used in the documentation of flood events (see subsection 17.1.3) and maybe to improve the accuracy of the simple flood model in the future.

As was described in Chapter 15, many respondents to the questionnaire indicated that they would like to get more information on what to do in case of a storm and/or coastal flood event. In the end, it was decided not to include this information in the tool interface, as the actions that should be taken depend on the community. Furthermore, different interviewees indicated that it can be very difficult to change the daily practices of the people living in the different communities. Some actions may require a change in routine for these people. Therefore, it is thought to be more useful to provide the people in the communities with this information in a face-to-face setting, for example during the sensitization sessions that are organized by CONPREC. Also, they could be specifically included in the training of the local CONPREC members.

Apart from the storm warnings, the central CONPREC team could also use the tool in the sensitatization sessions that they organize in the different communities. The goal of these sessions is to raise the awareness of the risks related to coastal flooding in these communities. To do this, it could be helpful to bring visual content that illustrates the consequences of coastal flooding for a certain community. For this goal, the visualisations that are generated with the tool should be understandable to the people in these communities. Only showing a flood map may not be very insightful for these people. Therefore, the tool contains different visualisations of flooding. This was already the case for the initial design of the tool. The main difference with this initial design is the visualisation of the cross-sections (see Figure 17.4). In this screen, the location of the different cross-sections is indicated in the flood map. The yellow line corresponds to the cross-section that is depicted in the screen.

For this application of the tool, it is believed that it is most useful to create visualisations of flooding, related to different return periods of the offshore conditions (i.e. for an event with a return period of 1 year, 5 years, 10 years etc.). Therefore, similar to the initial design of the interface, it should be possible to input the water levels and wave heights in two different ways: either manually (in that way, you can input the water level and wave height corresponding to a certain return period) or by linking the tool to a global model that predicts the offshore water level and waveheight up to a few days in advance.

17.1.3. Observatoire

The observatoire could use the tool in order to obtain information related to coastal flooding, include this information in their online information platform and in this way support both the central and local government(s) in their decisions (e.g. regarding the areas that should be build). From the interview with Abnilde, who works at the observatoire (see Chapter 15), it became clear that the online information platform wants to incorporate information regarding historic disaster events and information regarding the areas that are vulnerable to the different disaster types.

The information related to coastal flood events could be obtained directly from CONPREC. For this purpose, the screen showing the flood map, possibly in combination with an indication of the houses and the beach, could be used (see Figure 17.3). If the central CONPREC team would receive more accurate information regarding the maximum water level that occured during a certain event from the local CONPREC members (as suggested in Subsection 17.1.2), this information could also be communicated to the observatoire and incorporated in the overview of coastal flood events.

Furthermore, maps indicating the areas that are susceptible to coastal flooding are required. For this purpose, the screen as depicted in Figure 17.6 is included. In the initial design of the tool, the risk to the houses was included in the tool interface. However, for the observatoire, an indication of the areas that are at risk is more useful.

The interface of the tool is depicted as different figures below. However, there is also a digital version of the tool interface available, where you can click through the different screens to see how it works. The tool interface is available both in Portugues and in English. If you are interested, please send the author an email (martinerottink@hotmail.com) to get access to the interface.

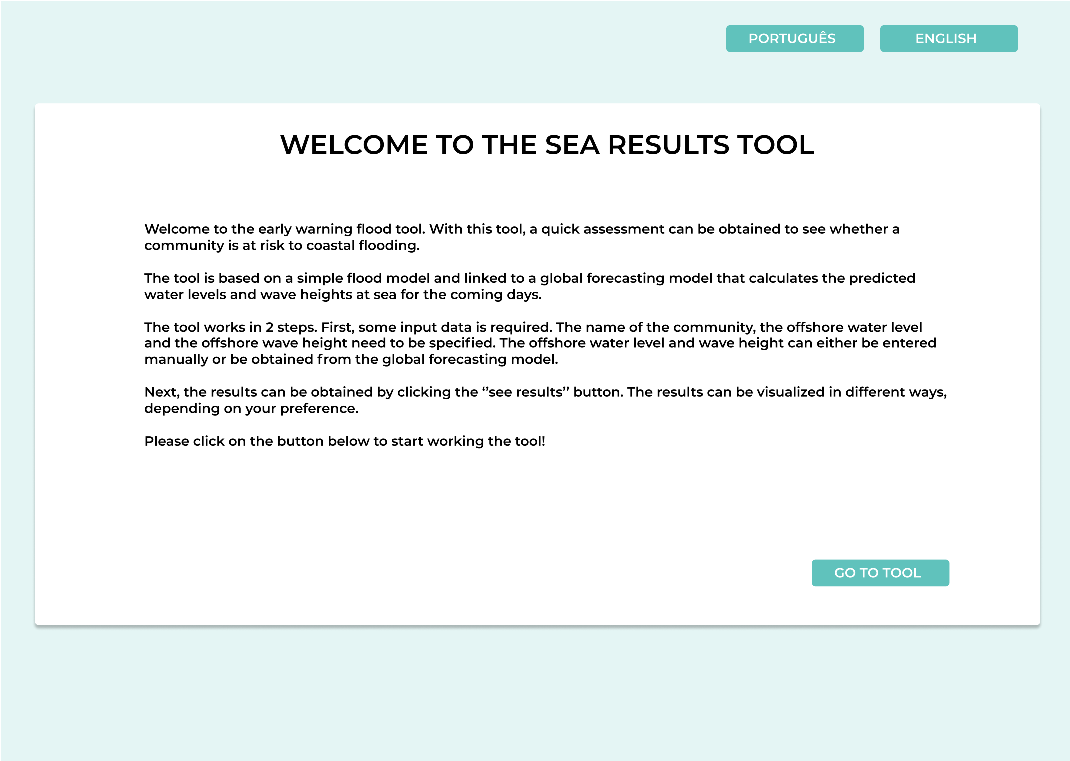


Figure 17.1: Start screen

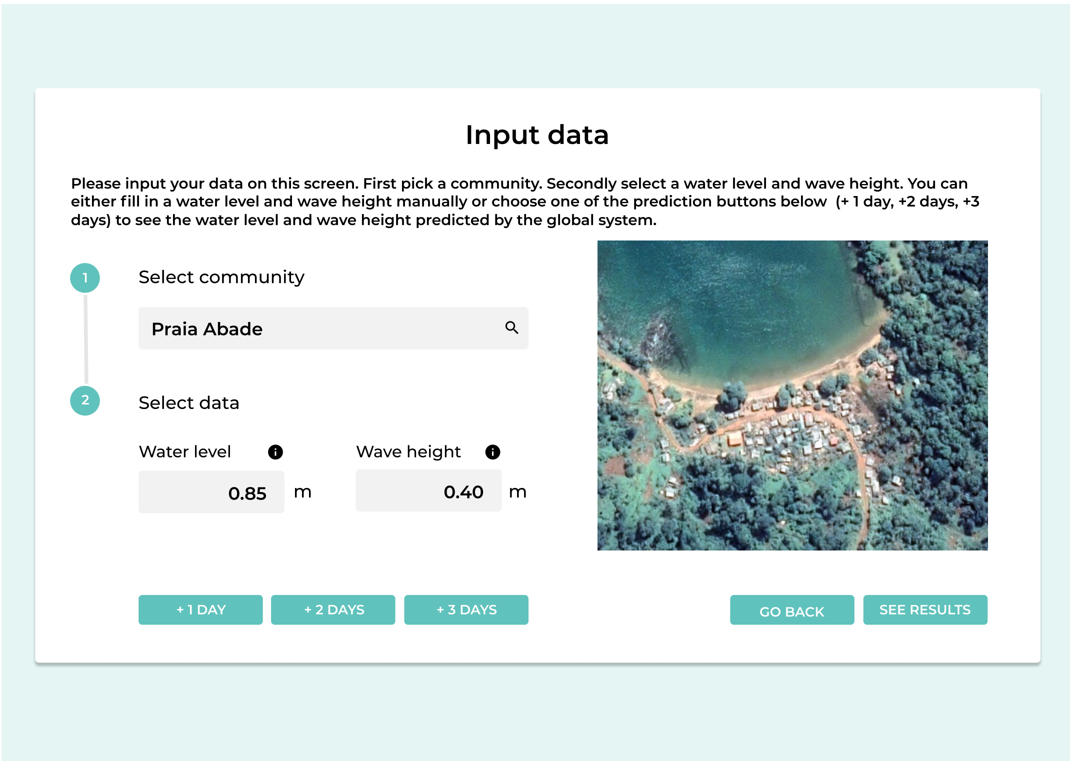


Figure 17.2: Input screen

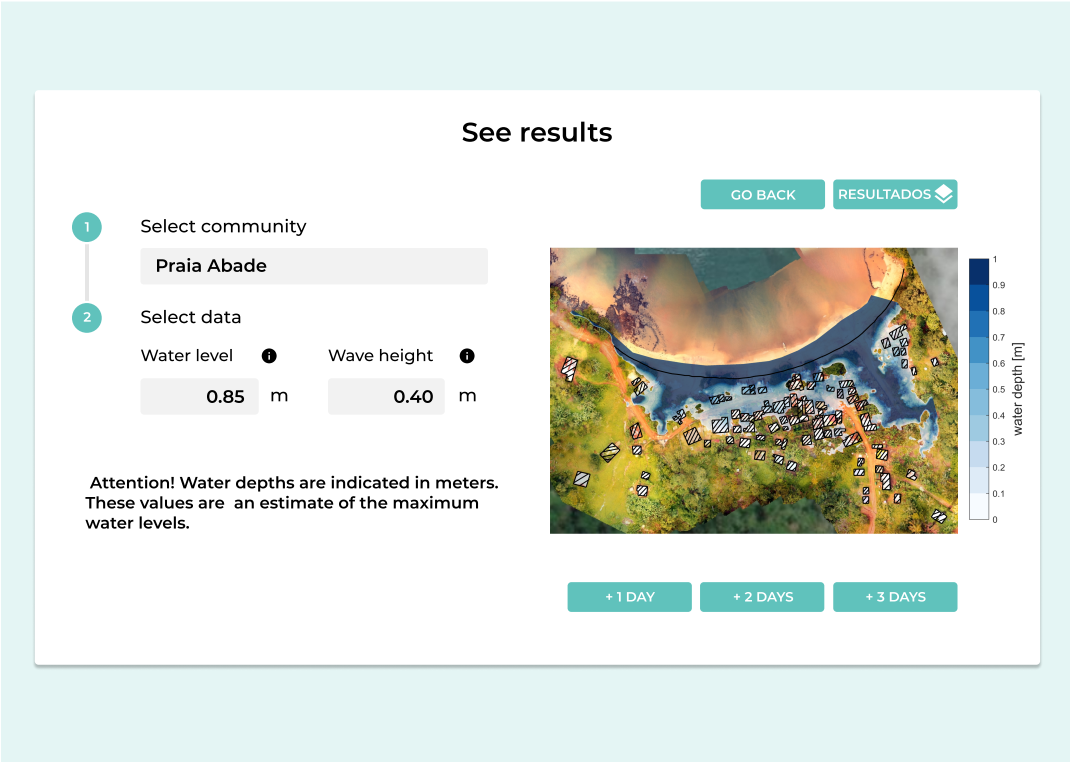


Figure 17.3: Output screen showing a flood map

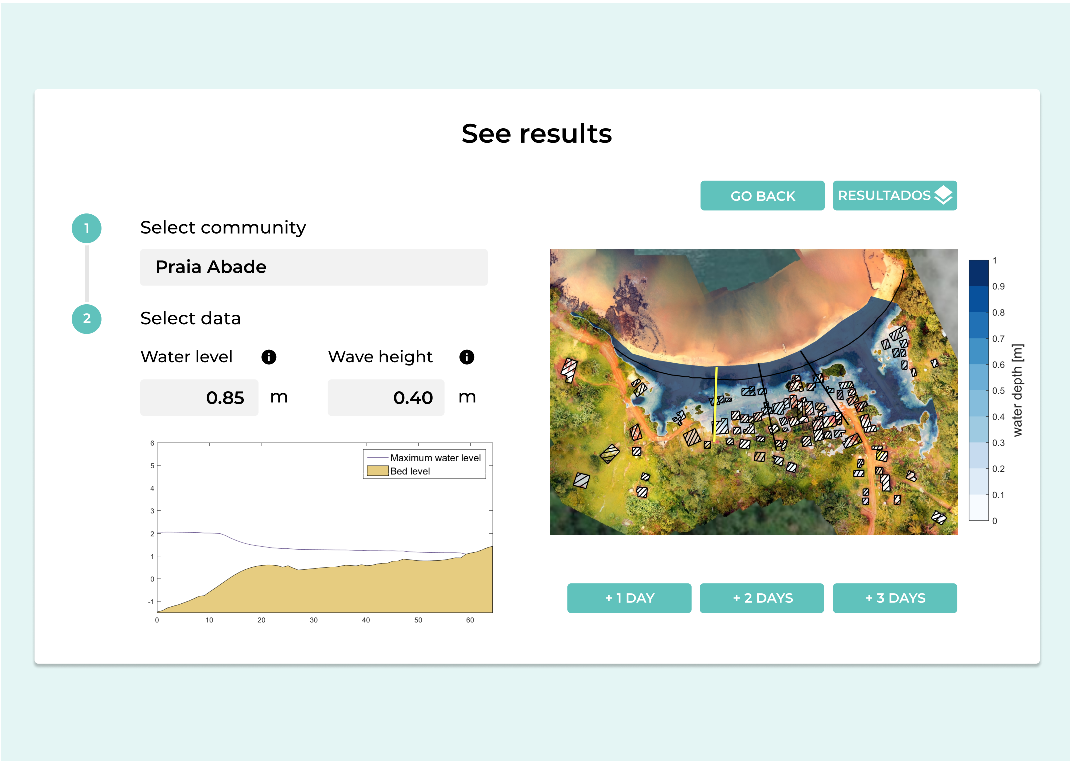


Figure 17.4: Output screen showing the water level in a cross-section

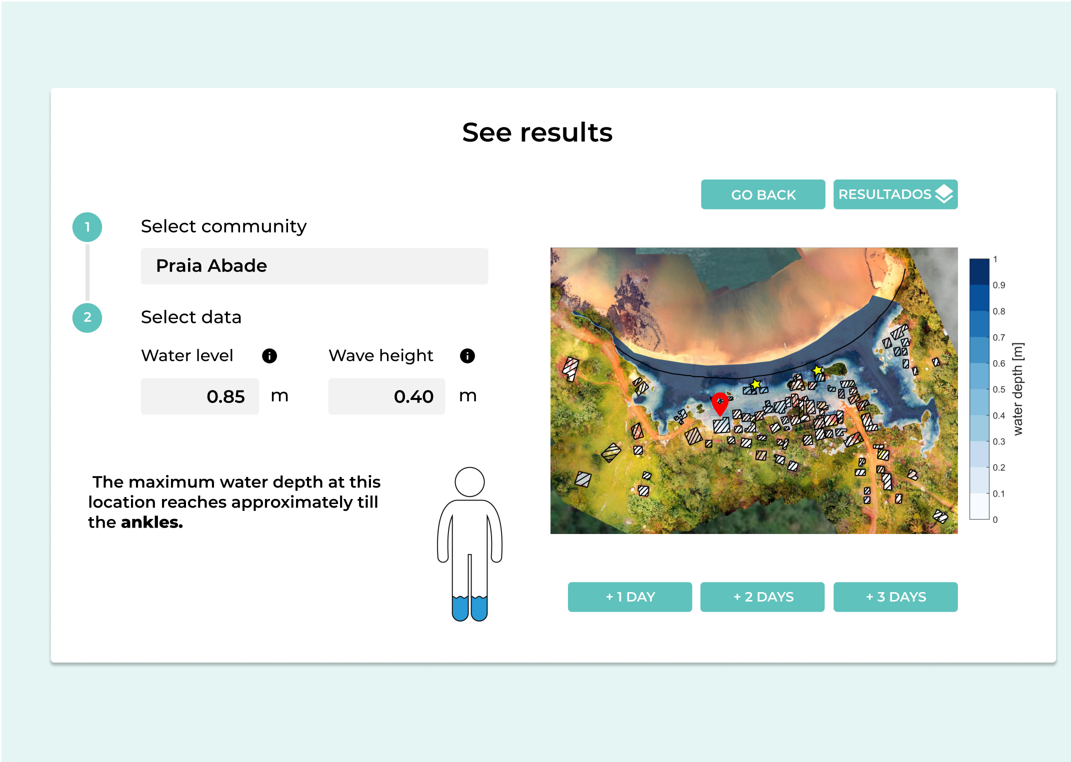


Figure 17.5: Output screen the water level at a certain location

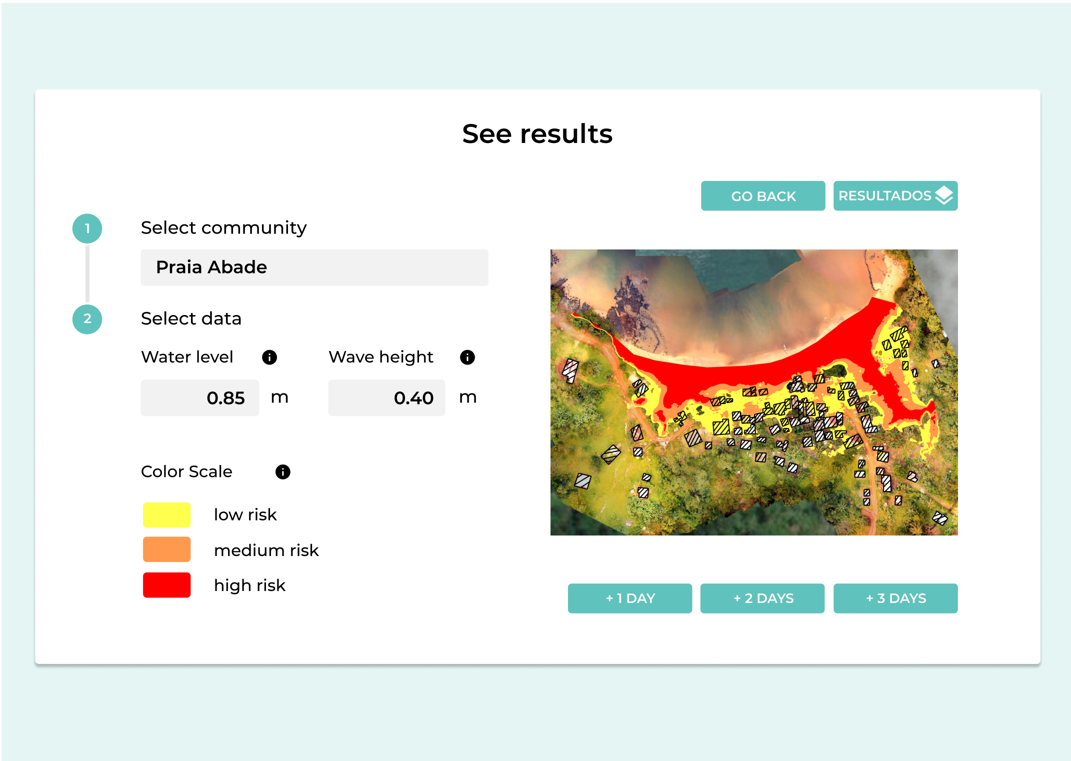


Figure 17.6: Output screen showing areas with different risks

17.2. Reflection of the tool in the context of São Tomé

There are several points that came up during the field trip that would help to improve the tool and increase its effect in the system of São Tomé. In this section, the three most important points will be discussed.

Firstly, from the interviews at the national institute of meteorology and the observatoire, it became clear that these institutions currently make use of global, instead of local, models for weather prediction. Also, for offshore water levels and wave heights, there are no local models in place and only global models can be used. During the different interviews, the interviewees mentioned that due to the small size of São Tomé relative to the grid size of most global models, these global models often give inaccurate predictions for the location of São Tomé. In order for an early warning tool for coastal flooding to work accurately in the context of São Tomé, the link with a global model for the prediction of offshore water levels and wave heights should be developed and validated. This might require quite extensive data collection, for example to gather accurate measurements of the bathymetry (i.e. the underwater topography) around the island.

Secondly, during the interview with Maria from PNUD, she explained that coastal flooding is an important risk in different coastal communities. However, in many communities flooding from the rivers that run through the communities is about equally as important. Since the storm events that lead to coastal flooding are usually accompanied by heavy rainfall, coastal and river flooding often occur simultaneously in the coastal communities. Also, the strong winds that can occur during storm events cause many problems, especially in the coastal communities (usually these winds are less strong for more inland communities). According to her, these three elements (i.e. coastal flooding, flooding from the river and strong winds) cause the most problems to the people in the coastal communities. Therefore, an early warning system that could warn the people for all three of these events combined would be really useful. However, she added that an early warning tool that only involves coastal flooding would already be a good start.

Lastly, during the interview with Carlos, the national coordinator of the central CONPREC team, he explained that even when the early warning tool for coastal flooding becomes operational, it might still be difficult to get the people in the coastal communities to listen to them and act on the information from the tool. This is especially true for long-term actions that should be taken in the communities. Carlos explained that even though they currently have no exact information on which areas are susceptible to coastal flooding (or flooding from the river), they already warn the people in the communities that they should not build on the areas close to the river or the sea. However, the central CONPREC team can only advice the people; they have no way to enforce it. Carlos furthermore explained that there are currently several institutions in São Tomé that sell or distribute land. Usually, the local governments have the power to distribute land in their districts. Currently, the local governments due not take the risk of coastal flooding into account when giving out or selling land and according to Carlos, this is the problem. You cannot blame the people to use and build the land that was given to them or that they bought. Therefore, it does not help to tell these people they should not build close to the river or the sea. Carlos mentioned that he thinks an institution should be created that has the authority to enforce this legally. This institution could use the information from the tool to determine which areas are too vulnerable to coastal flooding and should not be build. This institution should pass this information to the different institutions that give out the land (e.g. the local governments). According to Carlos, an important condition for such a system to work is that the institution giving out the information on which areas should not be build, should also have adequate resources to enforce this. A.o. this requires legal authority and enough financial resources (or support from the national police).

17.3. Chapter summary

Based on the user stories as described in Chapter 16, the design of the tool interface was iterated. The result is depicted in Figure 17.1 till 17.6.

During the fieldtrip, different points that are important to consider regarding the implementation of the simple flood tool in the context of São Tomé came up. Firstly, it is important to develop and validate the link between a global model for the prediction of offshore water levels and wave heights and the simple flood model; this might require an extensive data collection survey. Secondly, further research is recommended to investigate whether it is possible to combine the prediction of coastal flooding, river flooding and strong winds for the different coastal communities, as these often occur simultaneously during storm events. Lastly, in order to prevent people from building and living in high-risk areas, there should be an authority that has adequate resources to enforce this (e.g. legislation and support from the national police).

18
Conclusion

In this chapter, the research question as formulated in the introduction of this part (see Chapter 11) will be answered. In order to do this, first the different sub-questions will be answered. Lastly, an answer to the main research question will be formulated.

1. What is adaptive capacity and how can it be defined for a certain system?

Regarding the first research question, we can conclude that adaptive capacity represents a feedback loop in social vulnerability assessments, which is not present in technical risk assessments. When a system is exposed to certain risks, for example the risk of coastal flooding, the system will react to the consequences of these risks. Especially in the long term, this can alter the risk to the system. This response of the system is linked to its adaptive capacity; the general definition of adaptive capacity is therefore 'the ability or capacity of a system to cope, adapt or recover from a certain hazard or combination of hazards'.

Adaptive capacity is a system property; it is emergent from the different elements in a system and the interaction between these elements. Therefore, in order to analyse the adaptive capacity and identify the barriers to adaptive capacity for a certain system, a system-based approach is applied. In general, the systems that are relevant in relation to coastal flooding (and other natural hazards) can be represented by a network of actors, which are linked to each other via various interactions. Each of these actors draws on a resource base, which entails both physical and non-physical resources. The interplay between a system's actors, interactions and resources determine a system's adaptive capacity. For a specified system, the adaptive capacity related to a certain risk (e.g. coastal flooding) can be mapped by identifying the actors that are relevant in the context of this risk. Furthermore, the functions of these actors in the context of the specified risk and the interactions between the different actors need to be identified. Lastly, the resources needed by the different actors to fulfill their functions can be mapped. By assessing which barriers the different actors experience in relation to the resources that they need in order to carry out their functions, the interactions that they have with other relevant actors or the actors/functions that are missing in the system, the barriers to adaptive capacity related to a specified risk for a certain system can be identified.

2. What are the factors inhibiting the adaptive capacity to coastal flood-related disasters in São Tomé?

In order to answer the second sub-question, the theoretical framework as described in the previous paragraph was applied to the system of São Tomé in order to analyse the barriers to adaptive capacity related to coastal flooding for this system. The resulting overview of barriers to adaptive capacity and their interdependencies is depicted in Figure 15.15. The description of the different barriers and their interdependencies will not be repeated here; for this, the reader is referred to Chapter 15. However, some general conclusions regarding this overview can be made in the context of São Tomé.

First of all, from the overview in Figure 15.15, we can conclude that all barriers to adaptive capacity in the system of São Tomé are related to interactions and (a lack of) resources. Eventually, the barriers related to the interactions can be traced back to a lack of resources of the different actors. For example, the communication between the meteorological institute and the different coastal communities is very difficult, because the telephone line that the people in the coastal communities could use without charge to contact the institute does not exist anymore. It was shut down a few years ago because of a lack of financial resources at the institute. Therefore, it can be concluded that the barriers to adaptive capacity related to coastal flooding that are present in sytem of São Tomé are all directly or indirectly related to (a lack of) the resources that are present throughout the system.

Furthermore, it could be concluded that the different resources linked to a certain actor are interdependent and can influence each other. Therefore, a barrier related to one resource can cause a barrier related to another resource. In the context of São Tomé, we observe this for example in the context of the national meteorological institute. This institute experiences a lack of financial resources. This lack of financial resources also influences their capacity in terms of skilled people; they do not have enough budget to hire and/or educate enough people.

Lastly, we can conclude that the resources related to a certain actor can also influence the resources of other actors in the network. In the context of São Tomé, we saw this for example for the meteorological institute and the central CONPREC team. The lacking resources of the meteorological institute influence their ability to provide accurate and timely weather forecasts and storm warnings to the central CONPREC team. This information is an important resource for the central CONPREC team and is thus dependent on the resources related to the meteorological institute.

3. How can (part of) these inhibiting factors be adressed with a tool based on the simple flood model developed in the previous part of this thesis?

In order to answer the third sub-question, the overview of barriers to adaptive capacity related to coastal flooding for the system of São Tomé was analysed in order to identify the barriers that could be (partly) addressed with a tool based on the simple flood model. From this analysis, an overview of the barriers that could be addressed by the tool was obtained. In this overview, the barriers that cannot be addressed by the tool, but which are important to take into account in the design of the tool are also identified. This overview is depicted in Figure 16.1. From this analysis, it could be concluded that the potential users of the tool in the context of São Tomé would be the national meteorological institute (INM), the central CONPREC team and the observatoire. Since each of these potential users experiences different barriers and will use the tool in a different way, different user stories were developed for each of the potential users.

The national institute experiences a barrier related to their 'technical equipment' resource, as they currently do not have a model or way to determine whether a storm will lead to coastal flooding. This barrier could be addressed by the tool. The national meteorological institute will mainly use the tool in order to determine whether different coastal communities will experience coastal flooding during a predicted storm event. This information will be provided to the central CONPREC team. Furthermore, the meteorological institute experiences a lack of skilled people which limits their activities. This barrier cannot be addressed with the tool, but is important for its design; the simpler the tool, the better.

The central CONPREC team experiences a barrier related to the 'information' resource. Currently, the central CONPREC team does not have any information regarding coastal flooding. This barrier could be addressed by the tool. Since the central CONPREC team communicates with the coastal communities in two different ways, they will use the tool in two different ways; therefore two user stories were developed for this potential user.

The central CONPREC team communicates with the different coastal communities in an early warning context; they provide the coastal communities with warnings in case a storm event is predicted. In this early warning context, they will use (the information from) the tool to provide the local CONPREC members with information on coastal flooding in addition to the storm warnings they already give. Given the barrier experienced by the central CONPREC team related to the interaction with the local CONPREC members (i.e. this interaction can be difficult and only happens over radio and/or telephone), the most important information that the central CONPREC team needs in this context is whether or not a certain community will experience coastal flooding.

Furthermore, the central CONPREC team communicates with the different coastal communities in a training context. This entails both the training of the local CONPREC members and the sensitization sessions held with the entire community. This communication is characterized by face-to-face contact. Therefore, the central CONPREC team will use the tool to obtain visual output that is understandable to the people in the coastal communities. This information will be used to create awareness on the risks related to coastal flooding and teach the people on what to do to decrease these risks.

The observatoire also experiences a barrier related to the 'information' resource, which could be addressed by the tool. They will mainly use the tool in order to create an historic overview of coastal flood events and to produce maps indicating which areas are at risk to coastal flooding. Ideally, these maps should be combined with exposure maps, indicating the builded area. This information is relevant for the central and local government, to aid their decision-processes (for example, on which areas should not be build).

4. What could the design of a tool based on the simple flood model developed in the previous part of this thesis look like in order to address these inhibiting factors?

Based on the user stories that were developed in order to answer the third sub-question, the initial design for the tool interface was updated. The updated design for the tool interface is depicted in Chapter 17.

Eventually one tool interface was designed for all three different potential users. This decision was based on the consideration that it would be advantageous to have the different potential users use the same tool in different ways, because then they would know what the other actors are talking about when interacting with them. The different requirements of the potential users are all incorporated in the final design of the tool interface by creating multiple output screens, that visualize the results in different ways. The design of the tool interface as presented in Chapter 17 should be seen as an initial design; further development of both the simple flood model and the tool interface are still needed.

How can the simple flood model, as developed in the hydraulic engineering part of this thesis, be used to increase the adaptive capacity to coastal flood-related disasters of São Tomé?

In contrast to many models that are used in hydraulic engineering practice, the simple flood model that was developed in the hydraulic engineering part of this thesis has the potential to be implemented in a tool that can be used by people without an (hydraulic) engineering background as well.

In the context of São Tomé, such a tool could help to increase the adaptive capacity to coastal flood events that occur in different coastal communities. Currently, there are different barriers to the adaptive capacity to coastal flood events at the national level. Using a newly developed theoretical framework, an overview of the barriers to adaptive capacity to coastal flooding was created for the system of São Tomé. Not all of these barriers can be addressed by a tool based on the simple flood model. A tool based on the simple flood model could be used directly by three different actors in the system of São Tomé to adress some of the barriers that they face: the national meteorological institute (INM), CONPREC and the observatoire. These 3 actors experience different barriers related to the resources that they need to carry out their functions.

The INM experiences a barrier related to the resource 'technical equipment', as they currently do not have a way to predict coastal flooding. This barrier could be addressed by the tool, so that the INM is better able to provide CONPREC with accurate predictions regarding coastal flooding. For CONPREC, an important barrier is related to the resource 'information', as they currently do not have any information on coastal flooding. This barrier could be addressed by the tool, as they would receive more and more accurate information regarding coastal flooding from the INM. They could use this information to warn and prepare the people in the different coastal communities. Furthermore, CONPREC could use the information from the tool during trainings to raise the awareness of the people living in the coastal communities on the risks related to coastal flooding and learn them which actions to take to decrease these risks. Lastly, the observatoire also experiences a barrier related to the resource 'information'. This barrier could also be addressed by the tool, as they could use the tool to obtain information to create an overview of historic coastal flood events and maps in which the areas that are prone to coastal flooding are indicated. This information can subsequently be used by the central and local government(s).

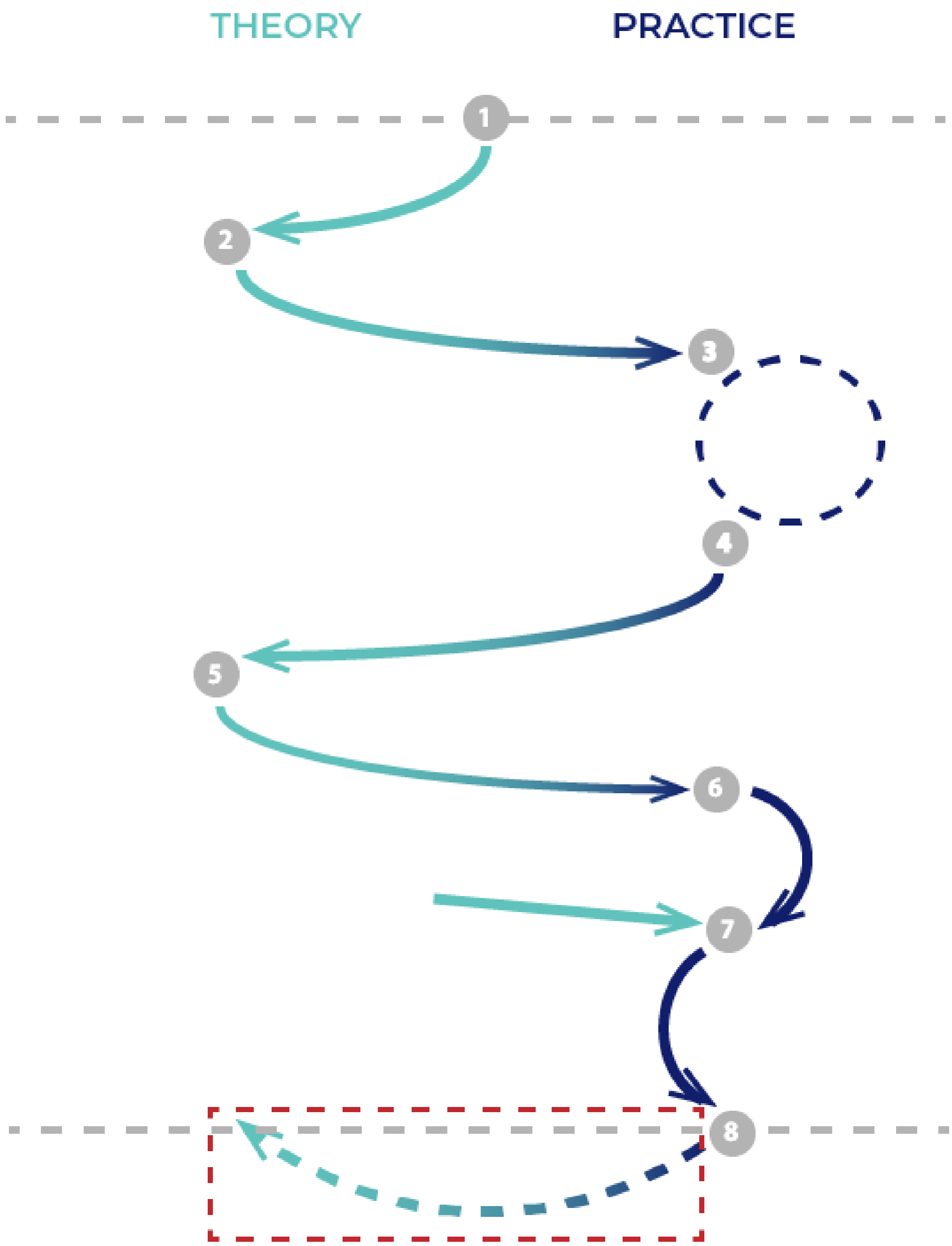


Figure 18.1: Discussion in the roadmap

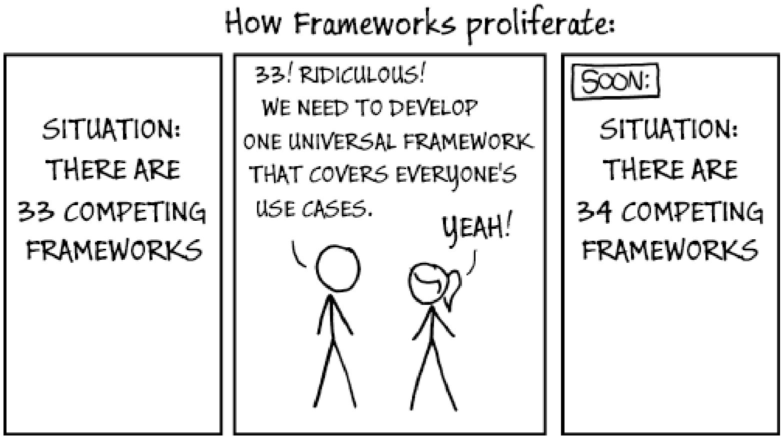
19
Discussion

The science communication part of this thesis has focused on analysing the barriers to the adaptive capacity to coastal flooding for the system of São Tomé and using these barriers to come up with a design for a tool interface that can help to adress (part of) these barriers. In other to do this, different research questions were formulated in Chapter 11. In Chapter 18, the answers to these research questions were formulated. In this chapter, the results of this study are discussed an put in a wider perspective.

In Section 19.1, the contribution of this research to the body of theory on adaptive capacity is discussed. Subsequently, in Section 19.2 different limitations of the study and their possible influences on the outcomes are described. Lastly, in Section 19.3, different opportunities for further research are given.

19.1. Contribution to theory

As part of this study, a new theoretical framework was developed with the aim to provide practical guidance in identifying and mapping the (barriers to) adaptive capacity for a certain system. Especially since there exist already quite some theoretical assessment frameworks for adaptive capacity in literature, it is useful to question whether this new framework really adds something to the current body of knowledge, or whether it is just the next framework that is added to the list. This is depicted in the comic below [1].



[1] This comic was adjusted from https://xkcd.com/927/

Despite the large amount of literature on adaptive capacity in SIDS, during the literature search for assessment frameworks for adaptive capacity in SIDS it became apparent that there are still some knowledge gaps regarding this body of knowledge. As stated by (Jones et al., 2010): "The identification of the characteristics or features that influence it [adaptive capacity] is hampered by our limited understandings of adaptive capacity.... the understandings of adaptive capacity is still very much in their infancy". The fact that the current understanding of adaptive capacity is limited is translated in the vast amount of assessment frameworks that were found in literature. Each of these frameworks is different and there is no general agreed upon framework for the identification and assessment of the adaptive capacity of a certain system. Creating a distinction between these frameworks based on the approach to adaptive capacity that was taken (i.e. qualitative vs. quantitative and top-down vs. bottom-up) helped to make sense of this seemingly chaotic overview of assessment frameworks. However, this distinction in combination with the insights obtained during the field trip to São Tomé exposed two limitations in the current assessment methods.

Firstly, each of the existing assessment frameworks for adaptive capacity regards adaptive capacity as the sum of a list of elements (i.e. either as a sum of different determinants or functions, depending on the approach that was taken). In some assessment frameworks the interdependence between these different elements is mentioned, but is not further explained. Since it was observed during the field trip that the interdependence between the different elements that make up adaptive capacity is crucial, this seriously limits the practical applicability of the different assessment frameworks as found in literature.

Furthermore, the elements that make up adaptive capacity in a certain system are very system-dependent; this makes it difficult to come up with a complete list of determinants that make up adaptive capacity. This is an important shortcoming of assessment frameworks that try to come up with a complete list of determinants; either these determinants are described in a way that does not make them applicable to all systems/ at all system scales or they are described in a very abstract way, which makes the practical translation to a specified system difficult.

The newly developed theoretical framework aims to address both limitations. By approaching the concept of adaptive capacity from a system-based perspective and defining the relevant systems as human networks, the new theoretical assessment framework provides practical guidance to mapping the (barriers to) adaptive capacity for a certain system, taking the interdependencies between the different barriers into account explicitly. Furthermore, the framework is set up in such a way that it is applicable to all systems and at different system scales, while still keeping the translation of the framework to a certain system clear. Many qualitative assessment frameworks focusing on the determinants of adaptive capacity formulate the different determinants in an abstract way. Although the abstract formulation of the different determinants makes these frameworks applicable to a wider range of systems and system scales, it also makes the application of these frameworks in a practical context less straight-forward. For example, in many assessment frameworks the 'effectiveness of institutions' is mentioned as an important determinant of adaptive capacity, but the translation of this determinant in a practical context is not clear. The different elements in the new theoretical framework (i.e. actors, interactions and resources) are also defined in an abstract way, but the application in a practical context is much more clear. Due to this abstract formulation, the general theoretical framework is applicable at a much wider range than only in the context of São Tomé and could be applied to other SIDS or developing countries as well.

In this study, the new theoretical framework was applied to the system of São Tomé. This led to a map of the barriers to adaptive capacity and made the interdependencies between these barriers explicit. This mapping exercise therefore provides a strong indication that the new theoretical framework indeed adds something the existing body of knowledge and addresses the knowledge gaps that were identified in the different existing assessment frameworks for adaptive capacity.

However, it is important to realize that this new framework still has its shortcomings. For example, the new framework does not provide a way to quantify adaptive capacity or compare the adaptive capacity of different systems to each other. This will be further discussed in Section 19.3.1. Furthermore, it is important to realize that with the new theoretical framework, the focus is very much on the current state of the system that you want to analyse. This means that even when all the barriers to adaptive capacity that are identified are addressed and 'solved', that does not mean that the system becomes a perfect adaptive system. It is very well possible that some elements, which may enhance the adaptive capacity of the total system, are not present in the current system and are therefore not identified as a barrier. For example, there is currently not an institution that works on the design and monitoring of (river) dykes, but such an institution might help to increase the adaptive capacity of São Tomé.

In that sense, it might not be possible to create one universal framework which is applicable to all situation (as suggested in the comic above). The choice for a certain framework depends on the question you want to answer and for different questions, different frameworks are needed.

19.2. Limitations

In this section, different limitations of the research and their possible influence on the outcomings of the research are discussed.

19.2.1. Interview protocol

A limitation of the research is related to the fact that the final theoretical framework that was used to map the system of São Tomé was finished after conducting the different interviews that served as the basis for the system mapping exercise. This was caused by the fact that the theoretical framework was adjusted based on insights obtained during the field trip. This influences the research in the sense that the interview protocol that was used as a basis for the semi-structured interviews with the different actors might have been different if it was based on the final theoretical framework. In the context of this study, the interview protocol was mainly based on the interview with Ilse Nederlof, who conducted a similar research in Curaçao and Aruba.

Evaluating the interview protocol in the context of the final theoretical framework led to the conclusion that the interview protocol would not have been very different. The main difference would be a slightly different perspective on the resources that each interviewee needs to carry out its tasks. In the interviews that were conducted during the field trip, the focus was on the resources that were lacking and the problems that the interviewee encountered in carrying out his or her tasks. Therefore, the different actor maps as depicted in Chapter 15, might not give a complete overview of the resources that the different actors need to carry out their tasks, but is biased towards the resources that are lacking. This bias did not influence the results and conclusions drawn in this study, as the information regarding the resources that were lacking and the problems that the different actors encountered were the most important for the final design of the tool. However, in order to get a more complete overview of the system in São Tomé, it might be important to focus on all resources instead of only the ones that are lacking.

For future studies, this would mean that the interview protocol should be adjusted. However, it is important that this is done only if it is important in terms of the final goal of the interviews, especially because it will take up more time during the interview. During the interviews that were held during the field trip, the available time for the interviews was generally limited at the side of the interviewees. This is an important constraint to keep into account.

19.2.2. Language barrier

Another important limitation of the research was the language barrier experienced during the field trip to São Tomé. Most people in São Tomé only speak Portuguese, due to the colonial past of the country. Some, more educated people, speak a little French, but almost nobody speaks English. This was an important limitation, as it restricts the conversations you can have with the local people. This language barrier influenced the interviews with the different actors and the input obtained from the people in the different coastal communities.

Since the different interviewees only spoke Portuguese and in some cases a little bit French, the interviews with the different actors were held with the help of an interpreter. The interpreter, António Ramos Aragão, spoke English pretty well, but still some difficulties occurred during the different interviews. Especially during the interviews with more technical people, like the general director of the institute of meteorology or Abnilde from the observatoire, the translation was not always complete. António mentioned that he found it more difficult to translate during those interviews, because he did not always understand the technical content. During these interviews, therefore I often had to asked for a clarification. Furthermore, I had to take this into account in the questions I asked to the interviewees (which also had to be translated); I had to make sure these questions were also understandable to António.

Apart from the fact that the conversations were sometimes more difficult, it also takes a lot more time to do an interview with an interpreter. Especially when the available time of the interviewee was limited, this meant that I had to be quite strict on the structure of the interview, so that I gathered all the important information in the set time frame. During some interviews, this meant that I had to cut-off interesting side tracks during the interview, which I would otherwise have followed.

Lastly, some interviews were with multiple people together; these interviews were especially challenging. During the planning of the different interviews, which happened during the first day of the field trip, I asked for interviews with one person at the time, since it is very challenging to have sessions with multiple people and an interpreter together. However, eventually the interviews with the national institute of natural resources and PNUD were with multiple people together. During these interviews, at some moments the interviewees started to talk all at once, or they talked for a very long time. During these moments, it was clear that some information was lost in translation, as António was not able to translate the entire conversation.

Despite these limitations experienced during the interviews, I think I still got a good overview of the system in São Tomé and the barriers that the different actors experience. However, without the language barrier, I might have obtained more detailed knowledge on the system, especially regarding the technical aspects of the different actors. During the interviews, it turned out to be very difficult to obtain information on more in-depth technical aspects, for example what exact models the different institutions were using (e.g. the weather model used by the INM, or the river flooding model used by the national institute of natural resources). It would have been nice to have some more information about this, especially because it could give an indication of the (technical) complexity that the people at the different institutions are used to work with. This could influence the design of the tool as it can give an indication of how simplified the model/tool should be.

The language barrier was also an important limitation in obtaining input from the people living in the different coastal communities. Since the interpreter was not able to come along during the field visits to the different coastal communities, it was not possible to interview the people living in the different coastal communities. Therefore, a questionnaire was made and used to obtain the input from these people. However, during the field trip it was experienced that this is not the ideal way to get input from these people. Firstly, the people living in the coastal communities never filled in a questionnaire before and are therefore not familiar with the concept. Furthermore, the people living in these communities are usually not involved in projects, even if these projects are related to their communities. Therefore, they are not used to give their opinion and are sometimes a bit shy to do so. Lastly, and maybe most importantly, many people in these communities cannot read and/or write or find it very difficult. This is especially true for the older people; most children nowadays attend primary school and learn how to read and write there. This meant that for many people, the questions had to be read to them. This was done by Andres, who accompanied me during the field visits. Andres also wrote down their answers. In the process of writing down their answers, the answers that the people in the communities gave were summarized. However, as both the people in the communities and Andres only spoke Portuguese, I did not understand the original answers that the people in the communities gave. Some information might have been lost in the process of writing down their answers to the questions.

The information that was obtained from the questionnaires was used in combination with information regarding the different coastal communities obtained during the interviews to analyse the adaptive capacity of the coastal communities on a larger scale (i.e. at the national scale). For this purpose, the information that was obtained was sufficient. However, more detailed information related to different individual coastal communities could have helped to get a better insight in the exacts needs of the local people regarding an early warning system for coastal floods. Also, it might be better known what visual information would be useful during the sensitization sessions organized by CONPREC.

19.2.3. Limited knowledge of the system (beforehand)

A last important limitation of the study was the fact that I had very limited knowledge of the system of São Tomé before the field trip. São Tomé is a small and relatively unknown country and there is not much (online) information available. This made it difficult to decide beforehand which actors would be important to interview during the field trip and to prepare for the field trip in general. I addressed this issue by talking to the different people who attended the previous trip to the island. Especially Luisa, who was responsible for the stakeholder analysis during the last field trip, could help me with identifying relevant actors in the context of my project. Also, during the field trip, some interviews were arranged on the spot. This was the case for the interviews with Abnilde from the observatoire and with Arlindo from the general directory of environment.

In the end, I think the most important actors were interviewed. However, it would have been interesting to interview someone working at one of the civil protection institutions as well (i.e. the fire department, coast guard, army or national police). During the interview with Carlos, the national coordinator of the central

CONPREC team, he explained that they work together with these institutions in case of an emergency in one of the communities. In the context of coastal flooding, probably the coast guard or the fire department would have been the most relevant. This could add to the research, since they could probably give a very practical perspective on the activities carried out in case of an emergency. However, since the interview with Carlos took place during the last day of the field trip, unfortunately it was not possible anymore to plan an interview with one of these institutions.

Although the limited knowledge of the system beforehand could be regarded as a limitation, I would like to argue that it was a benefit as well. Having little knowledge of the system beforehand really helped me to keep an open mind. If you already know a lot about the system you have to analyse, you might be biased in your focus and therefore miss certain things.

19.3. Opportunities for further research

In this section, different opportunities for further research are elaborated. A distinction is made between research opportunities focused on extending the body of knowledge regarding the adaptive capacity of SIDS (see Section 19.3.1) and more practical research opportunities (see Section 19.3.2 and 19.3.3).

19.3.1. Elaboration of the theoretical framework

The new theoretical assessment framework for adaptive capacity that was developed during this study could be further elaborated in subsequent studies. Below, two possible directions for the further development of this framework are given.

Firstly, the current framework entails the identification of relevant actors, interactions and resources in the system. In the framework a definition for these three elements is given, but it currently does not provide a categorization of these elements. Such a categorization, where for example different types of interactions are specified, could be useful because it provides a practical starting point for potential users of the framework without a science communication background. For such potential users, the current framework might still be a bit abstract and therefore difficult to apply. A categorization of the different elements could help in overcoming this difficulty.

The main difficulty in developing such a categorization is that it should be applicable to all systems. Therefore, it is difficult to develop such a categorization based on the case study of São Tomé alone. A possible approach to come to such a categorization could be to apply the current framework to multiple, different case studies. From an analysis of these different case studies, a general categorization might be derived.

A second direction for further development of the framework could be to develop a link between the current framework and the functions carried out by the system to which the framework is applied. As described above, the current framework entails the identification of a system's actors, interactions and resources that are relevant in the context of adaptive capacity to for example coastal flooding. These elements are very system-dependent; if the same mapping exercise would be carried out for São Tomé and for example the Netherlands, this would result in totally different systems. Therefore, the current framework helps in identifying the barriers to adaptive capacity for a certain system, but it does not lead to a (qualitative) measure of adaptive capacity that can be used to compare different systems to each other. In the context of the study described in this thesis, such a measure was not needed, so this limitation did not prove a problem. However, in a different context it might be desired to obtain such a measure. This could for example be relevant to an organisation like the World Bank, in order to decide how to divide its resources over different countries.

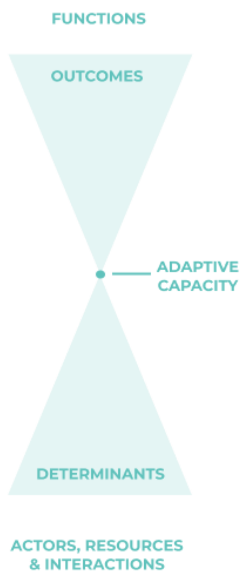


Figure 19.1: Different approaches to identify adaptive capacity

Due to the system-dependent nature of a system's actors, resources and interactions, it will be difficult to obtain a measure for adaptive capacity when focusing on these elements. This might be easier to do when focusing on the functions of the system. In Chapter 13, different qualitative assessment frameworks to adaptive capacity are described. In this chapter, it is explained that the main difference between these frameworks is the way in which the concept of adaptive capacity is approached. Most of these frameworks apply a bottom-up approach, focussing on the different determinants of adaptive capacity. However, some frameworks apply a more top-down approach, where adaptive capacity is identified based on the outcomes visible in the system. These frameworks identify certain functions that a system must be able to fulfill in order to adapt to for example coastal flood events. The extent to which the system is able to fulfill these functions is a measure of the adaptive capacity of the system. These different frameworks can be regarded as the two sides of the same coin: they both aim to identify the adaptive capacity of a certain system, but they take a different approach to do so (see Figure 19.1).

The theoretical framework developed in this thesis focuses on the determinants of adaptive capacity. As was described above, these are very system-dependent. The functions however might be formulated in such a way that they are applicable to all systems. Linking the current framework to the functions of the system could therefore provide a (qualitative) measure for adaptive capacity, which can be used to compare different systems. An important prerequisite is that the functions should be defined in such a way that they are applicable to all systems; they cannot be system-dependent.

19.3.2. Operationalization of the theoretical framework

Even when the theoretical framework is extended with a categorization for the actors, interactions and resources, there might still be a barrier to use the framework for potential users without a background in social sciences. Yet, I think there are many people without such a background for whom this framework could be useful. For example, it could be useful for international institutions like the World Bank and to consultancies like Deltares. For these parties, the framework could provide a practical tool to get an understanding of the situation in a certain context, get an overview of the different barriers to adaptive capacity in the system and help in deciding which actions are most effective. In case the actions that will be taken are already (partly) established (i.e. this was the case in the study described in this report), the framework helps to understand how exactly these actions may help and which additional actions can help to amplify its effects. Therefore, it might be a good idea to operationalize the framework by developing a tool or game based on the framework. A possible realization of such a tool could be a tangible version of the current framework as depicted in Figure 15.16.

In the study described in the report, I interviewed different stakeholders and used the input obtained from these interviews to map the system of São Tomé. However, institutions like the World Bank or Deltares might not have the time to conduct all these individual interviews. In order to address this time issue, the tool based on the theoretical framework could be used in a setting where the different actors of a specified system are asked to join. Together with these actors, the tool could be used to map the system. Such an approach would have two important advantages.

First of all, organizing such a session would be more time-efficient than conducting individual interviews. Some preparation is needed to identify the important stakeholders and organize the meeting, but this is also necessary in case individual interviews are conducted. Also, such a stakeholder or actor analysis might already be part of most projects anyway.

Second, and maybe even more important, is the fact that by creating such a map together with the different actors, this overview is not only known by the World Bank or Deltares, but to all the actors that are involved in the session. In this way, a mutually agreed upon system understanding is created. Furthermore, creating a system map during such a session may serve as a starting point to discuss the different barriers that are present in the system, the prioritization of barriers and possible solutions or actions with the different actors of the system. In this way, the tool could also be used to increase stakeholder participation in a project and increase ownership of the project by the different actors/stakeholders. I think that this could be beneficial in the context of many projects.

Such a tool might even be used by the actors in a certain system themselves, without the guidance of external organisations like the World Bank or Deltares. This would create a sort of second order adaptive capacity, as it could enable the actors in the system to identify the barriers to adaptive capacity in their system themselves. However, this might not be realistic in all contexts. During the field trip to São Tomé, I experienced that the people there have a very practical attitude and are very much solution-orientated. Such an abstract tool meant to identify the barriers to adaptive capacity might not always align with this attitude.

19.3.3. Design of the tool (interface)

Regarding the design of the tool (interface), it is important to realize that the design for the tool interface as depicted and described in Chapter 17, is still an initial design. Both the implementation of the simple flood model in combination with global models for the prediction of offshore water levels and wave heights, and the interface of the tool should be further developed and validated.

Regarding the 'technical' side of the tool (i.e. the simple flood model itself), different recommendations were already described in Chapter 17. The link between the simple flood model and global prediction models should be developed and validated in the context of São Tomé. This will require the collection of more local data, including both the topography of the different communities and the nearshore bathymetry.

The interface of the tool should be validated as well. The design of the tool interface as described in Chapter 17 is based on the information that was gathered during the field trip, but this design is not yet validated with the potential users. In the further development and validation of this tool, special attention should be paid to what visual content and/or information would be useful during the sensitization sessions organised by CONPREC in the different coastal communities. As was explained in Section 19.2.2, it was difficult to obtain input from the people living in these communities due to the language barrier. Therefure, this information could not be obtained in the current research. Ideally, this would be done in a session involving the people living in the different coastal communities. The main goal of such a session would be to investigate what visual content and/or information is most clear and useful to the people in the coastal communities. Based on the outcomes of such a session, the design of the tool could be iterated one more time.

Furthermore, it would be interesting to talk to different central governments that make use of the information that is made available by the observatoire and that have to decide on the use of land. Based on insights obtained from these interviews, the design of the tool could be further updated.

Final note

The added value of the social context

In the introduction to this report, I made a distinction between direct and indirect approaches to aid the SIDS. The final goal of both approaches is to decrease the vulnerability of the SIDS. Also, in both approaches, external parties are needed to accomplish this. The essential difference between the two approaches is the direct aim: where the direct approach aims to decrease the vulnerability of the SIDS directly, the indirect approach aims to increase the adaptive capacity of the system under consideration to a certain (range of) risk(s), so that the people living at the SIDS are better able to decrease their vulnerability themselves. The focus of the direct approach is therefore on the risk(s) to the social system, while the indirect approach focuses on the social system itself. This is schematically visualized in Figure 19.2.

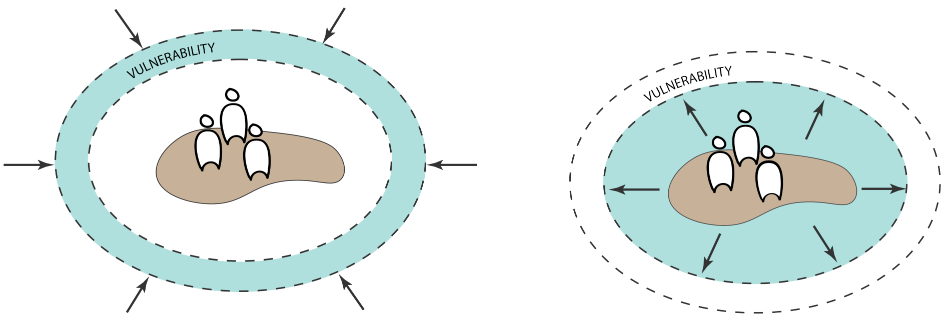


Figure 19.2: Direct and indirect approach

When applying the indirect approach, it is obvious that a thorough understanding of (the adaptive capacity of) the social system is required. However, it is important to note that although the direct approach aims to decrease the vulnerability of the SIDS directly without changing the social system, the social context is still important to take into account.

I would like to illustrate this with an example that occurred a few years ago. In September 2015, I participated in a multidisciplinary project in South-Africa, together with 5 other students with a water management or hydraulic engineering background. The project was about the flood events that occurred a few times a year in a little village called Ladysmith. One of the conclusions of this project was that these flood events were caused by a dysfunctional drainage system in the village. From a more technical perspective, the most obvious solution might be to install a new, better designed, drainage system. However, during different interviews with inhabitants of the village, we discovered that everybody dumped their garbage in the river bed and on the street, because there was not central garbage collection system in place. Also, the different fast food restaurants that popped up in the city over the last years, were used to dumping their frying fat on the street. This garbage and frying fat partly ended up in the drainage system and blocked it. Furthermore, several important parts of the pumps that were installed as part of the drainage system a few years ago got stolen. The people in this village were generally very poor and therefore some of them tried to sell these parts. Including this social context into our analysis made it clear that the design and construction of a new drainage system would not solve the problems on the long term; other, more social, measures were required as well.

I think this example highlights the importance of the social context and indicates that the best technical solution is not always the best solution. In general, I think that for many hydraulic engineering projects that aim to come up with a solution for a certain problem, it is important to consider the social context. Otherwise, there is a large risk of designing a technical solution that might not fit to the social context and therefore in the end does not lead to the desired result.

Furthermore, I think that involving the social context in a hydraulic engineering project can also add to a better technical analysis and/or design of a solution. From the hydraulic engineering part of this thesis, it was for example clear that the lack of accurate elevation data for most SIDS introduces very large errors in the calculation of flood risks for these islands. However, for the external parties aiming to help the SIDS to decrease their vulnerability, it is not feasible to collect more accurate data for all these islands by themselves. In this context, it could be beneficial to set up a measuring campaign involving the local people in the SIDS. Such citizen participation projects have been set up in other contexts as well and can be very successfull. In order to set up such a campaign successfully, it is very important to understand the local social context.

In my opinion, in order to be able to successfully work on solutions in a hydraulic engineering project, it is important to build a bridge between the technical and social perspectives and use both to come to the best analysis and/or solution. This is far from easy, but I think that the Science Communication master has given me a good foundation to work on this and hopefully to keep improving these skills in the future.

Reflection: how to analyse the social system?

As explained in the previous section, I think that in many hydraulic engineering projects, it is important to involve both the technical and social perspectives in order to come up with the best solution in a certain context. However, this is easier said than done. 'The social system' is very broad and abstract. How do you analyse 'the social system'? And how do you know what things are important?

In order to understand the difficulty in analysing a social system, I tried to find an analogy to describe a social system. Different ideas came up, but the final one is not really mine; during a meeting with Maarten he came up with the analogy of elephant trails (in Dutch: olifantenpaden), that really worked for me. He explained that a social system can be compared to the elephant trails in the jungle; there are many, many different trails, but if you take a closer look, you will notice that some of them are used more often, by more elephants. These are the most important trails and indicate the basis of the 'jungle infrastructure' for elephants. The same is true for a social system. If you want to analyse the social system in a certain context, this can get really complicated real fast. There are so many people, interests, interactions and processes going on that it becomes almost impossible to analyse everything (especially when you want to analyse the social system on a somewhat larger scale). Therefore, it is important to find the 'elephant trails' in the system; the aspects that are really important and that determine the fundamental structure of the system. These elephant trails do not only depend on the social system under consideration, but also on the content of the hydraulic engineering project. The difficulty with this is that you cannot focus on the most important trails right away. First you have to get 'into the jungle' and look around a bit before you can recognize which trails are more important. This requires an iterative process with many divergence and convergence steps; you have to scan a part of the jungle and subsequently you have to analyse what the most important trails in that part are.

I think this describes the process of the science communication part of my thesis very well. In this part, I made many iterations that each consisted of a diverging and converging part. For example, at the start of the science communication part I was looking for a definition for the term 'adaptive capacity'. In order to do this, I read a lot of literature related to this term; this was a diverging step. Subsequently, I used these studies to come up with a relevant definition of the term in the context of my thesis; this was a converging step.

In this process, I found that it really helped me to have a clear end goal of the study in mind. Already at the start of the science communication part, I had quite a clear idea of the question that I eventually wanted to answer. I wanted to know how a tool based on the simple flood model that I developed in the hydraulic engineering part of this thesis could benefit the country of São Tomé and Principe and what such a tool should look like. During the process, this really helped me to evaluate whether I was going into the right direction. For example, after I formulated a definition for the term 'adaptive capacity', I decided that this definition was not sufficient to answer my question. In order to reach the goal that I had set, I needed to know not only what adaptive capacity is, but also how to assess it. This led to the next diverging phase, in which I read a lot of studies related to assessment frameworks for adaptive capacity. At the start of my science communication thesis this happened more subconsiously, but after a while, when I realised that it really helped to take a step back sometimes, I used these 'reflection points' more deliberately.

Also, I found that it really helped to switch between theory and practice. Since science communication literature can be very abstract, I sometimes find it difficult not to loose the relation to 'the real world'. Using my observations from practice really helped me to focus and find my way trough literature. However, during this thesis I discovered that it can also work the other way around. Before I started this thesis, I had never heard of

São Tomé and Principe and before I went there for my field trip, I knew very little about this country. The only information I had came from a few reports that were available and the experience of other people at Deltares who had been there before. I think such a starting position can both be an advantage and a disadvantage. On the one hand you have much less prejudices, but on the other hand it is more difficult to know where to start. During this part of the thesis, I discovered that the literature (mostly regarding adaptive capacity) that I had read in advance really helped me to decide who I wanted to interview during the field trip and what I wanted to ask them.

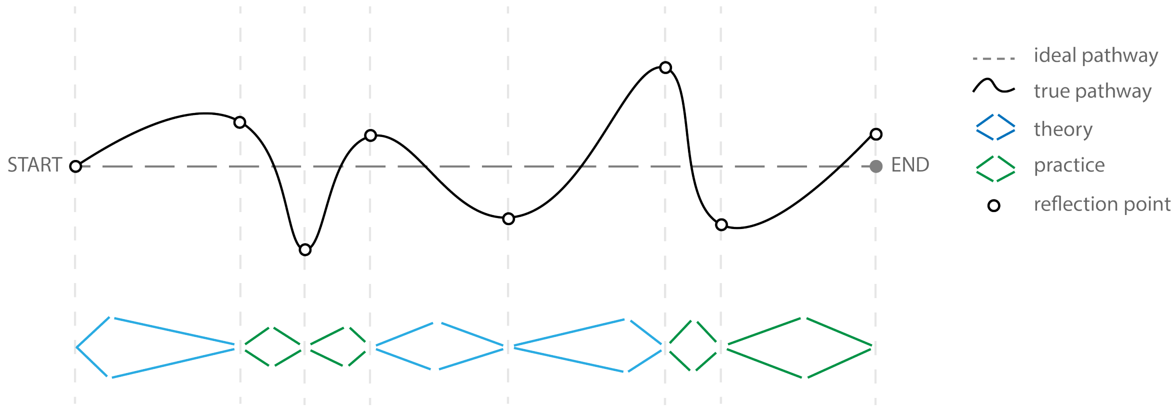


Figure 19.3: Process during Science Communication part of this thesis

In Figure 19.3, I visualized the most important aspects of the process in the science communication part of my thesis. In summary, I think the most important aspects in this process were the iteration of diverging and converging phases, the alternation between theory and practice and the reflection points that I used to decide on the next step that was needed in order to reach the final goal.

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A

Satellite-based DEMs

A.1. DEM Measuring techniques

In this appendix, a short introduction on how the publicly available satellite-based DEMs are measured. The different publicly available satellite-based DEMs are all constructed using either SAR interferometry or stereo viewing. Both measuring techniques will be shortly explained below.

A.1.1. SAR interferometry

Synthetic Aperture Radar (SAR) imaging is used to construct high-resolution, weather-independent images of the earth's surface. Since these images are constructed using radar pulses emitted by a satellite (i.e. active remote sensing), the SAR system can 'see' day and night, which makes it a very suitable technique for remote sensing. The drawback to traditional SAR is that it views a three-dimensional world in planimetric view: SAR images have no resolution in the vertical and therefore do not contain information on elevation (Uys, 2016). To measure the surface topography, the SAR interferometry technique is used. The idea of this technique is to compare, for a given area, the phase of two or more complex radar images (consisting of an amplitude and a phase) that have been acquired from slightly different positions, either simultaneously or at different moments in time. This is called across-track (or single-pass) and along-track (or repeat-pass) interferometry respectively (Moreira et al., 2013).

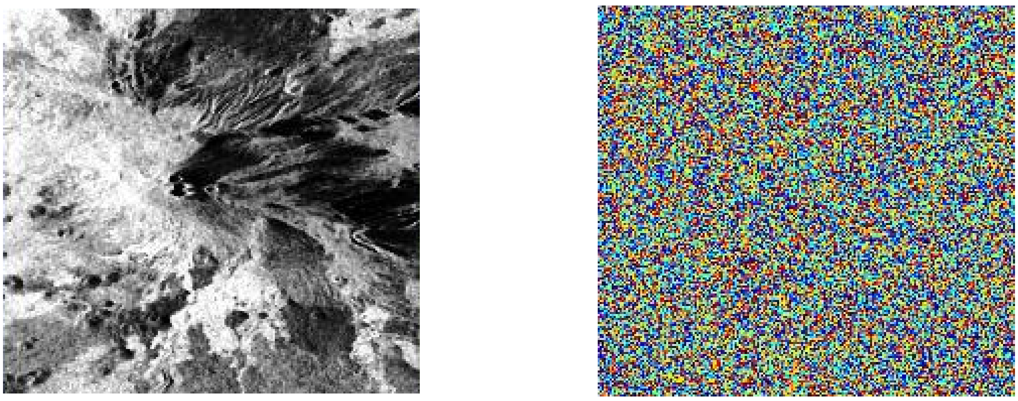


Figure A.1: SAR amplitude (left) and phase (right) of Mount Etna, Italy

Simply put, SAR works in the following way. A sensor emits a microwave pulse to the ground, this wave is scattered at the ground and travels back to the sensor. The received amplitude and phase of the backscattered wave can be used to construct an image of the ground. An example of such a picture is shown in figure A.1. The received amplitude depends on the power of the sensor, the distance between the sensor and the object and on the scene reflectivity. The received phase depends on the distance between the sensor and the object and on the so-called object phase (see equation A.1). The object-phase is dependent on the scattering process of the object and for distributed targets (i.e. the earth's surface), this is a random value. Therefore, the phase of a SAR image is usually completely random as well. This is also clear from the right image in figure A.1. Because of the unknown, random object phase, a single SAR image cannot be used to infer information about the elevation.

$$\Phi = \frac{2\pi}{\lambda} r + \Phi^{obj} \tag{A.1}$$

In order to be able to get information on the elevation, a second image is used. This image of the same area should be taken from a slightly different position. This is depicted in figure A.3. In this picture, B is the baseline between the two satellite positions, r_1 and r_2 are the satellite slant ranges, θ is the off-nadir or look angle, α is the baseline inclication, h_0 is the height of the satellite position above a reference level and z is the topographic elevation above the reference level. In case the two images are taken from slightly different positions, it is assumed that the (random) object phase for a certain pixel is the same for the two images. This means that the phase difference for a certain pixel between the two images reflects the difference in sensor-scatterer distance (or satellite slant range). This is expressed in equation A.2 en is depicted in figure A.2. From this figure it can be seen that although the two phase SAR images seem completely random, the difference of these images shows a much less random pattern, indicating that the random object scatter is indeed (close to) constant between these two images.

$$\Delta\Phi = \frac{2\pi}{\lambda} \Delta r \tag{A.2}$$

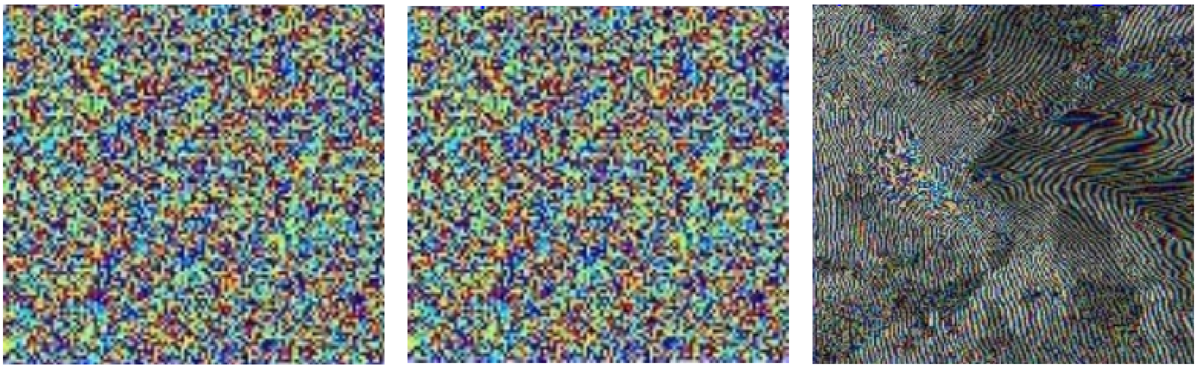


Figure A.2: Two SAR phase images and the corresponding phase interferogram

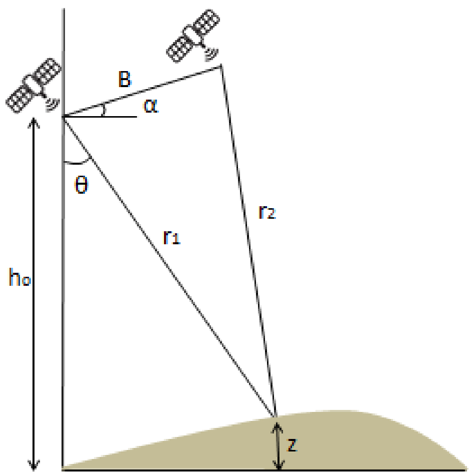


Figure A.3: Principle of SAR interferometry

This phase difference can subsequently be used to calculate the off-nadir or look-angle θ, as depicted in figure A.3. This is done using the cosine law and the relation between r1 and r2 as expressed in equations A.3 and A.4.

$$r_2^2 = r_1^2 + B^2 + 2r_1 sin(\theta - \alpha) \quad (A.3)$$

$$r_2 = r_1 + \Delta r_{12} \quad (A.4)$$

Using equation A.4 to substitute r_2 in equation A.3, equation A.5 is obtained. Since r_1 is very large with respect to Δr_{12} and B, the last two terms in this equation can be neglected. Combining this equation with equation A.2, it is possible to calculate the look-angle θ, based on the phase difference between the two images. Using this in combination with the satellite slant range r_1, the height z can be calculated, see equation A.6.

$$Bsin(\theta - \alpha) = \Delta r_{12} + \frac{\Delta r_{12}}{2r_1} - \frac{B^2}{2r_1} \quad (A.5)$$

$$h = h_0 + r_1 cos(\theta) \quad (A.6)$$

The look-angle θ can also directly be determined from equation A.3, based on r_1 and r_2. This is called the radar stereo-grammetric approach. However, r_1 and r_2 are only known with a precision of several meters, which limits the height resolution to values of around 100 m. The difference in satellite slant range Δr_{12} can be determined with sub-wavelength precision (i.e. millimeters), which highly improves the resolution of the look-angle calculation and therefore the height resolution.

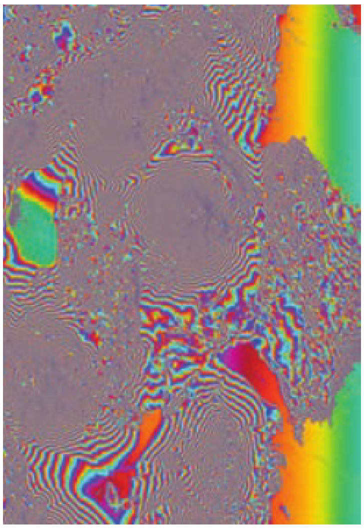
The two (or more) SAR images are not exactly overlapping. In order to be able to create an phase interferogram, the pixels of the two images have to be linked to each other. This is a complicated process (called coregistration) and one of the largest contributions in terms of computational time in the process of creating elevation maps from SAR images. When the two images are aligned, the corresponding pixels contain signals from the same points; the phase difference per pixel than contains information on the topographic height (Rees, 2001). However, before this phase difference can be linked to topographic elevation, the flat-earth contribution should be removed. A part of the observed phase difference is caused by pulses that are send back from points with the same topographic height but with a different horizontal range distance. The contribution to the phase difference by a flat surface is known and can therefore be seperated from the measured phase differences. The resulting phase interferogram contains only contributions from the topography.

The resulting phase differences after coregistration and flat-earth removal are measured modulo 2π. This means that if the phase difference between the two backscattered pulses is 3π, a phase difference of 1π is given in the interferogram. The height difference that corresponds to a phase difference of 2π is called the ambiguity height. If the height relief in a certain area exceeds the ambiguity height, the phase will be wrapped and the phase interferogram will appear as a contour map. To every phase the correct multiple of 2π has to be added; this is called 'phase unwrapping'. Phase unwrapping is a complicated process, which is not completely solved for until now. Several algorithms exist to perform this step (van Zyl, 2001). The difference between a wrapped and an unwrapped phase interferogram is shown in figure A.4.

A.2. Radar stereogrammetry

Stereo analysis, or stereogrammetry, is an older technique than SAR interferometry and is often assumed a more robust method (Gelautz et al., 2003). It is based on the more general technique of photogrammetry, which is depicted schematically in figure A.5. In this figure the point P, with coordinates (x, y, h), is imaged at the point P' on the film, where the coordinates of P' are (x', y', H+f). x' and y' can be derived mathematically by equation A.7 and A.8. For a horizontal surface with no relief (i.e. h=0 at all locations), the image of this surface has a constant scale of f/H.

$$x' = -\frac{fx}{H-h} \quad (A.7)$$



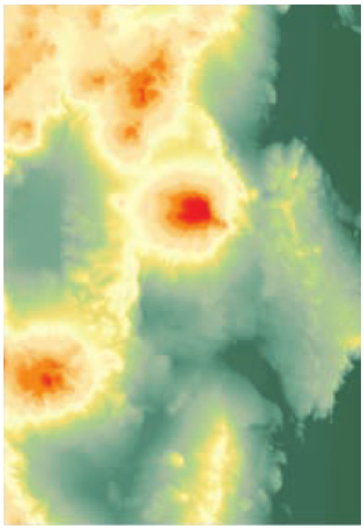


Figure A.4: Wrapped image (left) and unwrapped image (right) of the Atacama desert in Chile (Moreira et al., 2013)

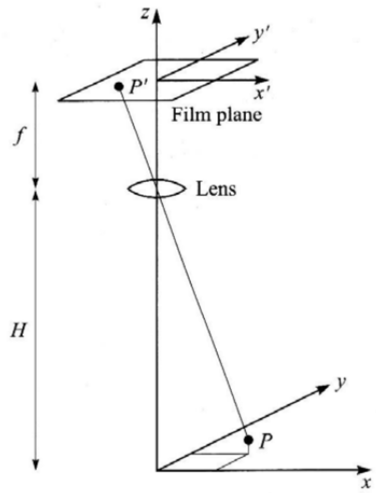


Figure A.5: Principle of photogrammetry (Rees, 2001).

$$y' = -\frac{fy}{H-h} \tag{A.8}$$

From these equations it can be seen that points with the same horizontal position but a different height will be imaged at different locations on the film. For example, the base of a tower with coordinates (x, 0, 0) will be imaged at (-fx/H, 0) and the top of this tower with coordinates (x, 0, h) will be imaged at (-fx/[H-h]). So, these points are seperated on the film by a height-dependent amount, as illustrated in figure A.6. This phenomenon is called relief displacement and can be used to infer elevation information from optical images. The height-dependent distance h' is the projection of the height h on the film and is given by A.9.

$$h' = \frac{fx}{H-h} - \frac{fx}{H} = \frac{hfx}{H(H-h)} = \frac{hx'}{H-h} \tag{A.9}$$

This equation can be simplified to A.10, assuming that the height of the lens above the ground surface H is much higher than the height of the point h. This equation shows that the height of a vertical object can be inferred from a single vertical aerial photograph, if the height H is known and if the object is not located in the principal point of the lens (i.e. if the object would be located at (0, 0, h) in figure A.5, the height cannot be obtained).

$$h' = \frac{hx'}{H} \tag{A.10}$$

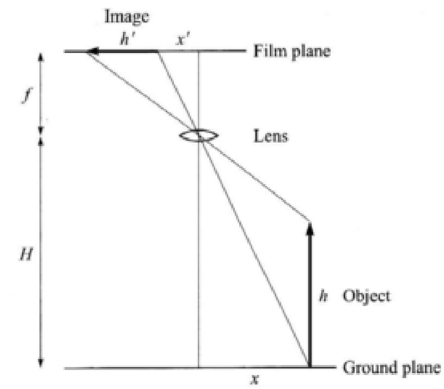


Figure A.6: Relief displacement (Rees, 2001).

There are two conditions that have to be met in order to be able to infer the elevation of an object from a single vertical aerial photograph. First, the object must not be located in the principal point of the lens and second of all, both the top and bottom of the object must be visible in the image. Especially the second condition is often not met in the case of topographic features. These restrictions can be overcome if not one, but two aerial images are used. This is called stereo viewing or stereophotography and is schematically depicted in figure A.7. With this technique not one, but two images are taken from two different positions at the same height, but horizontally separated by a distance B, called the baseline.

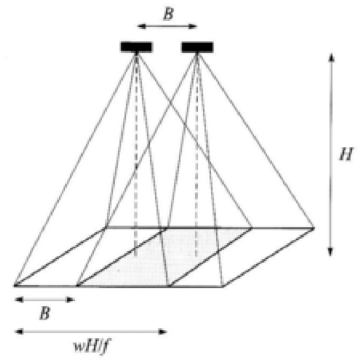


Figure A.7: Principle of stereophotography (Rees, 2001).

Now, there are two cameras at positions (0, 0, H) and (B, 0, H) taking an image of the ground surface. For points that are located in the overlapping area of the two images, the elevation can be calculated. A certain point with coordinates (x, y, h) will be imaged at (x', y') in the first image (relative to the principal point of the first image) and at (x'_2, y'_2) in the second image (relative to the principal point of the second image). x'_2 and y'_2 can be derived with equations A.11 and A.12. In this example, y'_2 will be the same as y'.

$$x'_2 = -\frac{f(x-b)}{H-h} \tag{A.11}$$

$$y'_2 = -\frac{fy}{H-h} \tag{A.12}$$

From x', x'_2 and y' (or y'_2), the object coordinates x, y and h can be calculated using equation A.13, A.14 and A.15.

$$x = -\frac{x'B}{x' - x'_2} \tag{A.13}$$

$$y = -\frac{y'B}{x' - x'_2} \tag{A.14}$$

$$h = H + \frac{fB}{x' - x'_2} \tag{A.15}$$

The baseline length B for stereo viewing is often larger than the baseline length for SAR interferometry (Gelautz et al., 2003). The difference in relief displacement between two images is directly linked to the baseline length. This can be seen from the comparison of equations A.7 and A.11. From these equations it can be seen that the difference in relief displacement between the two images is equal to $Bf/(H-h)$. The difference in relief displacement, and thus the accuracy of the measured elevations, increases for increasing baseline lengths. However, a larger baseline length will also decrease the overlap between the two different images. In practice, a reasonable compromise between a maximum overlap area and a high height accuracy has to be found (Rees, 2001).

B

Error statistics

B.1. Conversion of the vertical reference level for the different DEMs

In this section the conversion of the vertical datum for the different reference and satellite-based DEMs is described.

The measured DEM for the island of Ebeye is based on GPS measurements, which are referenced to the WGS84 ellipsoid. The DEM was converted to MSL by substracting the GPS measurement for local MSL (equal to 31.4 m) from the measured values. This value was used in combination with the EGM08 geoidheights (with respect to the WGS84 ellipsoid) to convert the measured DEM for Ebeye to the EGM08 datum.

The measured DEM for the island of Roi Namur was referenced to the WGS84 ellipsoid and could be converted to the EGM08 datum using the EGM08 geoidheights. The same was true for the measured DEM of Majuro. As described above, this DEM is referenced with respect to a local model representing local MSL. On request, the USGS provided the DEM for Majuro with respect to the WGS84 ellipsoid, that was subsequently converted to the EGM08 datum.

The measured DEMs for the Wadden islands are referenced with respect to NAP. From the PCTrans tool, a geodetic tool developed by the Dutch ministry of Defense, a map with the NAP levels with respect to the WGS84 ellipsoid was obtained (Ministerie van Defensie, 2019). This map in combination with the EGM08 geoid heights was used to convert the measured DEMs for the Wadden islands to the EGM08 datum.

For the islands of Tutuila, Aunu'u and Ofu-Olosega, the measured DEMs were referenced with respect to the NAVD83 datum (North American Vertical Datum 1983). The vertical datum of these measured DEMs was converted from NAVD83 to EGM08, using the online VDatum tool. This tool is developed by the National Ocean Service in order to transform elevation data among a variety of ellipsoidal, geoidal and tidal vertical datums.

The different satellite-based global DEMs were all converted to the EGM08 datum using EGM96 geoidheight and EGM08 geoidheight maps. These geoidheight maps are referenced with respect to the WGS84 ellipsoid and were obtained using the geoidheight function in Matlab.

B.2. Coral atolls

In this section, the results from the error analysis described in chapter 3 are given for the coral atolls. For each island, the error statistics, the histograms of the DEM error for the different satellite-based DEMs, the difference plots and the unbiased difference plots are given.

B.2.1. Ebeye

Error statistics

Table B.1: Error statistics for the island of Ebeye

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	1,74	2,13	1,35	2,45	1,73	-3,49	6,74	3,69
ASTER	5,42	5,45	2,00	5,97	2,50	-2,35	13,23	8,54
MERIT	0,76	1,64	1,45	1,93	1,77	-4,34	4,83	3,07
SRTM	1,20	1,56	1,11	1,85	1,41	-3,10	5,25	2,94
SRTMvf	1,12	1,60	1,19	1,87	1,50	-3,44	4,60	2,90
TanDEM-X	-0,27	0,92	0,94	1,23	1,20	-4,07	3,62	2,22

Histograms DEM error

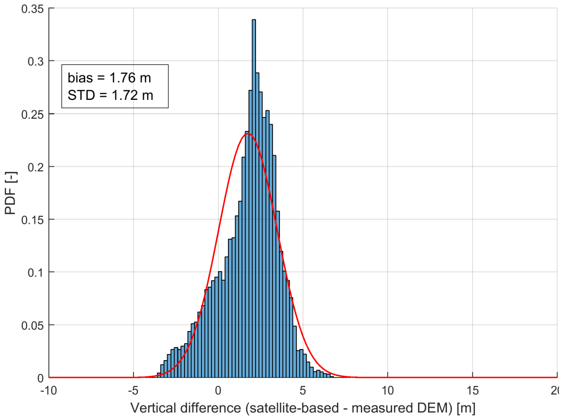


Figure B.1: Histogram DEM error ALOS, Ebeye

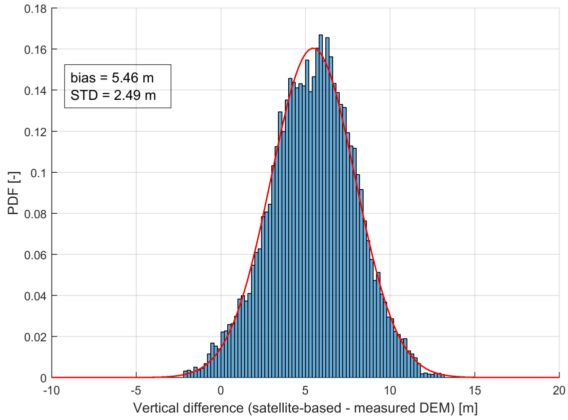


Figure B.2: Histogram DEM error ALOS, Ebeye

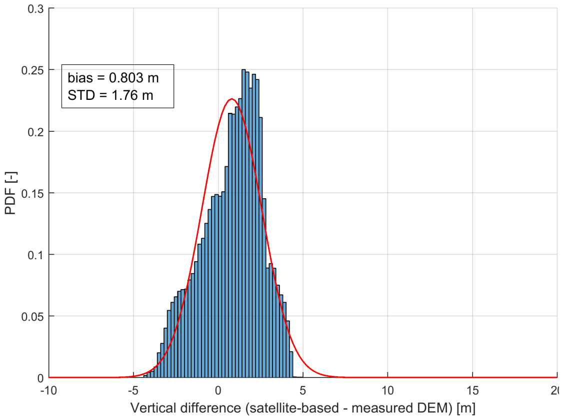


Figure B.3: Histogram DEM error MERIT, Ebeye

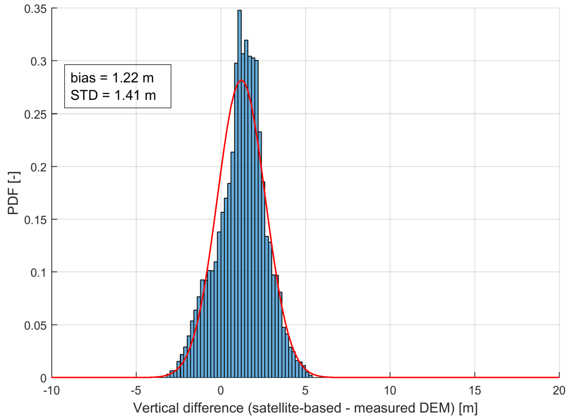


Figure B.4: Histogram DEM error SRTM, Ebeye

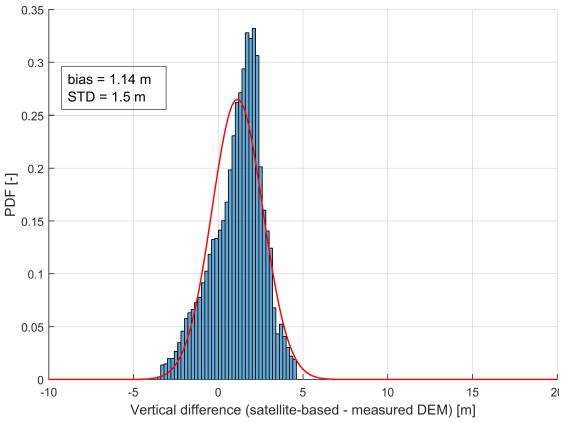


Figure B.5: Histogram DEM error SRTMvf, Ebeye

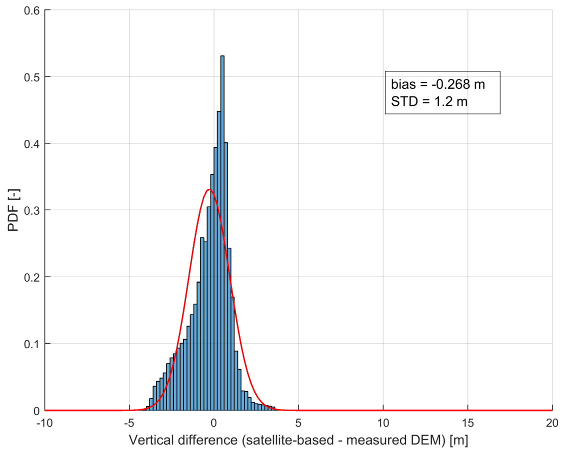


Figure B.6: Histogram DEM error TanDEM-X, Ebeye

Difference plots

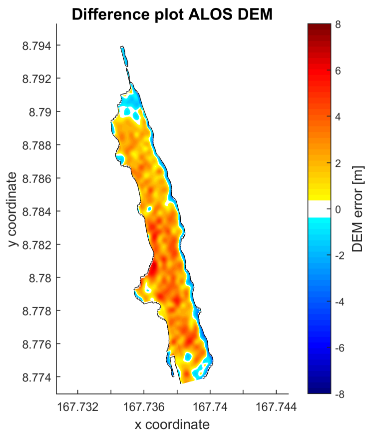


Figure B.7: Difference plot ALOS, Ebeye

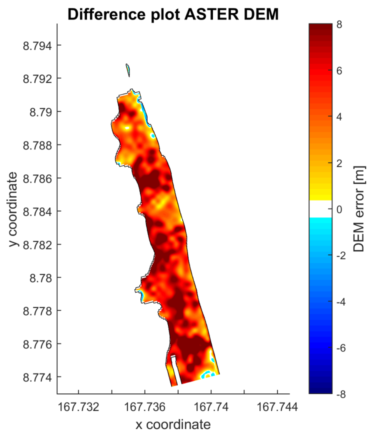


Figure B.8: Difference plot ASTER, Ebeye

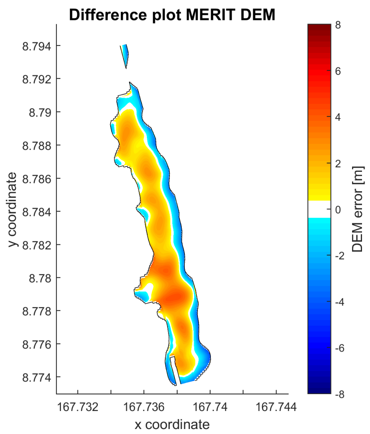


Figure B.9: Difference plot MERIT, Ebeye

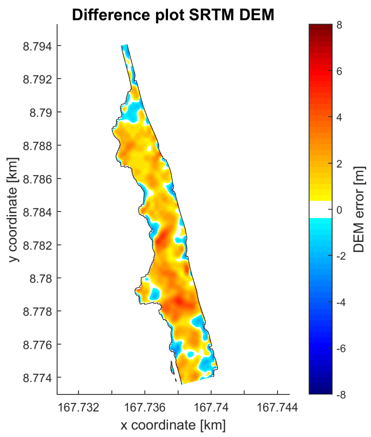


Figure B.10: Difference plot SRTM, Ebeye

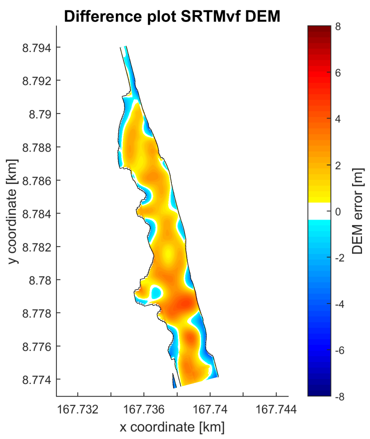


Figure B.11: Difference plot SRTMvf, Ebeye

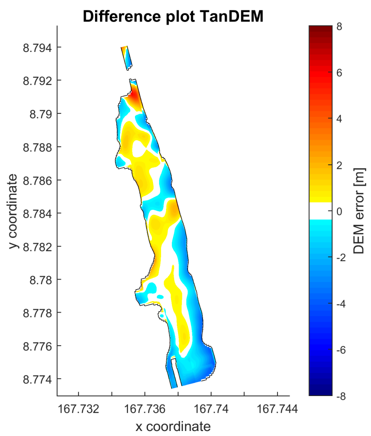


Figure B.12: Difference plot TanDEM-X, Ebeye

Unbiased difference plots

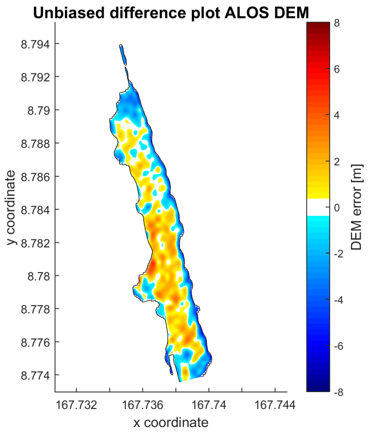


Figure B.13: Unbiased difference plot ALOS, Ebeye

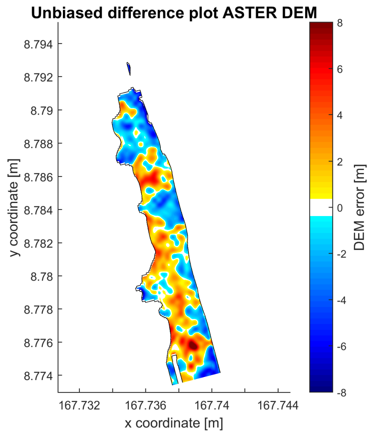


Figure B.14: Unbiased difference plot ASTER, Ebeye

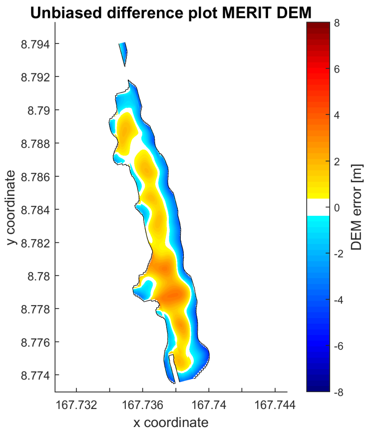


Figure B.15: Unbiased difference plot MERIT, Ebeye

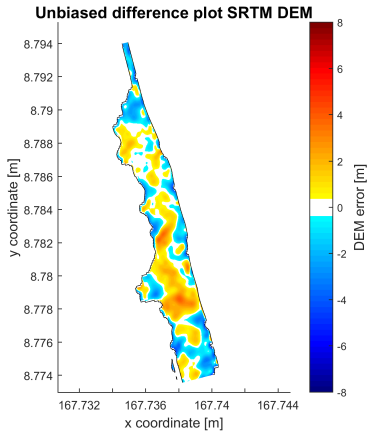


Figure B.16: Unbiased difference plot SRTM, Ebeye

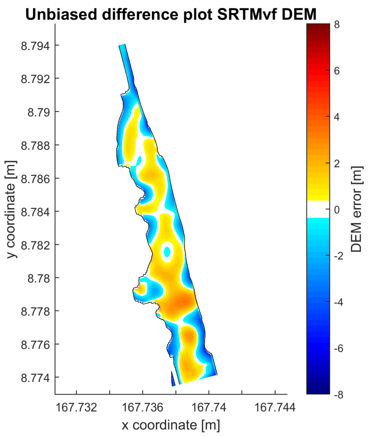


Figure B.17: Unbiased difference plot SRTMvf, Ebeye

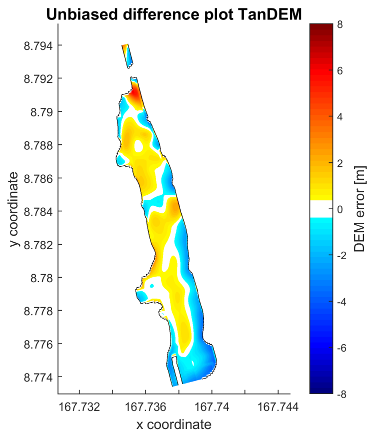


Figure B.18: Unbiased difference plot TanDEM-X, Ebeye

B.2.2. Roi Namur

Error statistics

Table B.2: Error statistics for the island of Roi Namur

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	2,05	2,36	1,39	2,85	1,99	-4,45	8,68	4,50
ASTER	7,13	7,30	2,50	7,88	3,35	-3,32	17,49	11,07
MERIT	1,54	1,92	1,42	2,34	1,76	-3,76	5,96	3,99
SRTM	1,75	2,25	1,72	2,78	2,16	-4,80	8,31	4,66
SRTMvf	1,62	1,98	1,48	2,44	1,82	-3,89	6,09	4,18
TanDEM-X	0,11	1,64	1,65	2,02	2,02	-9,80	6,73	3,34

Histograms DEM error

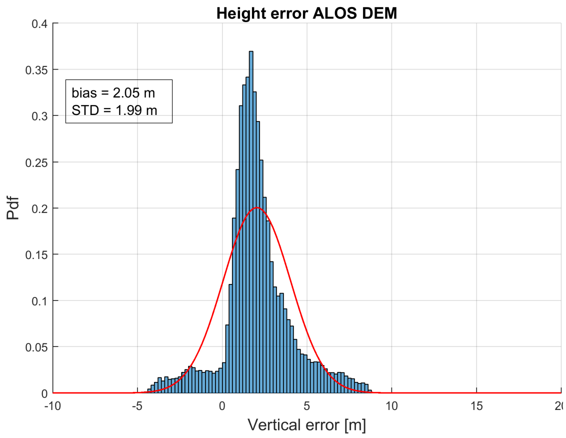


Figure B.19: Histogram DEM error ALOS, Roi Namur

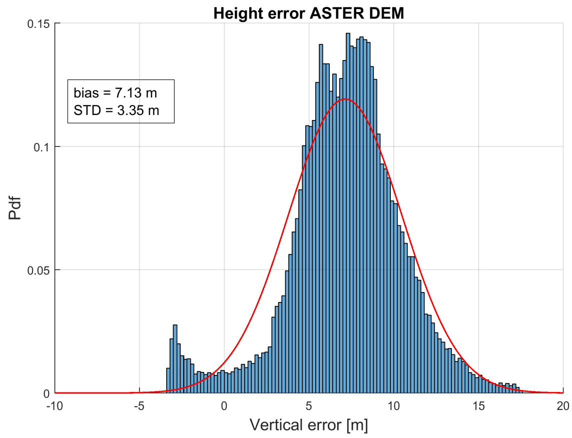


Figure B.20: Histogram DEM error ALOS, Roi Namur

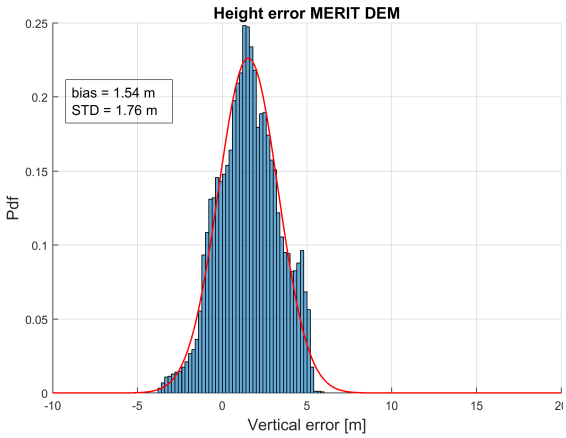


Figure B.21: Histogram DEM error MERIT, Roi Namur

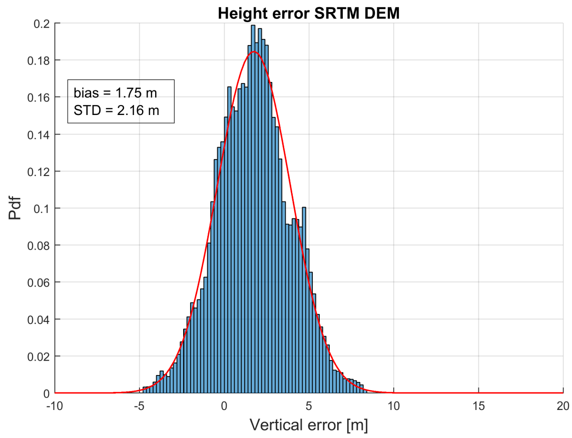


Figure B.22: Histogram DEM error SRTM, Roi Namur

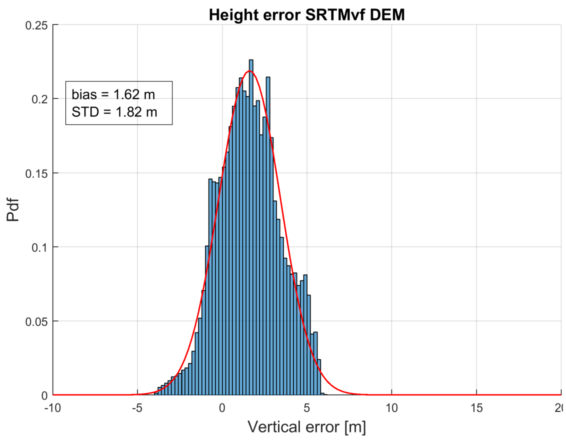


Figure B.23: Histogram DEM error SRTMvf, Roi Namur

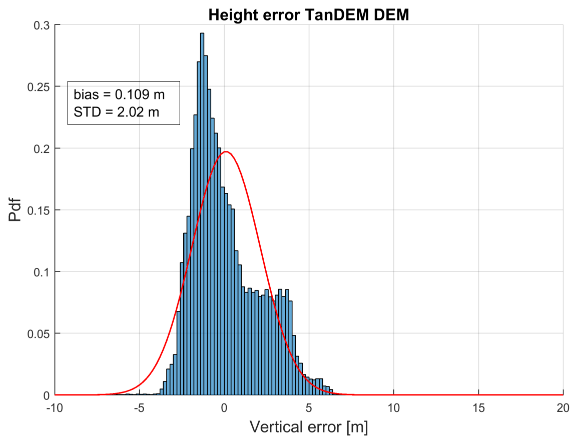


Figure B.24: Histogram DEM error TanDEM-X, Roi Namur

Difference plots

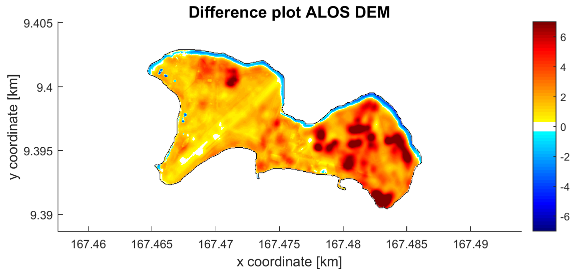


Figure B.25: Difference plot ALOS, Roi Namur

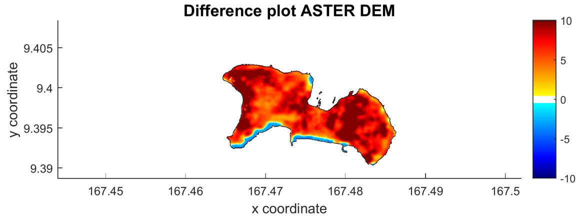


Figure B.26: Difference plot ASTER, Roi Namur

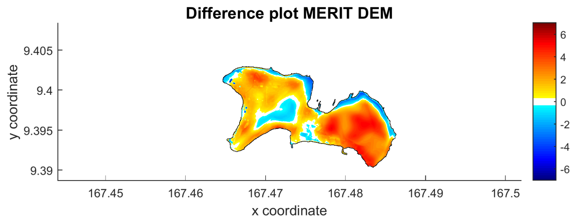


Figure B.27: Difference plot MERIT, Roi Namur

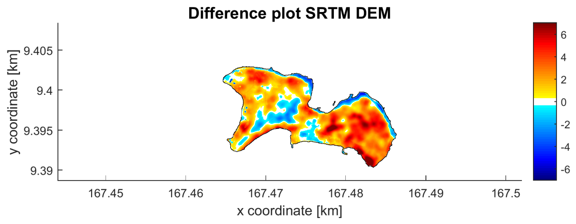


Figure B.28: Difference plot SRTM, Roi Namur

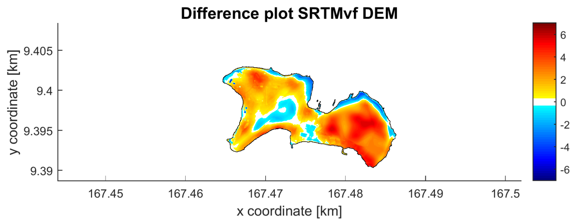


Figure B.29: Difference plot SRTMvf, Roi Namur

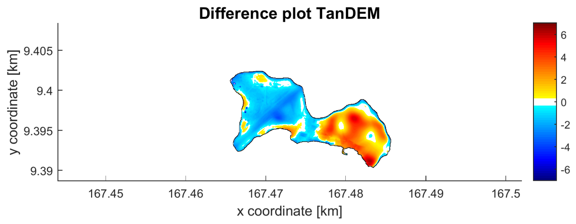


Figure B.30: Difference plot TanDEM-X, Roi Namur

Unbiased difference plots

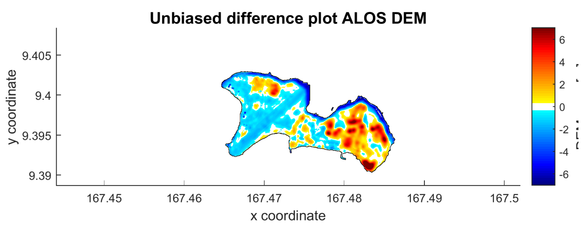


Figure B.31: Unbiased difference plot ALOS, Roi Namur

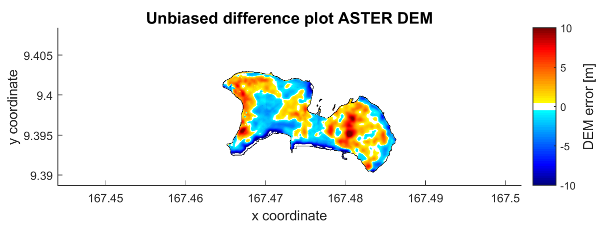


Figure B.32: Unbiased difference plot ASTER, Roi Namur

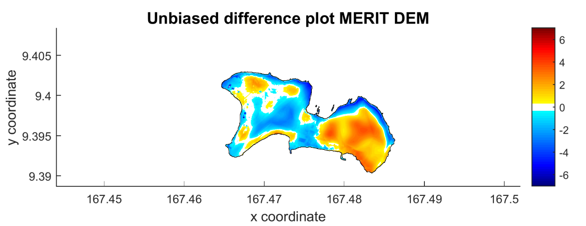


Figure B.33: Unbiased difference plot MERIT, Roi Namur

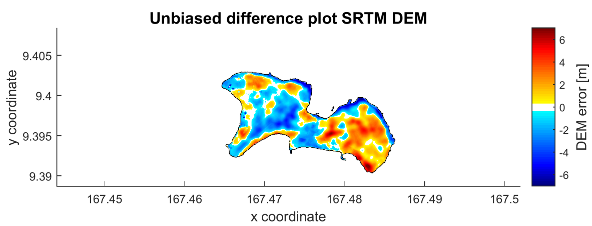


Figure B.34: Unbiased difference plot SRTM, Roi Namur

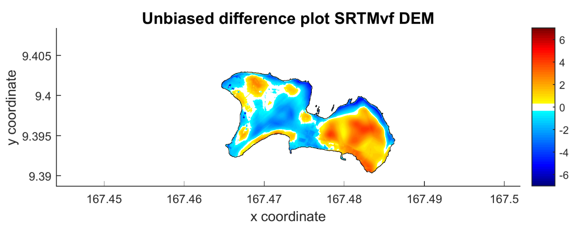


Figure B.35: Unbiased difference plot SRTMvf, Roi Namur

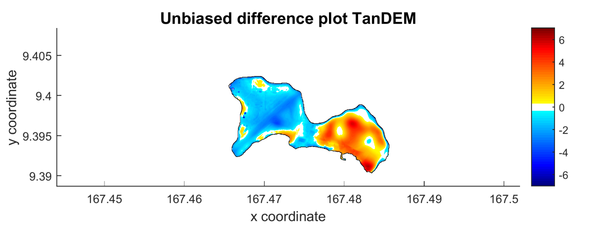


Figure B.36: Unbiased difference plot TanDEM-X, Roi Namur

B.2.3. Majuro

For the island of Majuro, only the error statistics and histograms of the DEM error are included in this appendix. Due to the size and shape of the island, both the difference plots and unbiased difference plots cannot be displayed clearly in a report of A4 size. For these plots, please contact the author (martinerottink@hotmail.com).

Error statistics

Table B.3: Error statistics for the island of Majuro

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	2,23	2,31	1,07	2,65	1,43	-3,28	8,03	3,96
ASTER	7,34	7,37	2,85	8,17	3,59	-3,57	18,31	12,27
MERIT	1,83	2,10	1,53	2,67	1,94	-4,62	8,56	4,43
SRTM	2,77	2,93	1,88	3,66	2,39	-4,92	10,68	6,04
SRTMvf	2,03	2,27	1,59	2,88	2,04	-4,65	8,96	4,79
TanDEM-X	0,83	1,60	1,59	2,19	2,03	-8,26	11,74	3,44

Histograms DEM error

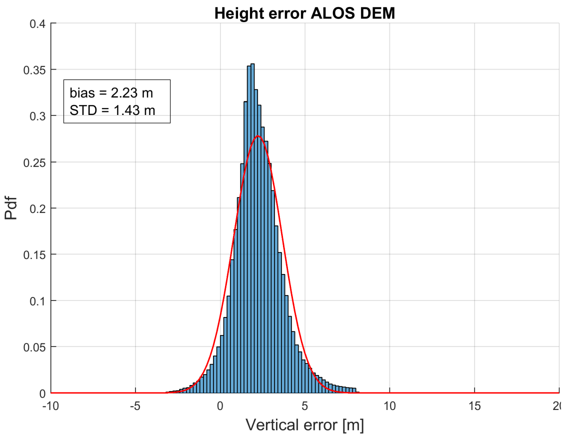


Figure B.37: Histogram DEM error ALOS, Majuro

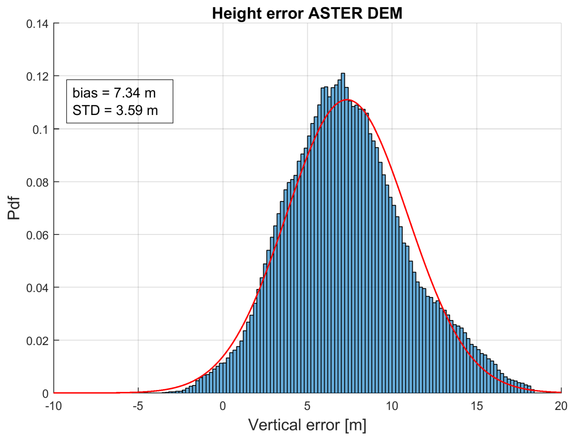


Figure B.38: Histogram DEM error ALOS, Majuro

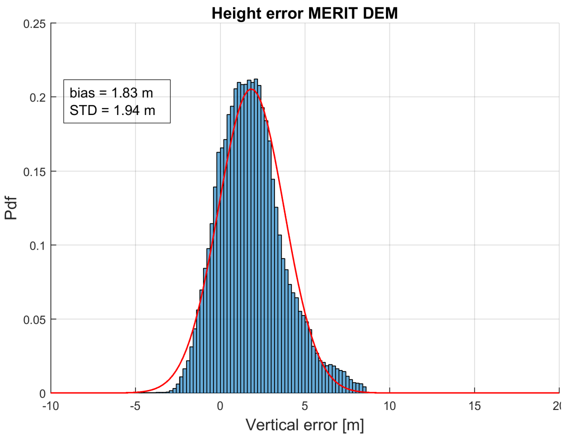


Figure B.39: Histogram DEM error MERIT, Majuro

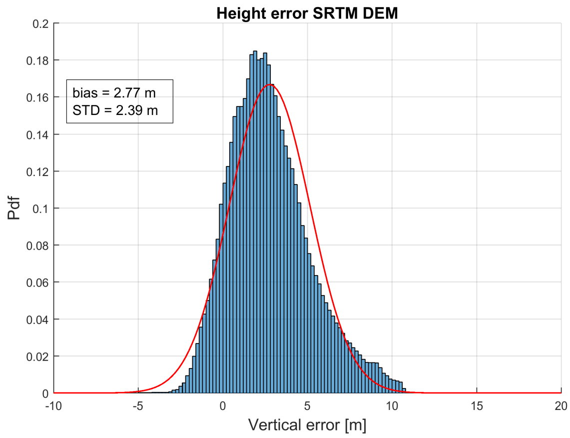


Figure B.40: Histogram DEM error SRTM, Majuro

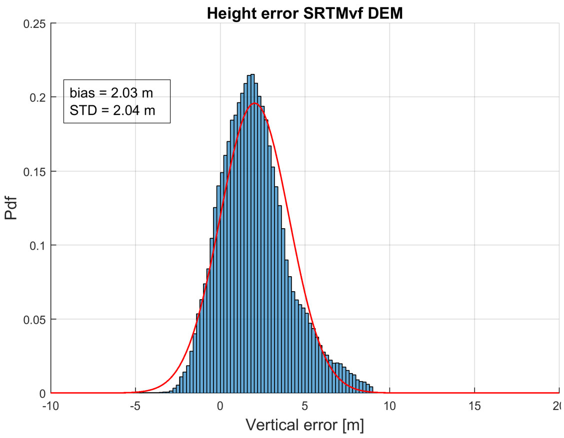


Figure B.41: Histogram DEM error SRTMvf, Majuro

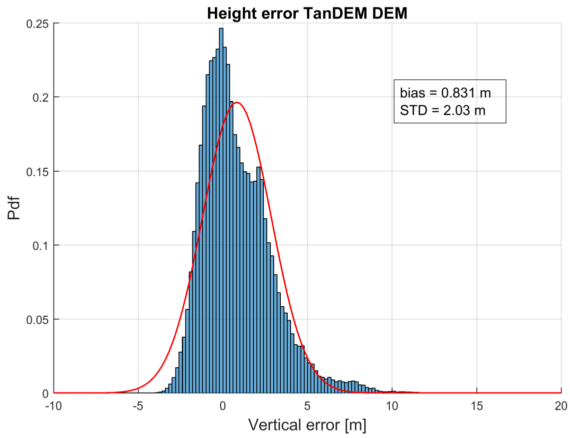


Figure B.42: Histogram DEM error TanDEM-X, Majuro

B.3. Wadden islands

In this section, the results from the error analysis described in chapter 3 are given for the Wadden islands. For each island, the error statistics, the histograms of the DEM error for the different satellite-based DEMs, the difference plots and the unbiased difference plots are given.

B.3.1. Texel

Error statistics

Table B.4: Error statistics for the island of Texel

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	-0,94	1,64	1,31	2,04	1,81	-8,66	7,26	3,12
ASTER	7,27	7,33	2,26	7,86	2,98	-2,97	17,50	10,62
MERIT	-0,60	0,78	0,59	1,03	0,84	-4,22	2,81	1,54
SRTM	-1,02	1,33	0,89	1,59	1,23	-6,16	4,44	2,42
SRTMvf	-1,01	1,28	0,81	1,53	1,15	-5,96	4,20	2,19
TanDEM-X	0,26	0,75	0,82	1,52	1,49	-9,42	10,17	1,88

Histograms DEM error

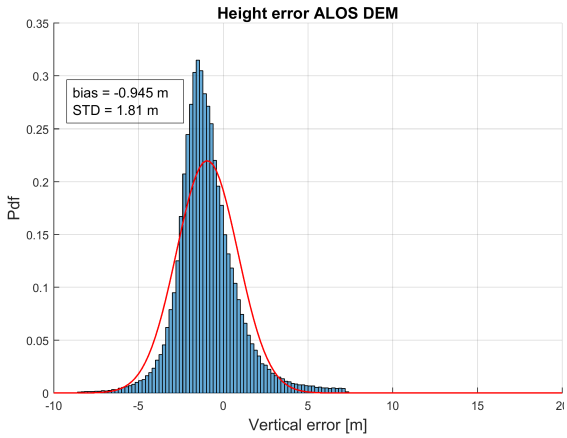


Figure B.43: Histogram DEM error ALOS, Texel

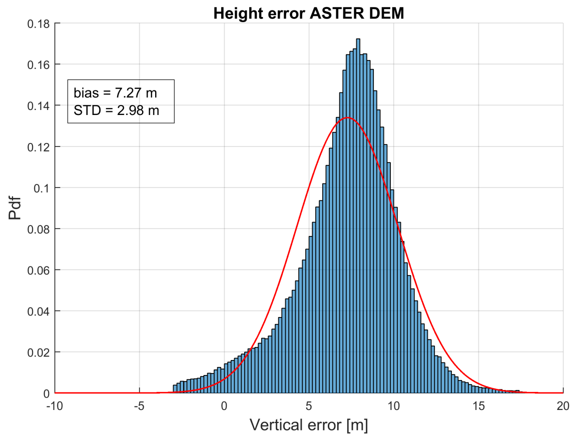


Figure B.44: Histogram DEM error ALOS, Texel

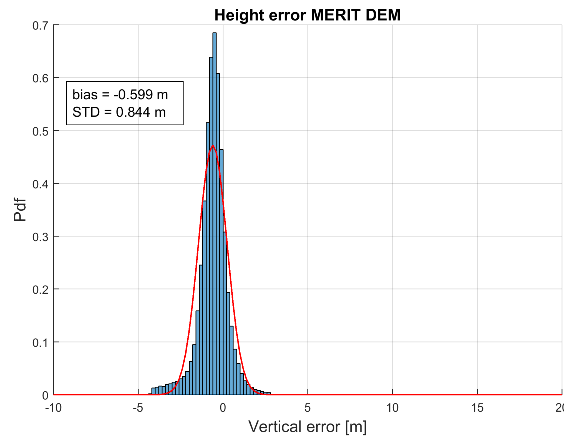


Figure B.45: Histogram DEM error MERIT, Texel

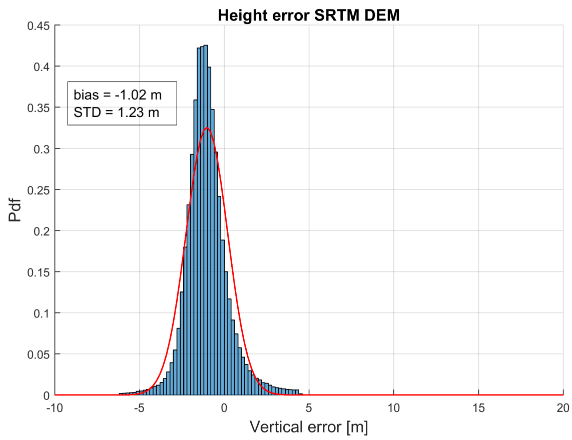


Figure B.46: Histogram DEM error SRTM, Texel

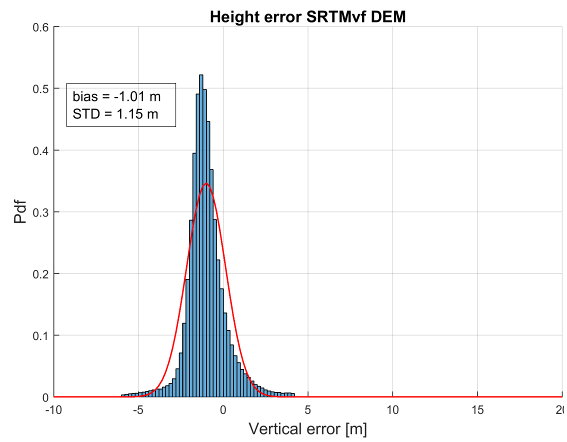


Figure B.47: Histogram DEM error SRTMvf, Texel

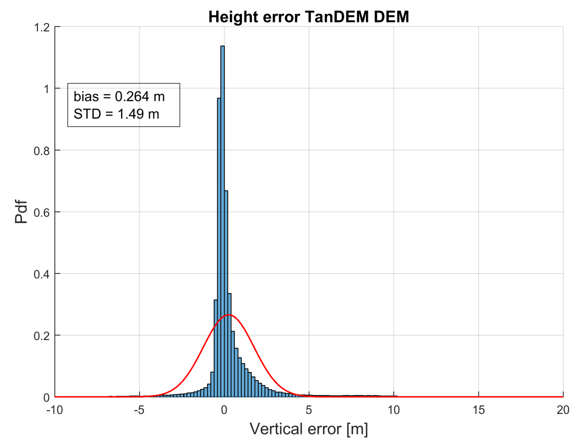


Figure B.48: Histogram DEM error TanDEM-X, Texel

Difference plots

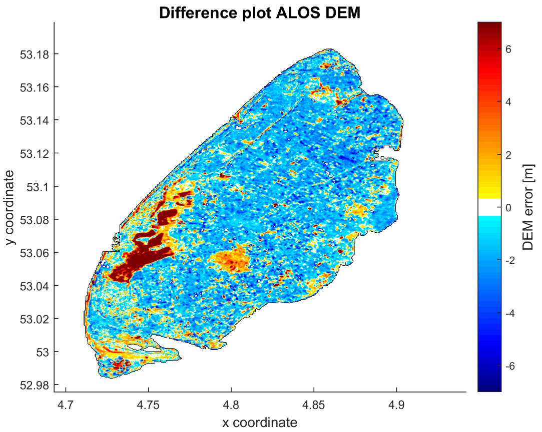


Figure B.49: Difference plot ALOS, Texel

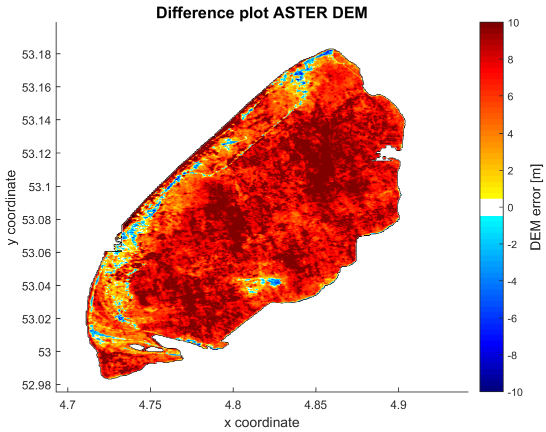


Figure B.50: Difference plot ASTER, Texel

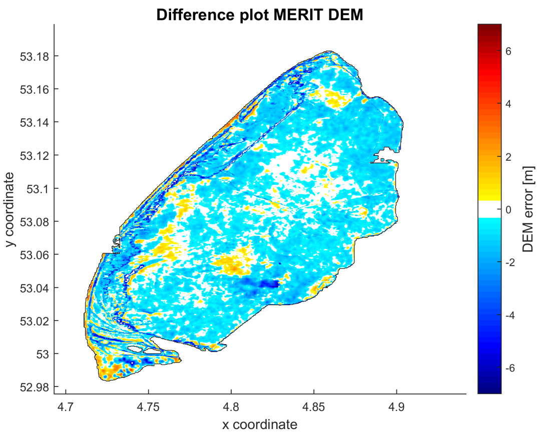


Figure B.51: Difference plot MERIT, Texel

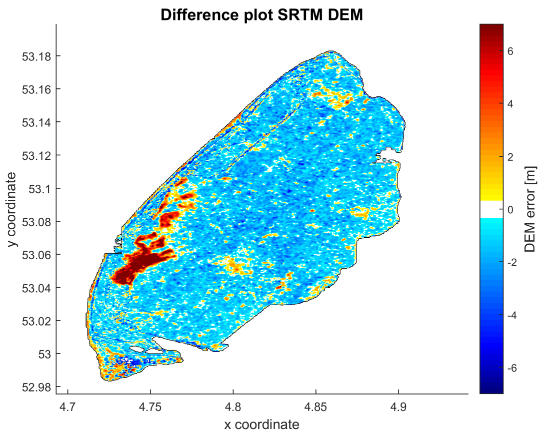


Figure B.52: Difference plot SRTM, Texel

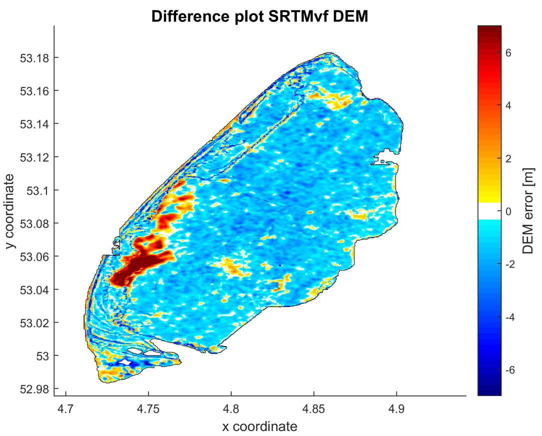


Figure B.53: Difference plot SRTMvf, Texel

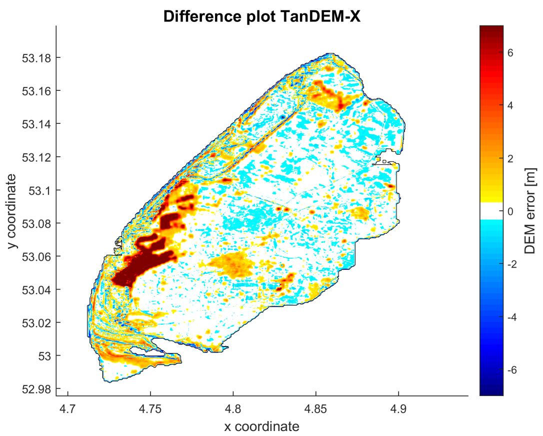


Figure B.54: Difference plot TanDEM-X, Texel

Unbiased difference plots

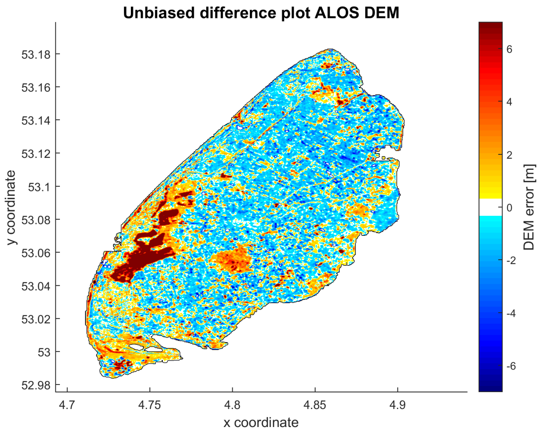


Figure B.55: Unbiased difference plot ALOS, Texel

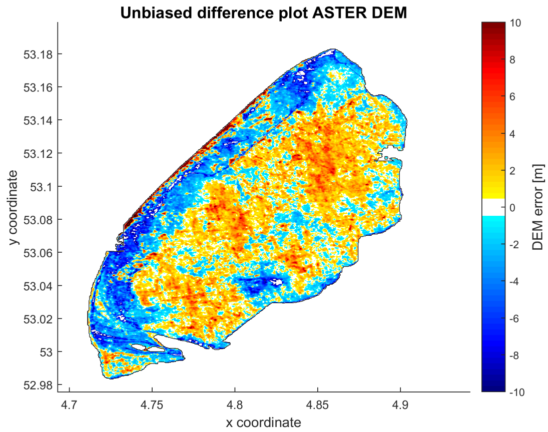


Figure B.56: Unbiased difference plot ASTER, Texel

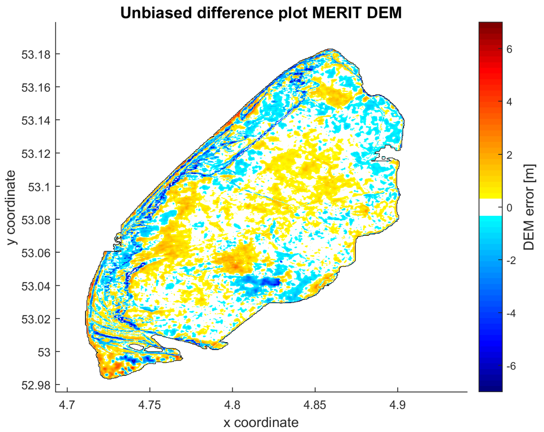


Figure B.57: Unbiased difference plot MERIT, Texel

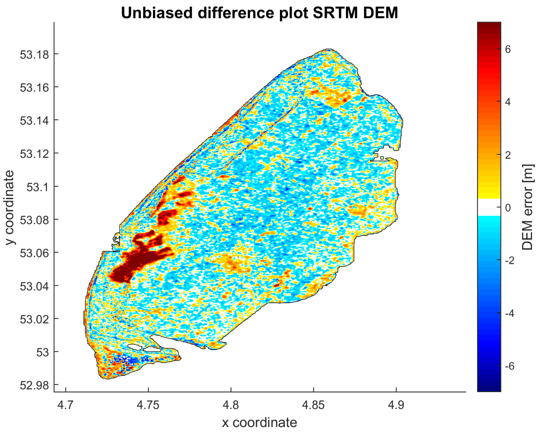


Figure B.58: Unbiased difference plot SRTM, Texel

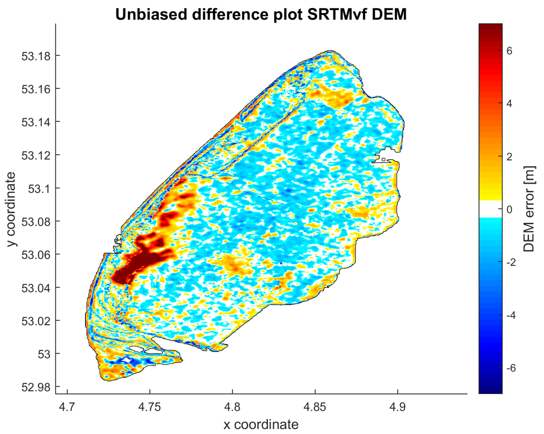


Figure B.59: Unbiased difference plot SRTMvf, Texel

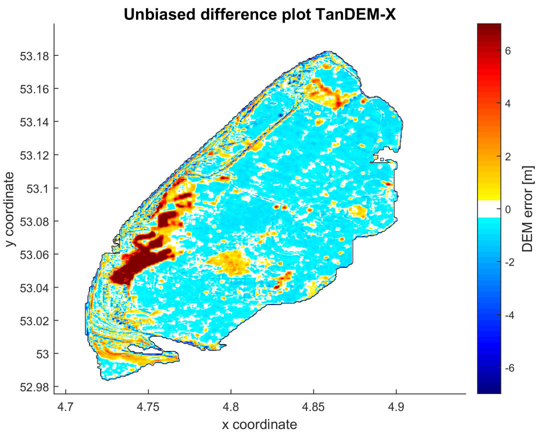


Figure B.60: Unbiased difference plot TanDEM-X, Texel

B.3.2. Vlieland

Error statistics

Table B.5: Error statistics for the island of Vlieland

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	-0,34	1,55	1,45	2,22	2,19	-8,40	7,88	3,84
ASTER	4,50	5,03	2,92	5,83	3,69	-7,35	16,16	8,86
MERIT	-0,27	1,68	1,67	2,20	2,19	-7,63	6,99	3,62
SRTM	-0,08	1,69	1,68	2,18	2,18	-7,21	7,04	3,60
SRTMvf	-0,11	1,57	1,56	2,03	2,03	-6,77	6,47	3,35
TanDEM-X	1,75	2,93	3,26	5,69	5,42	-23,13	34,10	7,47

Histograms DEM error

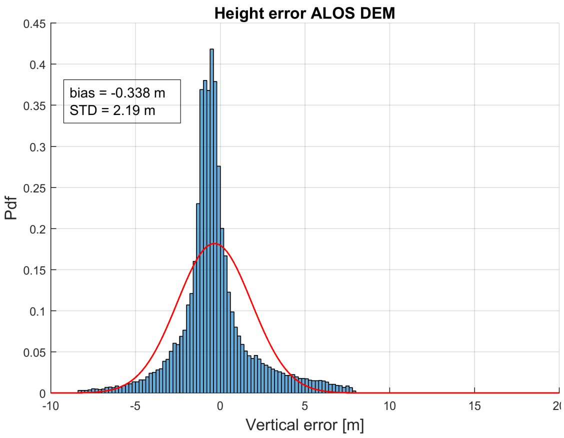


Figure B.61: Histogram DEM error ALOS, Vlieland

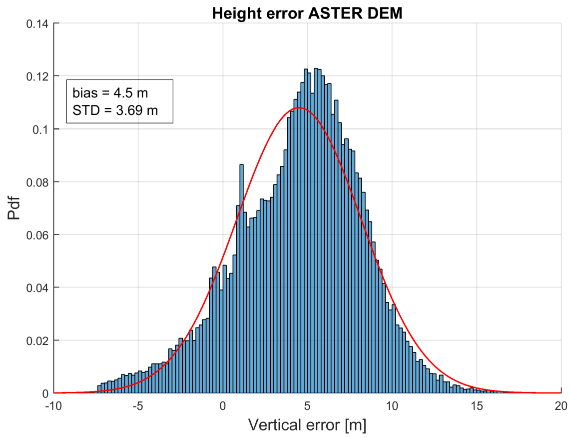


Figure B.62: Histogram DEM error ALOS, Vlieland

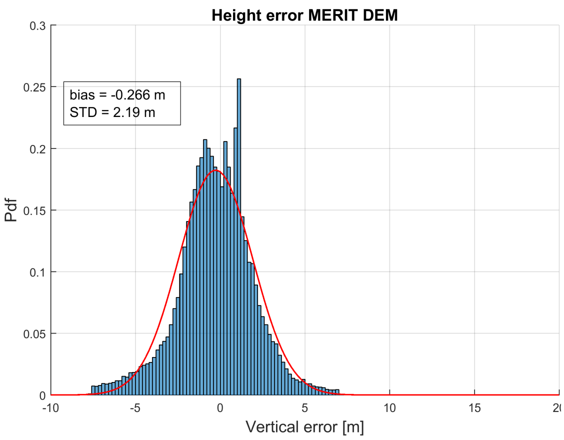


Figure B.63: Histogram DEM error MERIT, Vlieland

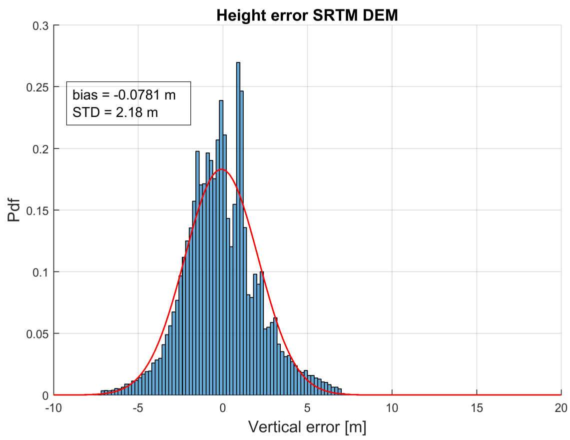


Figure B.64: Histogram DEM error SRTM, Vlieland

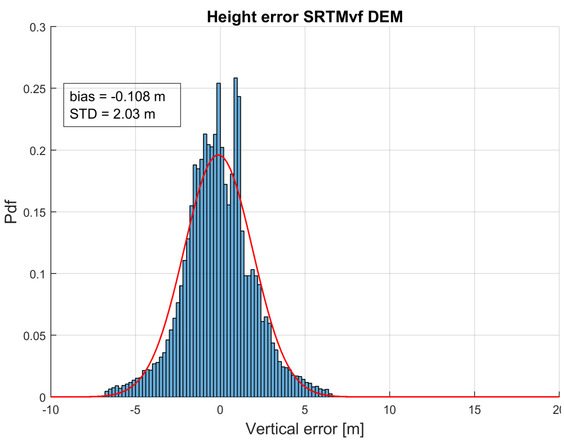


Figure B.65: Histogram DEM error SRTMvf, Vlieland

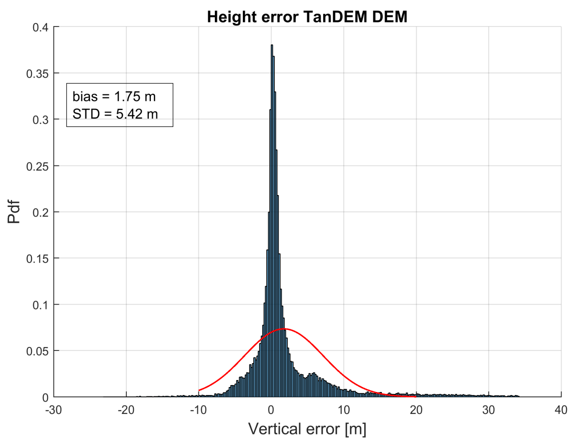


Figure B.66: Histogram DEM error TanDEM-X, Vlieland

Difference plots

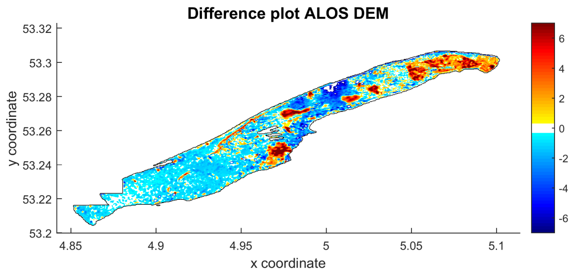


Figure B.67: Difference plot ALOS, Vlieland

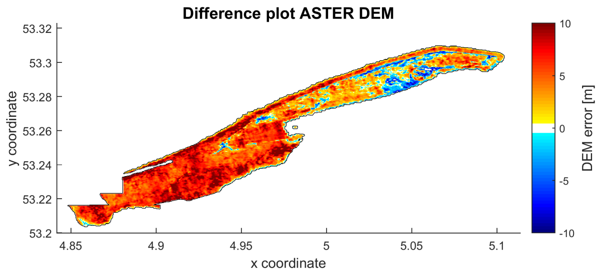


Figure B.68: Difference plot ASTER, Vlieland

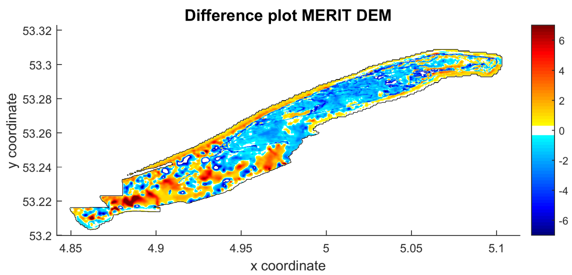


Figure B.69: Difference plot MERIT, Vlieland

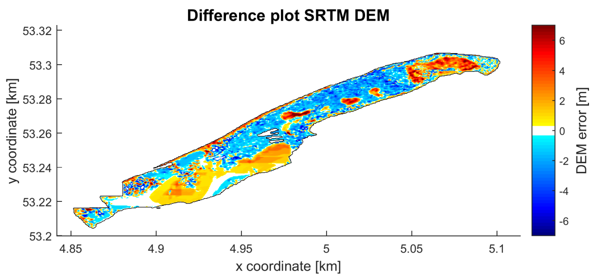


Figure B.70: Difference plot SRTM, Vlieland

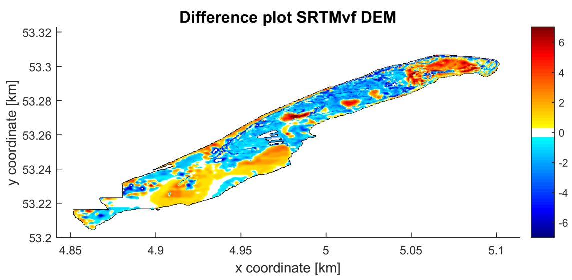


Figure B.71: Difference plot SRTMvf, Vlieland

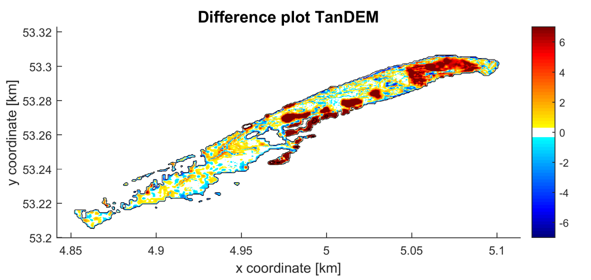


Figure B.72: Difference plot TanDEM-X, Vlieland

Unbiased difference plots

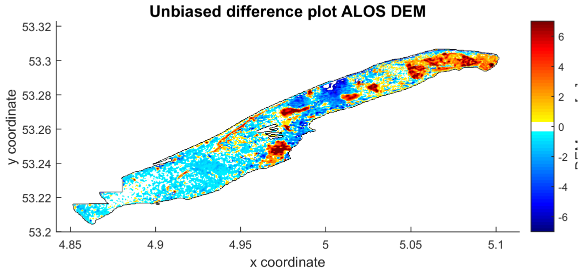


Figure B.73: Unbiased difference plot ALOS, Vlieland

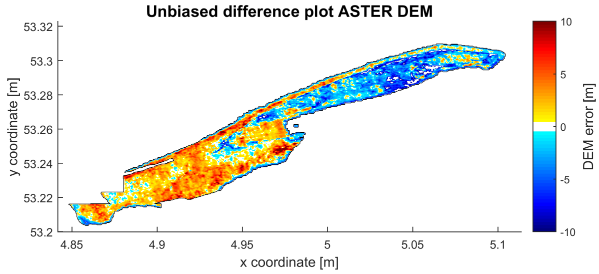


Figure B.74: Unbiased difference plot ASTER, Vlieland

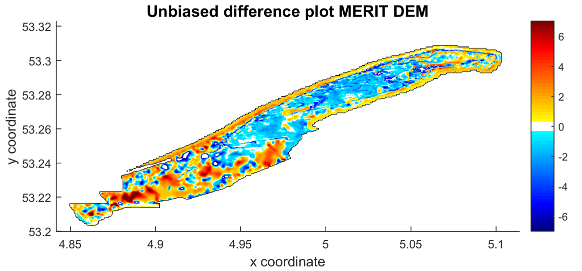


Figure B.75: Unbiased difference plot MERIT, Vlieland

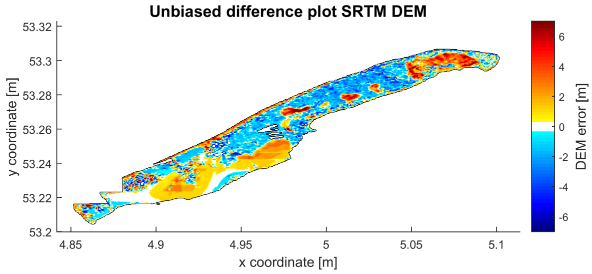


Figure B.76: Unbiased difference plot SRTM, Vlieland

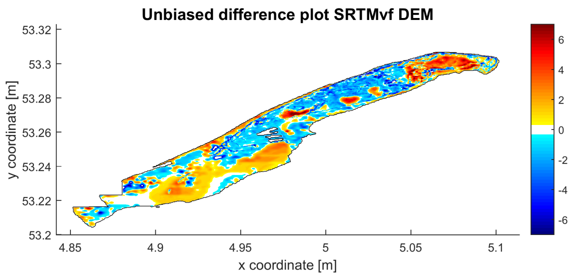


Figure B.77: Unbiased difference plot SRTMvf, Vlieland

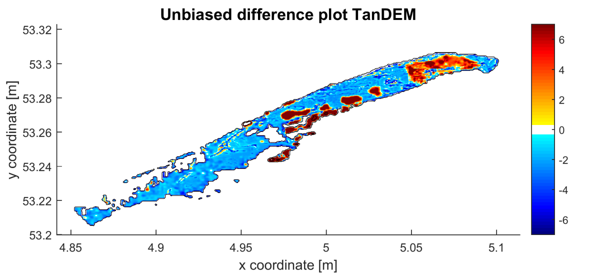


Figure B.78: Unbiased difference plot TanDEM-X, Vlieland

B.3.3. Terschelling

Error statistics

Table B.6: Error statistics for the island of Terschelling

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	-0,02	1,25	1,24	1,76	1,76	-7,36	7,78	2,61
ASTER	4,12	4,41	2,26	5,02	2,87	-5,11	13,19	7,46
MERIT	-1,12	1,37	0,95	1,78	1,38	-6,85	4,37	2,72
SRTM	-0,85	1,57	1,22	1,97	1,77	-7,61	6,38	2,99
SRTMvf	-0,81	1,48	1,18	1,90	1,72	-7,30	6,06	2,89
TanDEM-X	0,65	1,27	1,28	2,14	2,04	-6,98	8,83	3,57

Histograms DEM error

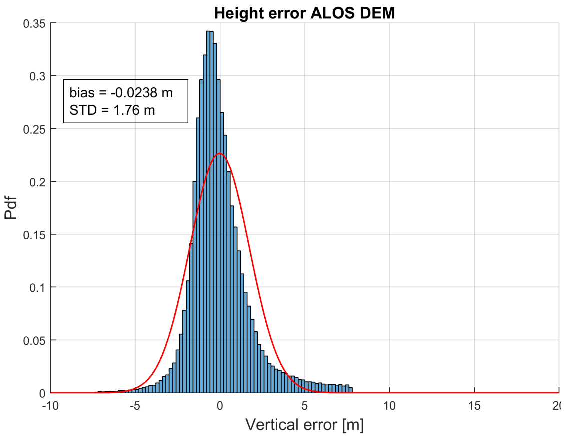


Figure B.79: Histogram DEM error ALOS, Terschelling

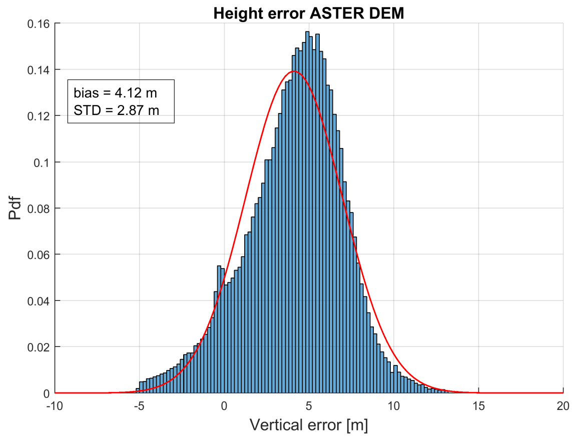


Figure B.80: Histogram DEM error ALOS, Terschelling

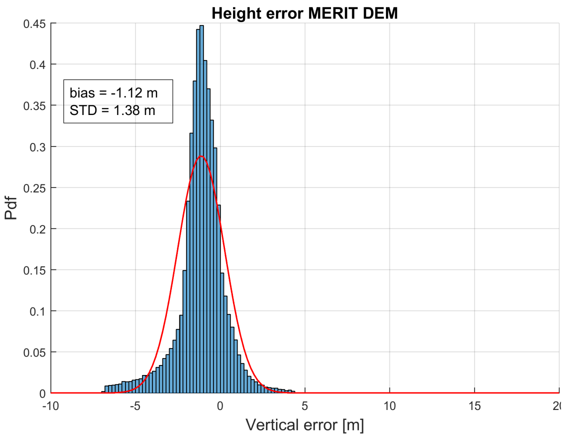


Figure B.81: Histogram DEM error MERIT, Terschelling

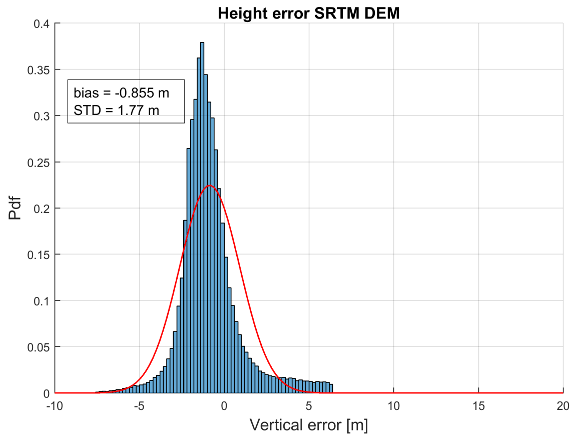


Figure B.82: Histogram DEM error SRTM, Terschelling

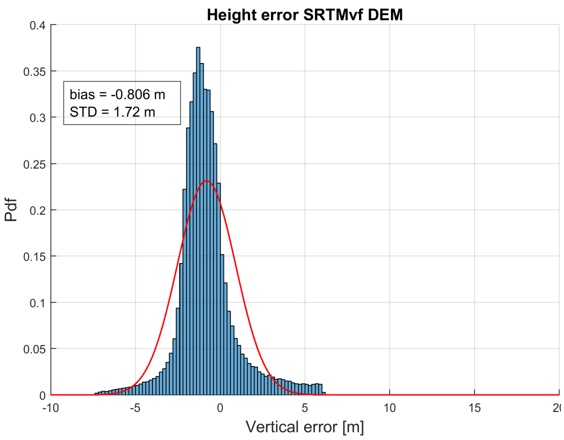


Figure B.83: Histogram DEM error SRTMvf, Terschelling

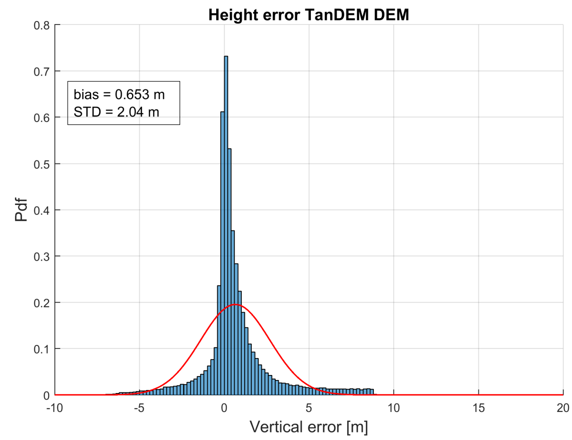


Figure B.84: Histogram DEM error TanDEM-X, Terschelling

Difference plots

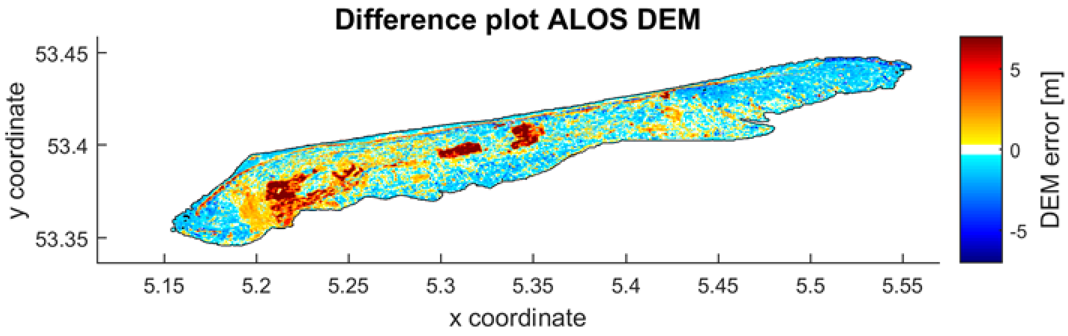


Figure B.85: Difference plot ALOS, Terschelling

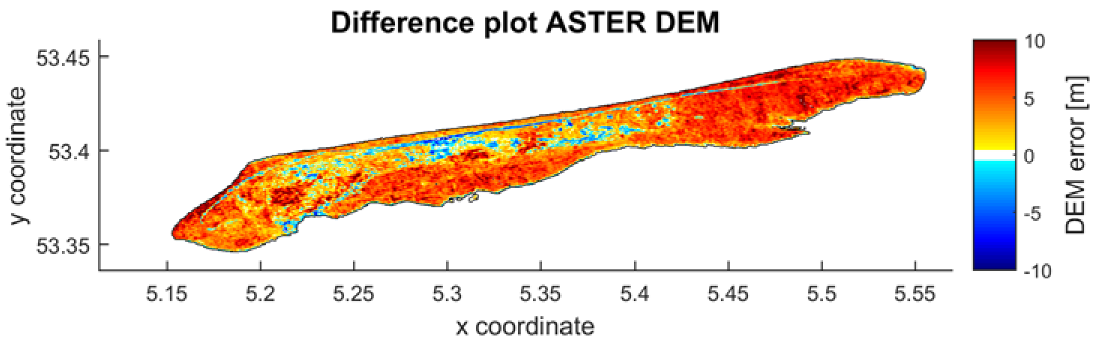


Figure B.86: Difference plot ASTER, Terschelling

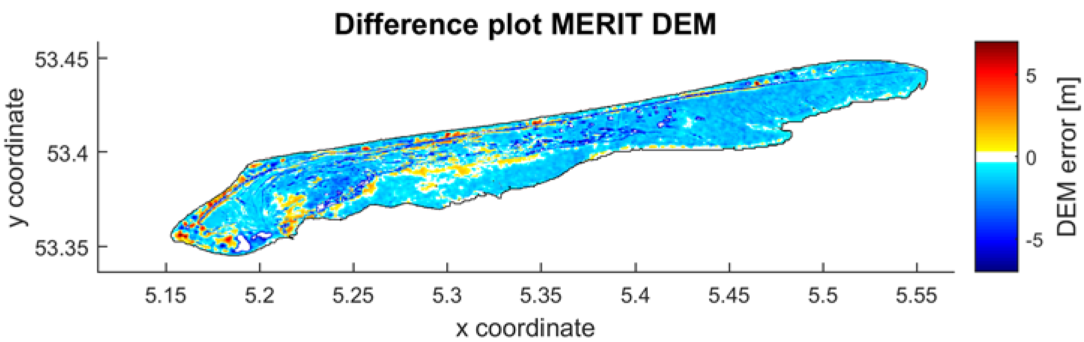


Figure B.87: Difference plot MERIT, Terschelling

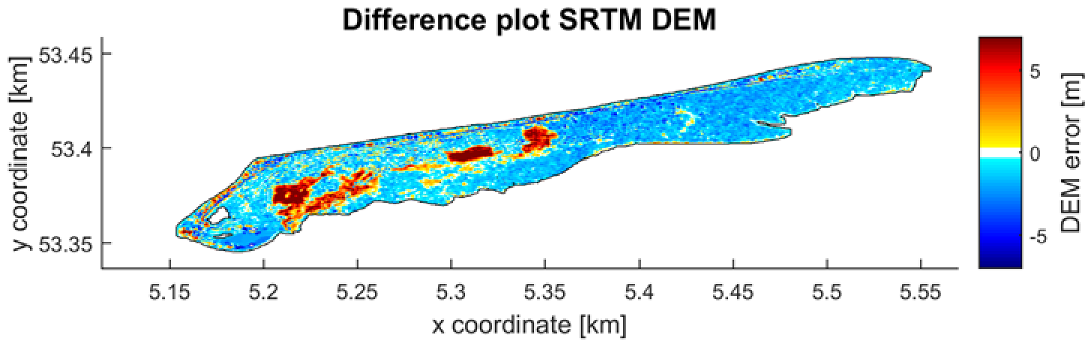


Figure B.88: Difference plot SRTM, Terschelling

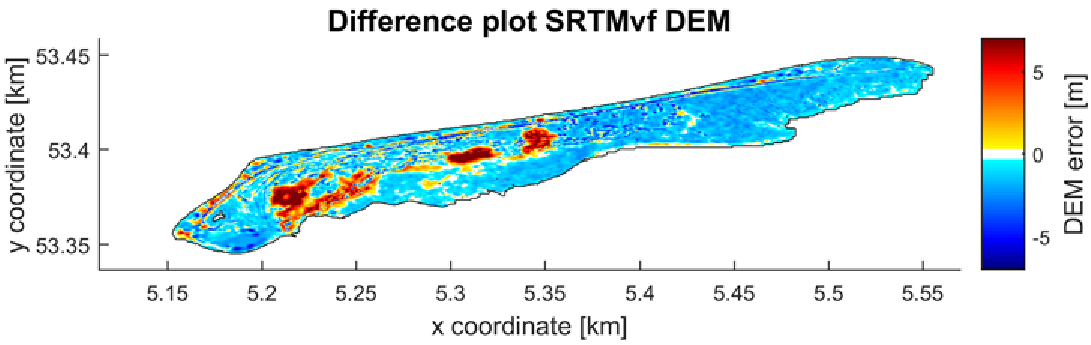


Figure B.89: Difference plot SRTMvf, Terschelling

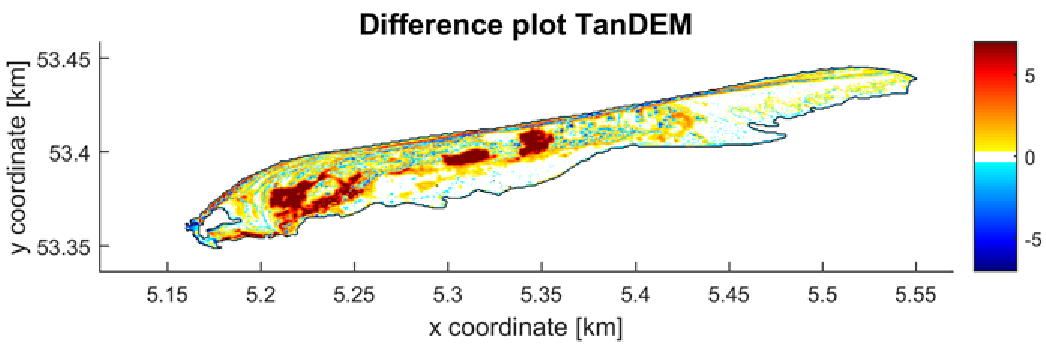


Figure B.90: Difference plot TanDEM-X, Terschelling

Unbiased difference plots

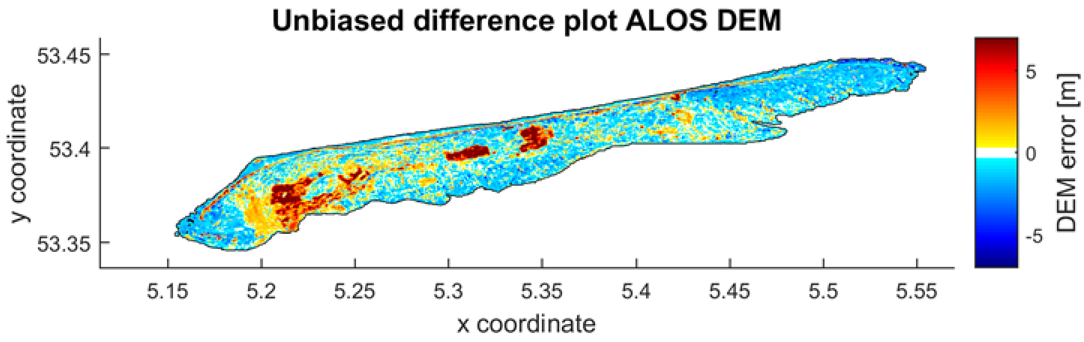


Figure B.91: Unbiased difference plot ALOS, Terschelling

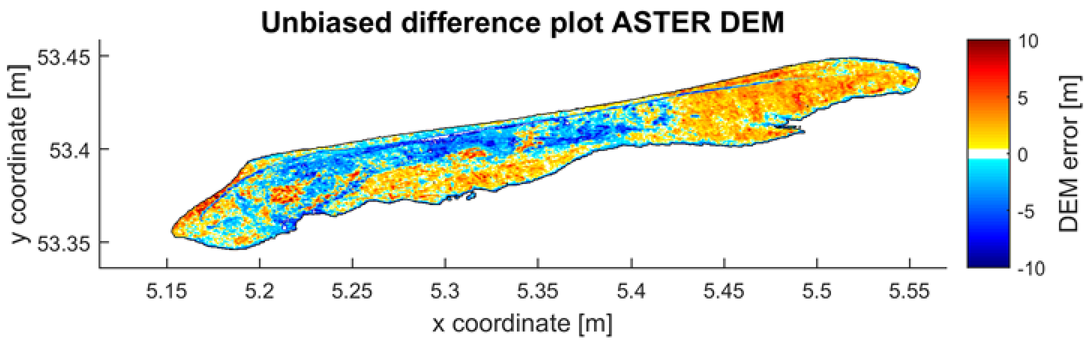


Figure B.92: Unbiased difference plot ASTER, Terschelling

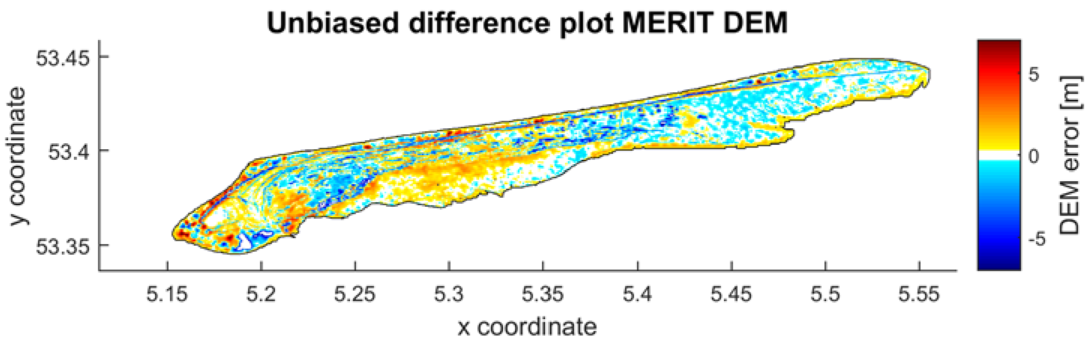


Figure B.93: Unbiased difference plot MERIT, Terschelling

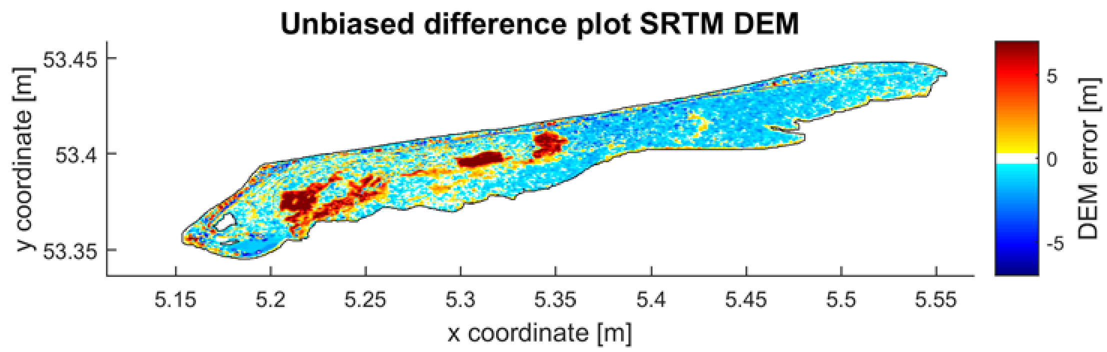


Figure B.94: Unbiased difference plot SRTM, Terschelling

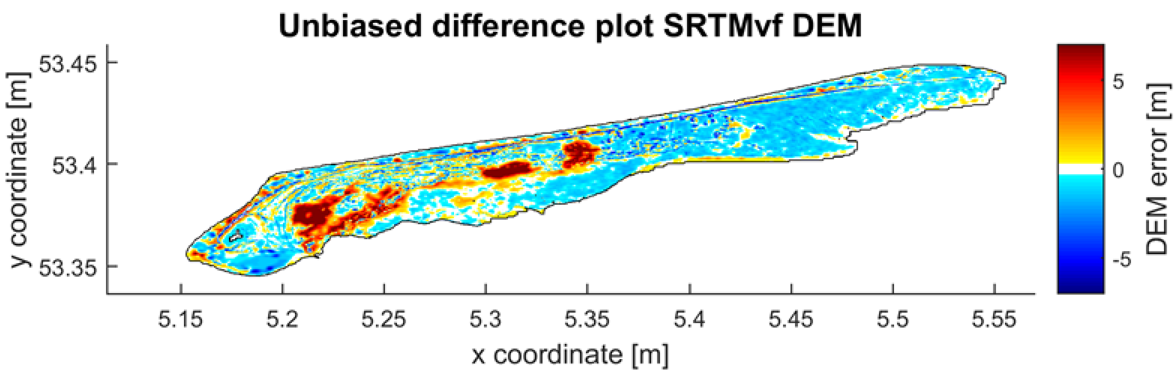


Figure B.95: Unbiased difference plot SRTMvf, Terschelling

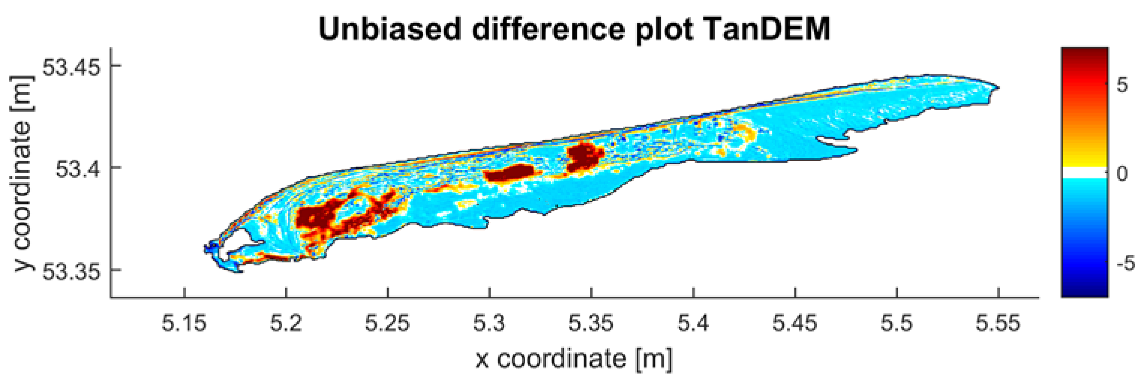


Figure B.96: Unbiased difference plot TanDEM-X, Terschelling

B.3.4. Ameland

Error statistics

Table B.7: Error statistics for the island of Ameland

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	-1,70	1,92	1,03	2,23	1,44	-8,62	5,53	3,34
ASTER	5,04	5,07	1,51	5,42	2,01	-1,68	11,70	7,38
MERIT	-1,46	1,56	0,83	1,89	1,20	-7,85	4,91	2,68
SRTM	-1,62	1,77	0,92	2,03	1,22	-6,19	3,15	3,00
SRTMvf	-1,54	1,68	0,89	1,95	1,20	-5,87	2,89	2,84
TanDEM-X	0,29	0,76	0,74	1,23	1,20	-5,07	5,89	2,01

Histograms DEM error

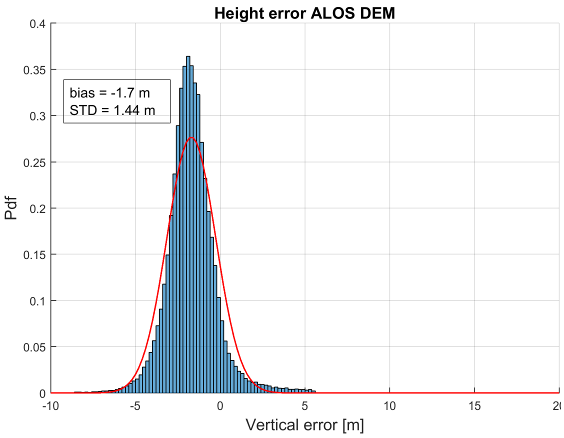


Figure B.97: Histogram DEM error ALOS, Ameland

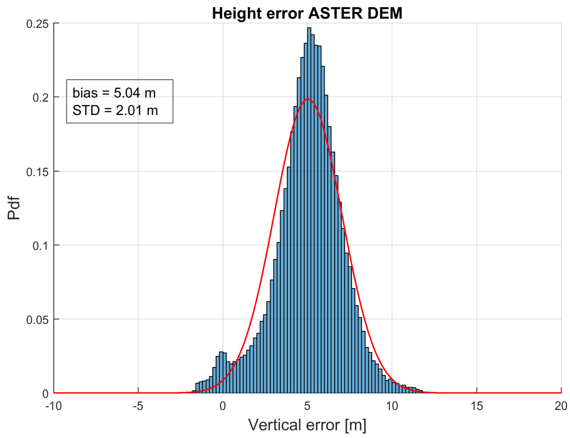


Figure B.98: Histogram DEM error ALOS, Ameland

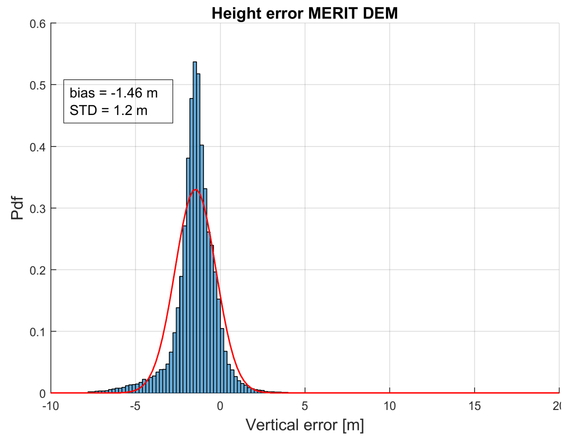


Figure B.99: Histogram DEM error MERIT, Ameland

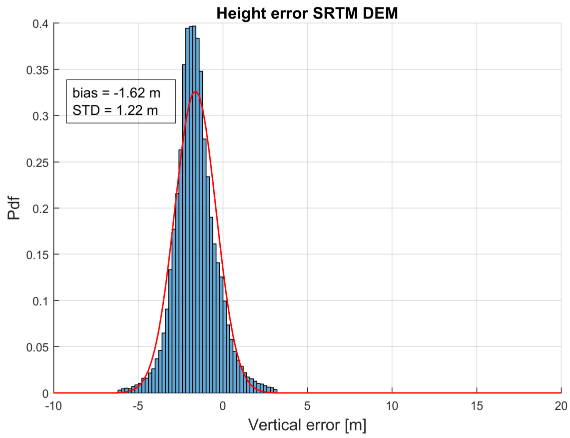


Figure B.100: Histogram DEM error SRTM, Ameland

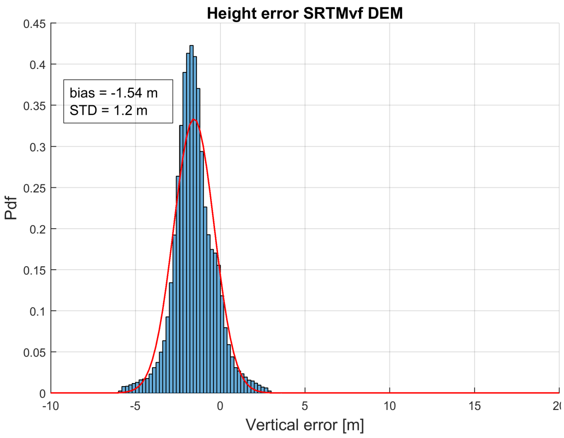


Figure B.101: Histogram DEM error SRTMvf, Ameland

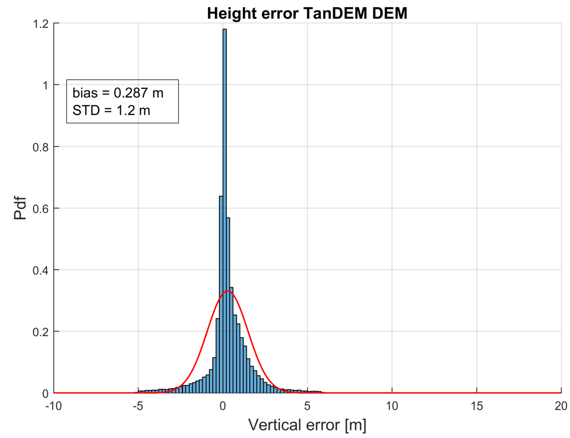


Figure B.102: Histogram DEM error TanDEM-X, Ameland

Difference plots

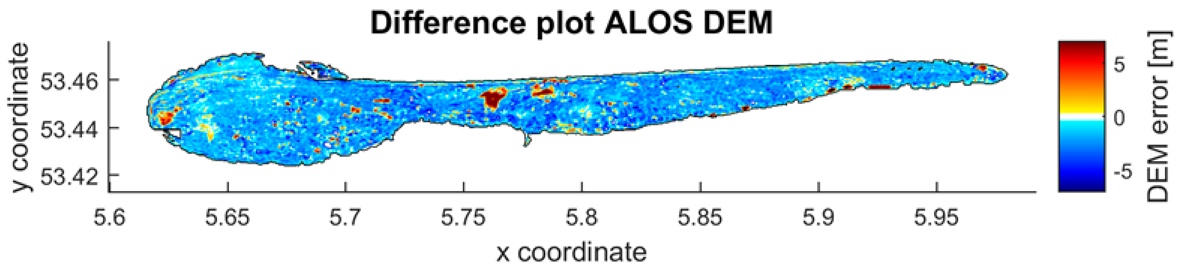


Figure B.103: Difference plot ALOS, Ameland

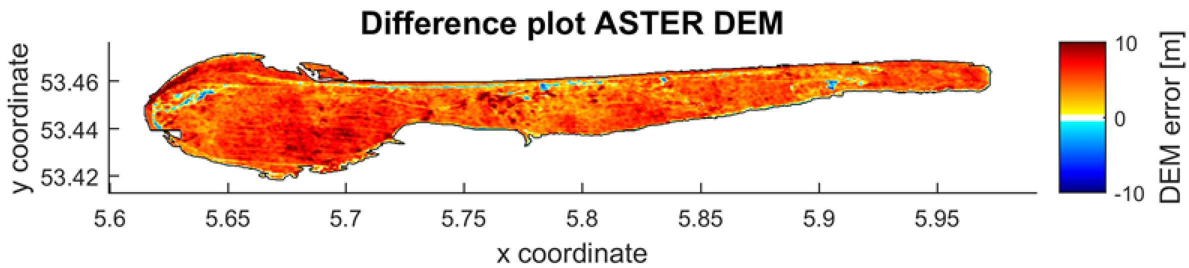


Figure B.104: Difference plot ASTER, Ameland

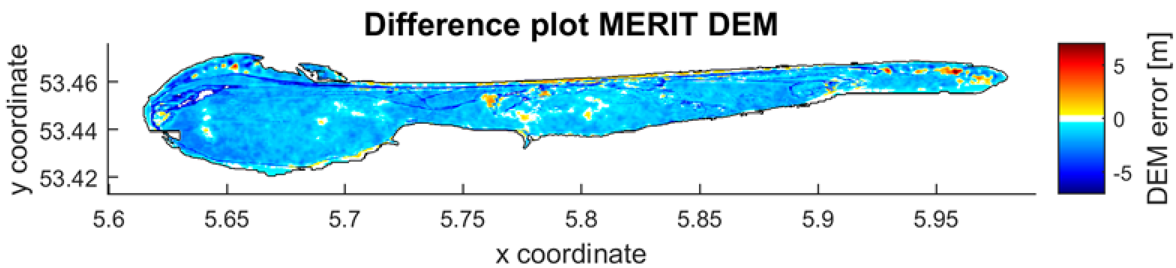


Figure B.105: Difference plot MERIT, Ameland

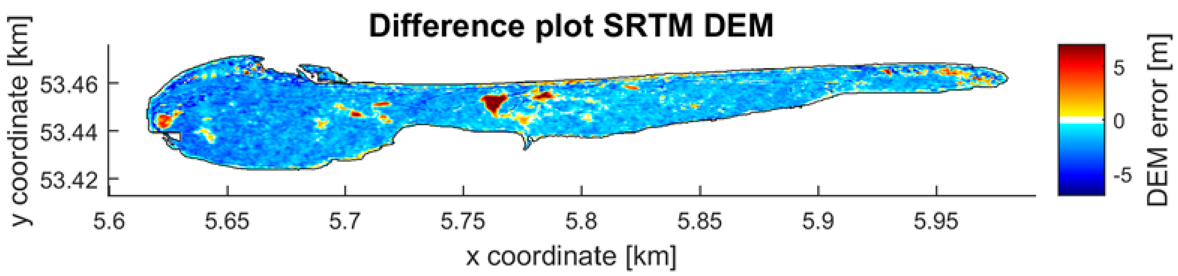


Figure B.106: Difference plot SRTM, Ameland

Unbiased difference plots

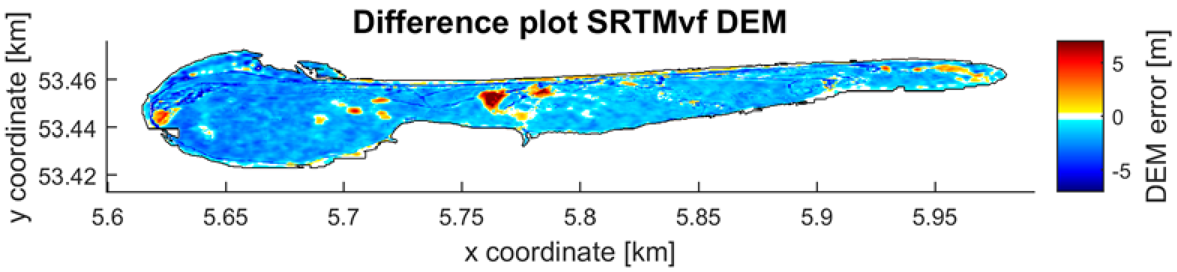


Figure B.107: Difference plot SRTMvf, Ameland

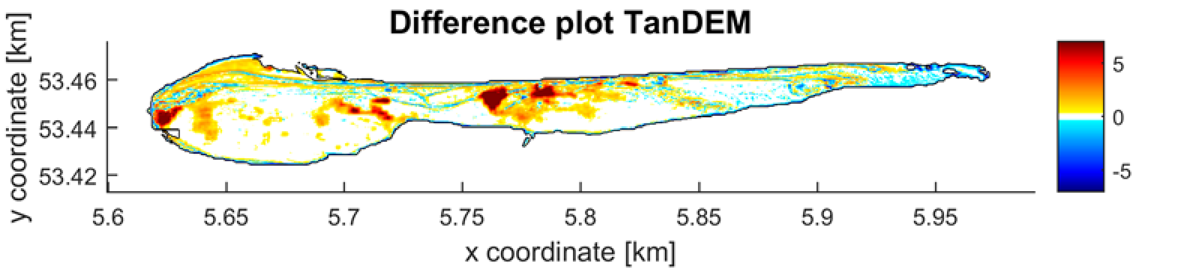


Figure B.108: Difference plot TanDEM-X, Ameland

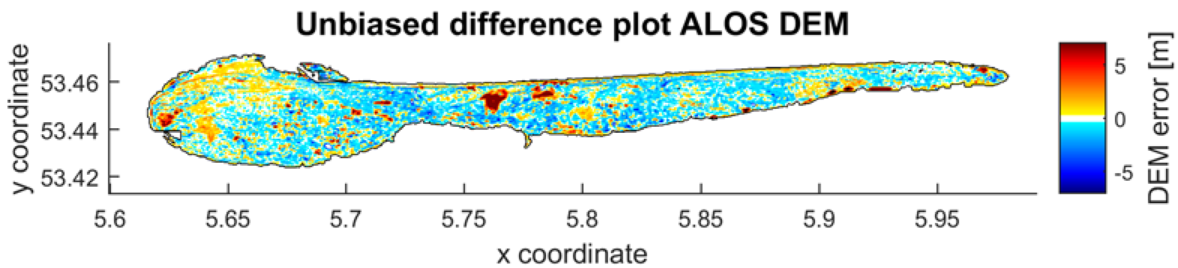


Figure B.109: Unbiased difference plot ALOS, Ameland

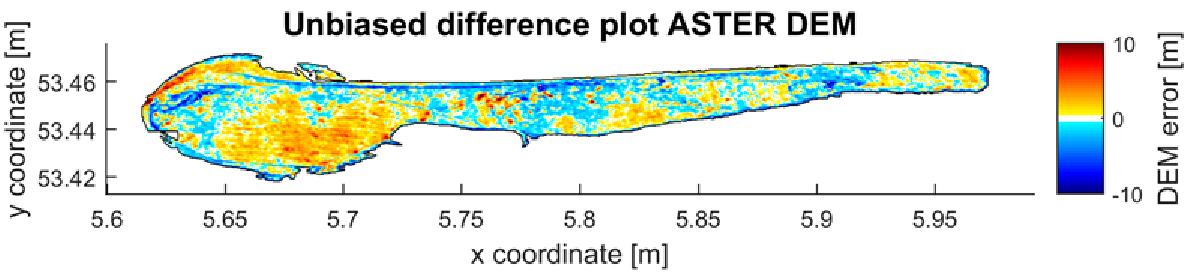


Figure B.110: Unbiased difference plot ASTER, Ameland

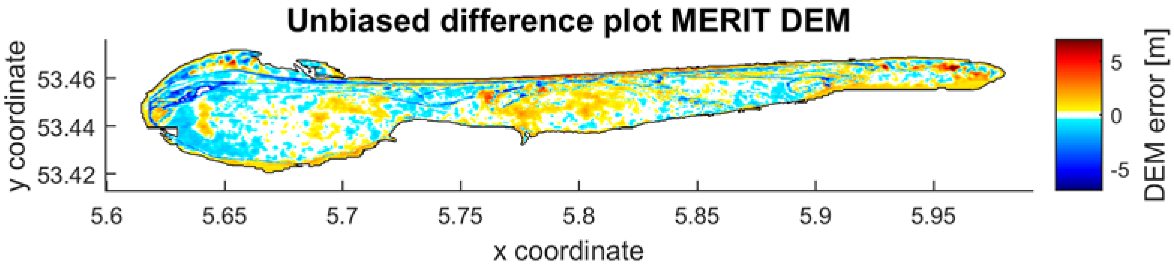


Figure B.111: Unbiased difference plot MERIT, Ameland

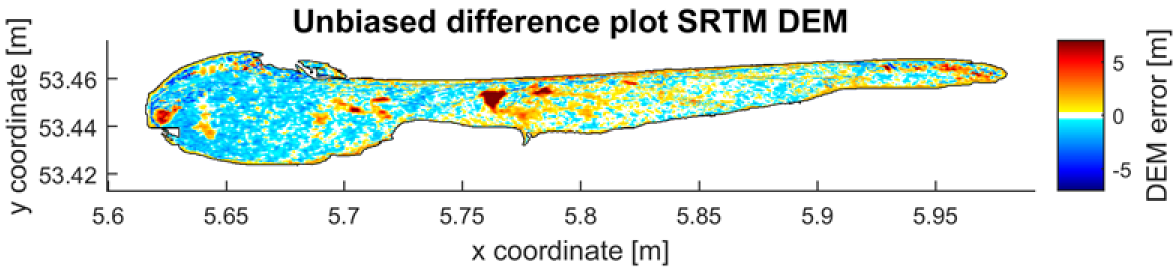


Figure B.112: Unbiased difference plot SRTM, Ameland

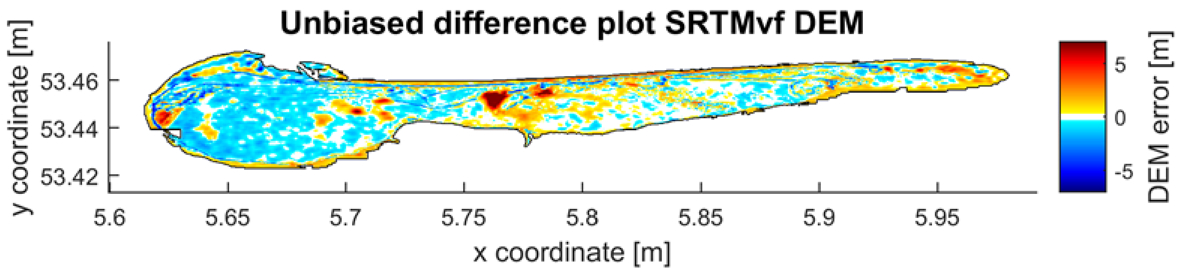


Figure B.113: Unbiased difference plot SRTMvf, Ameland

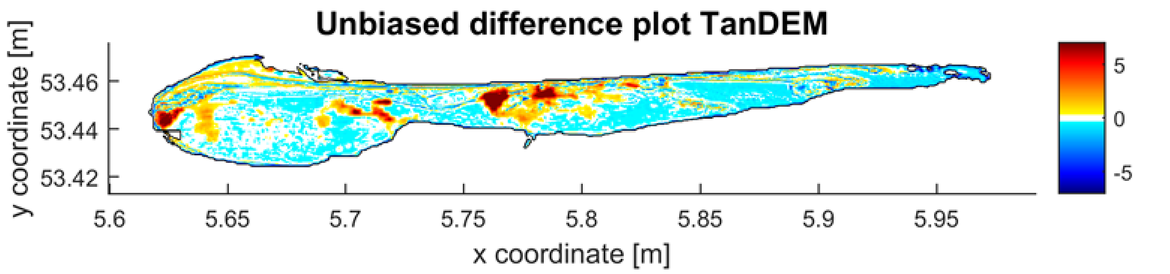


Figure B.114: Unbiased difference plot TanDEM-X, Ameland

B.3.5. Schiermonnikoog

Error statistics

Table B.8: Error statistics for the island of Schiermonnikoog

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	-0,77	1,17	0,87	1,45	1,23	-7,14	5,95	2,18
ASTER	5,52	5,53	1,44	5,85	1,94	-0,72	11,76	7,82
MERIT	-1,64	1,70	0,84	2,00	1,14	-6,08	2,69	2,99
SRTM	-1,79	1,95	1,01	2,25	1,37	-7,13	3,65	3,23
SRTMvf	-1,72	1,83	0,92	2,11	1,21	-6,13	2,80	3,04
TanDEM-X	0,06	0,80	0,82	1,41	1,41	-8,29	8,64	2,15

Table B.9: Error statistics for the island of Schiermonnikoog

Histograms DEM error

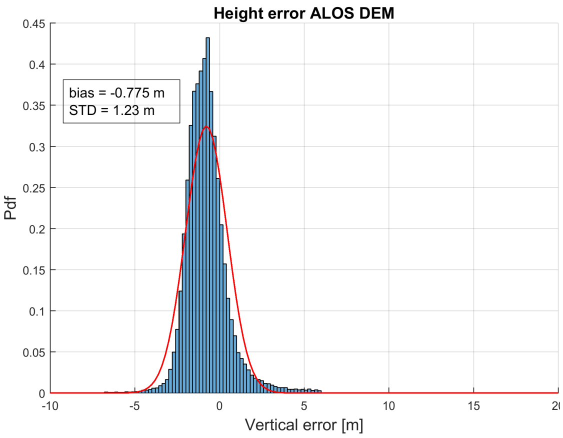


Figure B.115: Histogram DEM error ALOS, Schiermonnikoog

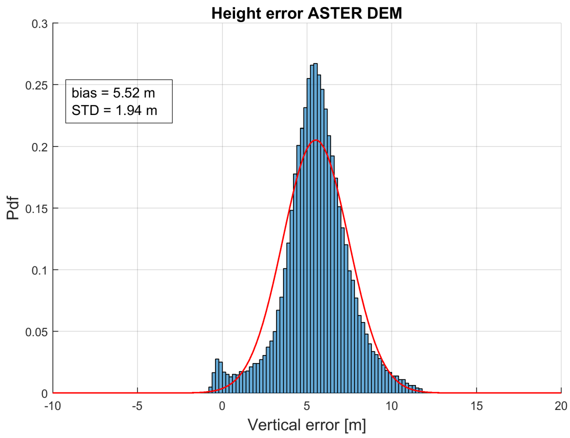


Figure B.116: Histogram DEM error ALOS, Schiermonnikoog

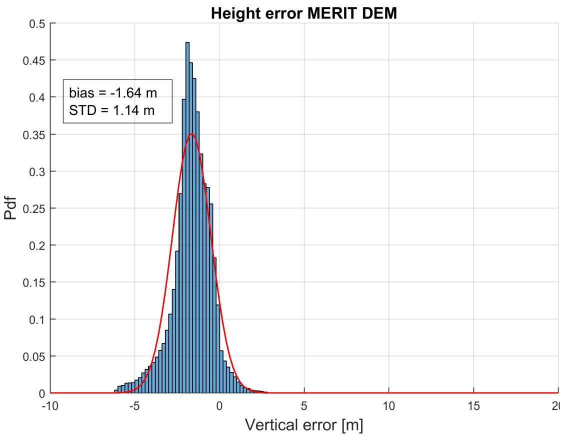


Figure B.117: Histogram DEM error MERIT, Schiermonnikoog

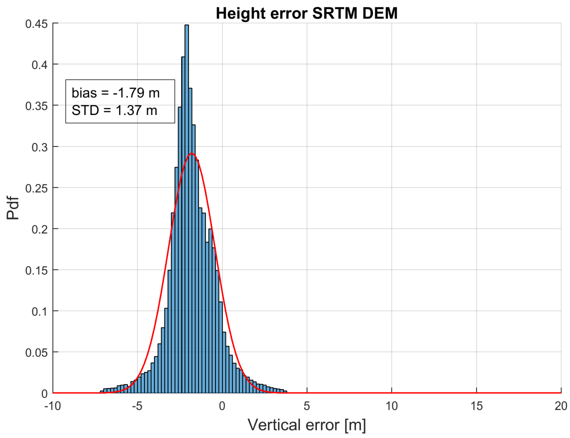


Figure B.118: Histogram DEM error SRTM, Schiermonnikoog

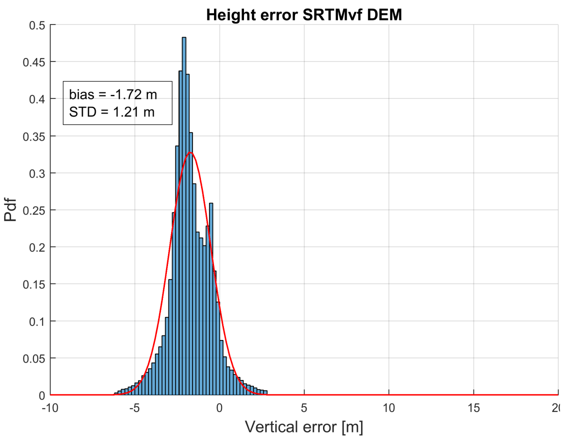


Figure B.119: Histogram DEM error SRTMvf, Schiermonnikoog

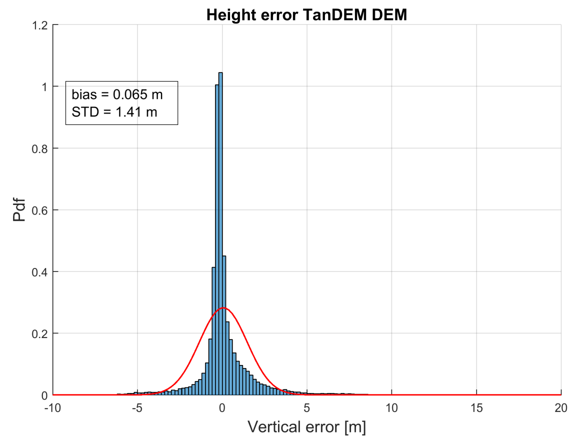


Figure B.120: Histogram DEM error TanDEM-X, Schiermonnikoog

Difference plots

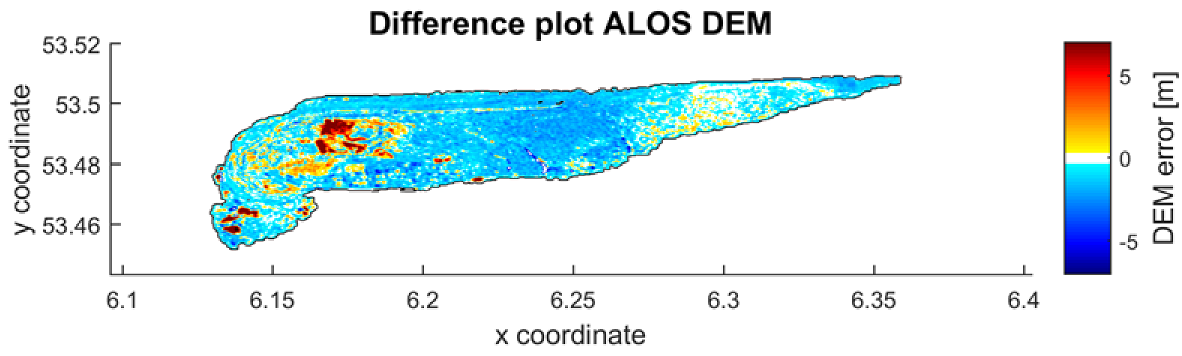


Figure B.121: Difference plot ALOS, Schiermonnikoog

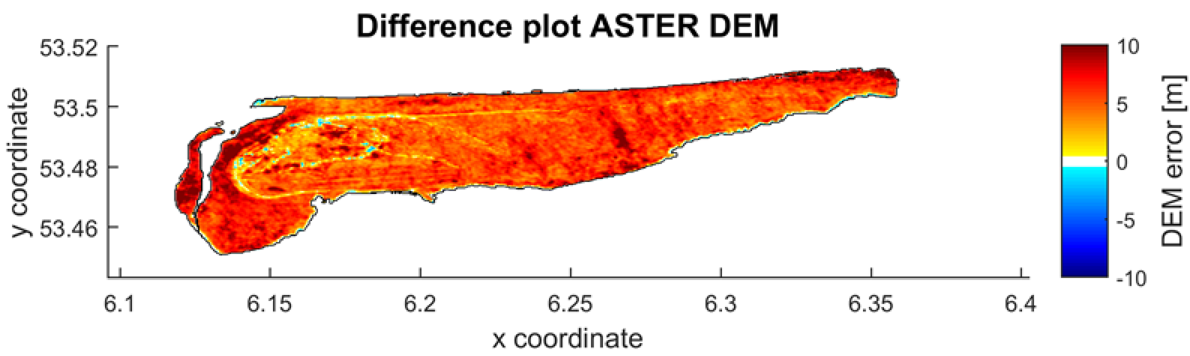


Figure B.122: Difference plot ASTER, Schiermonnikoog

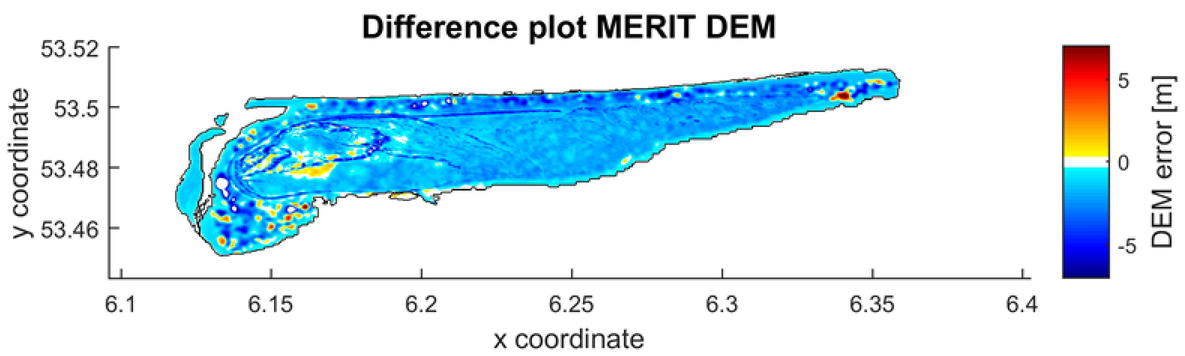


Figure B.123: Difference plot MERIT, Schiermonnikoog

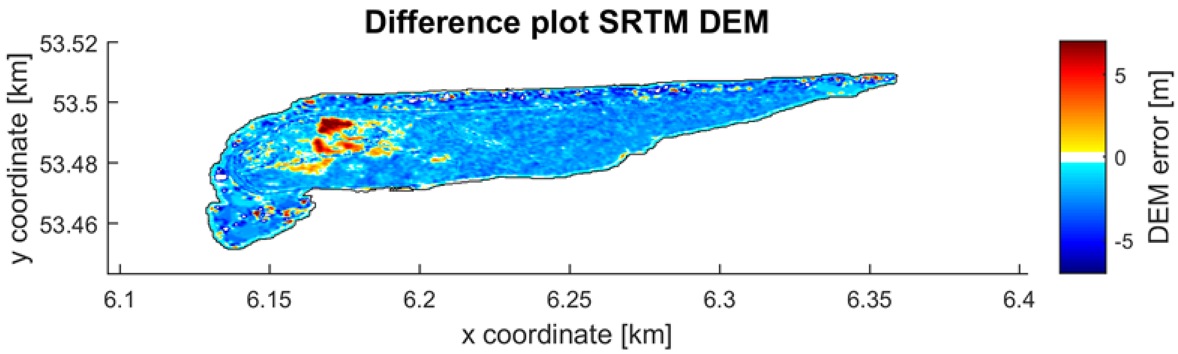


Figure B.124: Difference plot SRTM, Schiermonnikoog

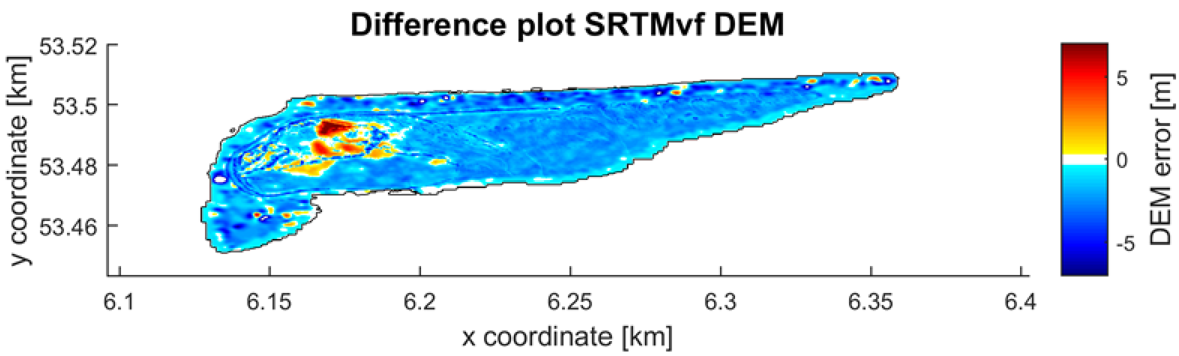


Figure B.125: Difference plot SRTMvf, Schiermonnikoog

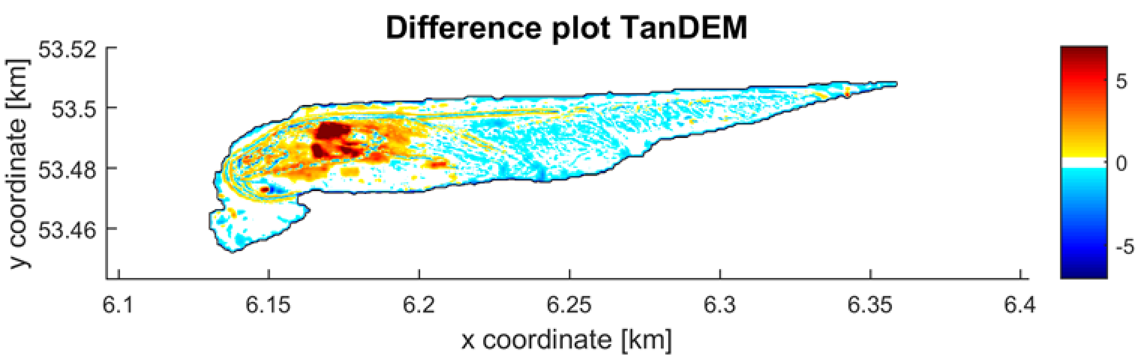


Figure B.126: Difference plot TanDEM-X, Schiermonnikoog

Unbiased difference plots

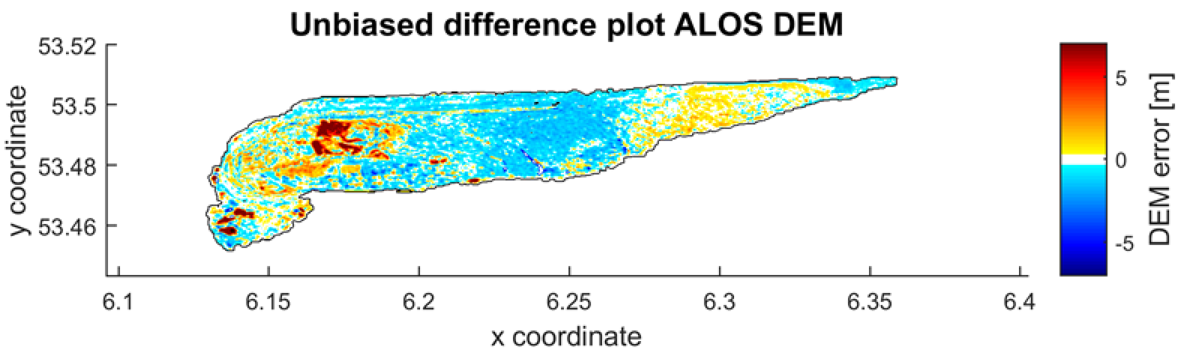


Figure B.127: Unbiased difference plot ALOS, Schiermonnikoog

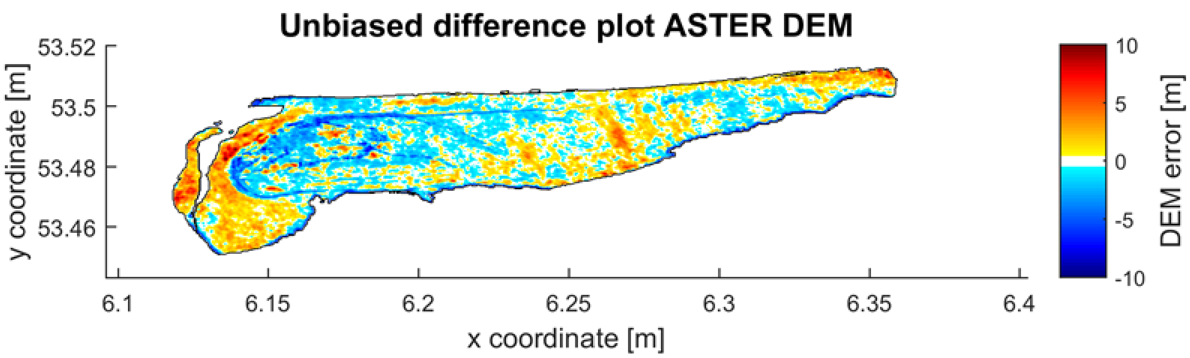


Figure B.128: Unbiased difference plot ASTER, Schiermonnikoog

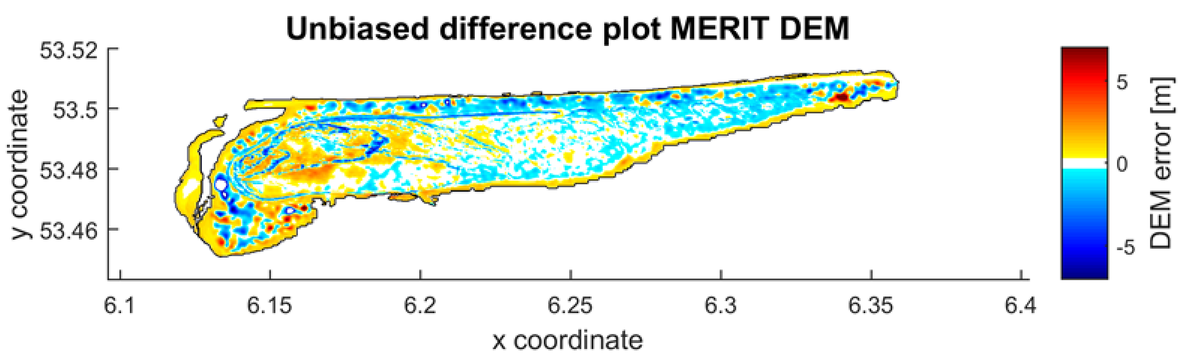


Figure B.129: Unbiased difference plot MERIT, Schiermonnikoog

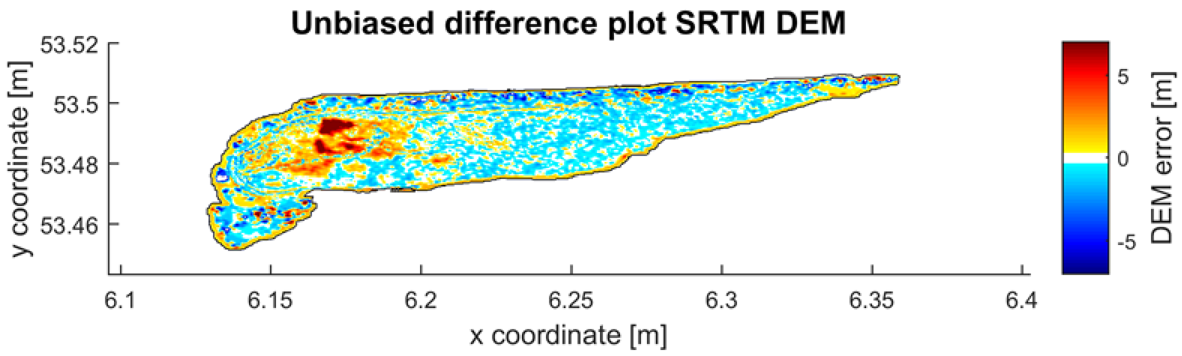


Figure B.130: Unbiased difference plot SRTM, Schiermonnikoog

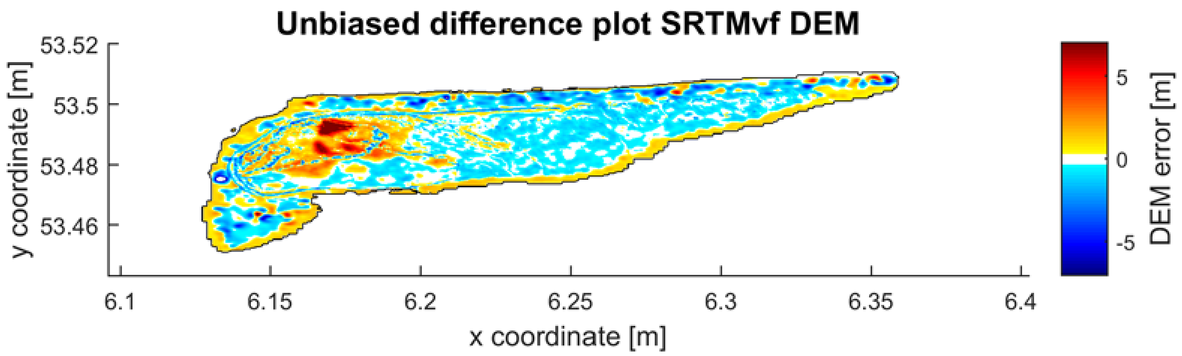


Figure B.131: Unbiased difference plot SRTMvf, Schiermonnikoog

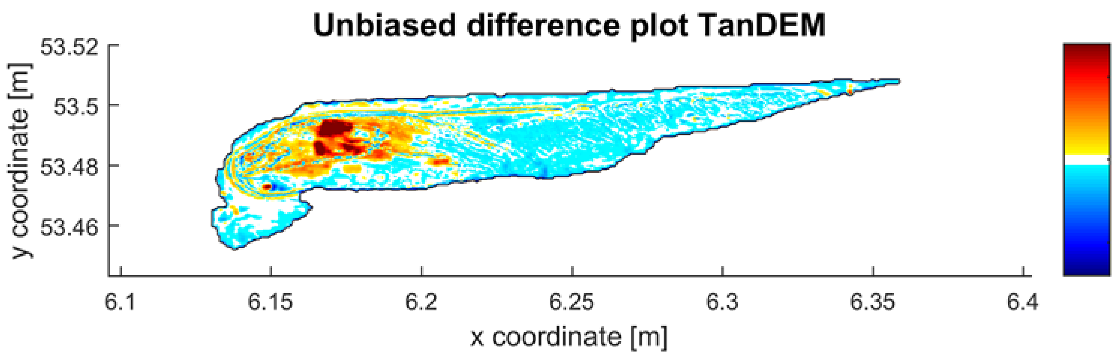


Figure B.132: Unbiased difference plot TanDEM-X, Schiermonnikoog

B.4. Volcanic islands

B.4.1. Tutuila

For the island of Tutuila, only the error statistics and histograms of the DEM error are included in this appendix. Due to the size and shape of the island, both the difference plots and unbiased difference plots cannot be displayed clearly in a report of A4 size. For these plots, please contact the author (martinerottink@hotmail.com).

Error statistics

Table B.10: Error statistics for the island of Tutuila

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	3,15	3,80	3,16	5,25	4,21	-10,97	21,02	8,52
ASTER	13,32	13,46	6,32	15,88	8,66	-11,19	51,56	24,32
MERIT	6,24	6,52	5,29	9,17	6,72	-10,91	31,99	16,36
SRTM	4,19	4,53	3,51	6,38	4,81	-10,86	25,26	10,70
SRTMvf	5,98	6,24	5,01	8,79	6,44	-10,75	31,16	15,65
TanDEM-X	4,87	5,67	5,59	9,04	7,62	-10,87	46,52	15,02

Histograms DEM error

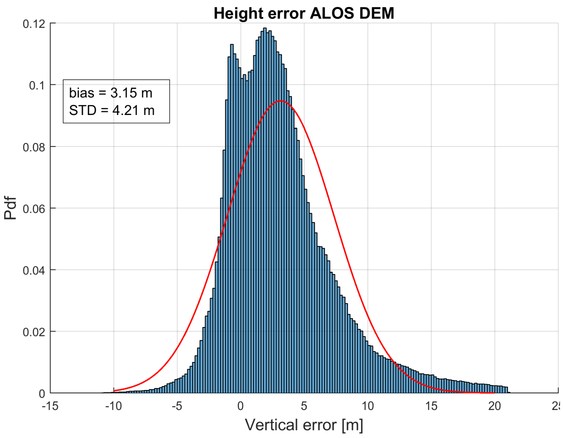


Figure B.133: Histogram DEM error ALOS, Tutuila

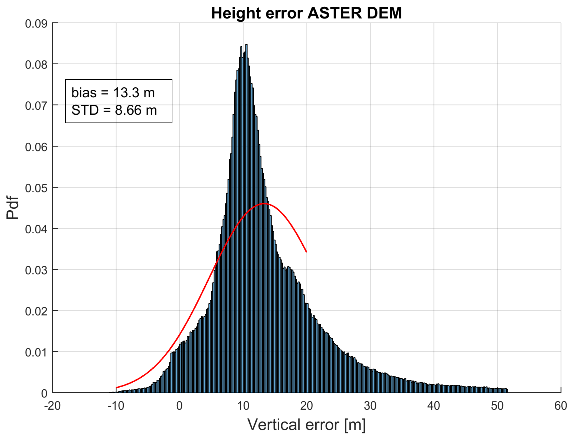


Figure B.134: Histogram DEM error ALOS, Tutuila

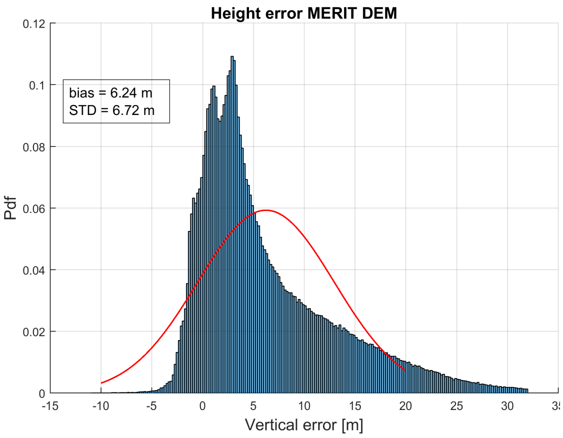


Figure B.135: Histogram DEM error MERIT, Tutuila

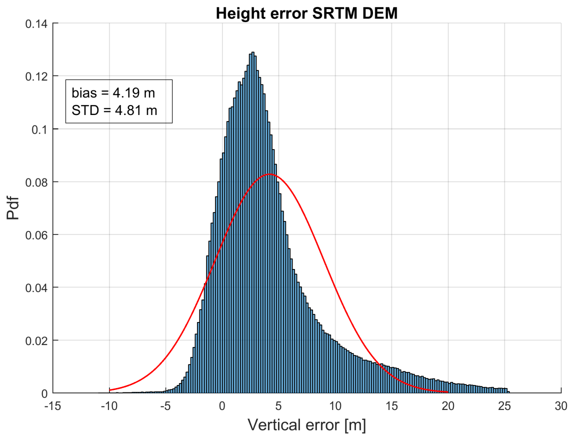


Figure B.136: Histogram DEM error SRTM, Tutuila

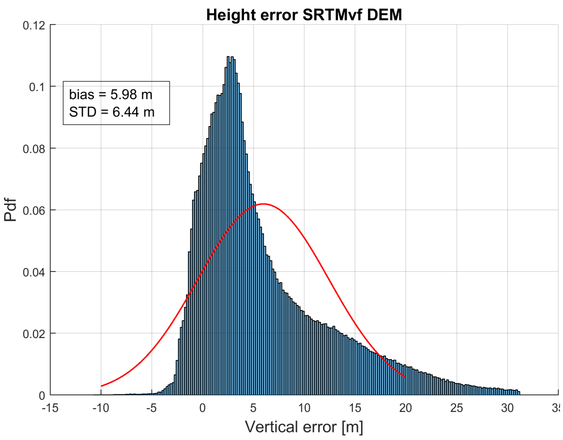


Figure B.137: Histogram DEM error SRTMvf, Tutuila

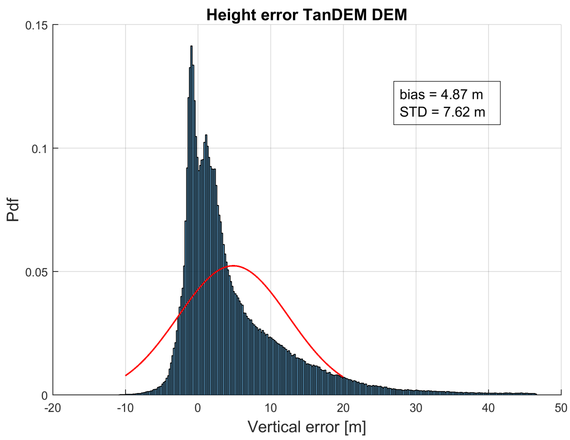


Figure B.138: Histogram DEM error TanDEM-X, Tutuila

B.4.2. Aunuu

Error statistics

Table B.11: Error statistics for the island of Aunuu

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	3,19	3,73	3,20	4,89	3,71	-8,05	14,56	8,27
ASTER	12,98	13,11	9,64	19,05	13,95	-10,80	70,41	30,97
MERIT	2,63	3,02	2,71	4,40	3,53	-5,69	15,22	8,12
SRTM	2,06	2,57	2,21	3,53	2,87	-4,74	13,23	5,90
SRTMvf	2,58	2,99	2,65	4,32	3,46	-5,26	14,98	7,90
TanDEM-X	1,74	2,92	2,89	4,30	3,94	-10,44	25,50	7,07

Histograms DEM error

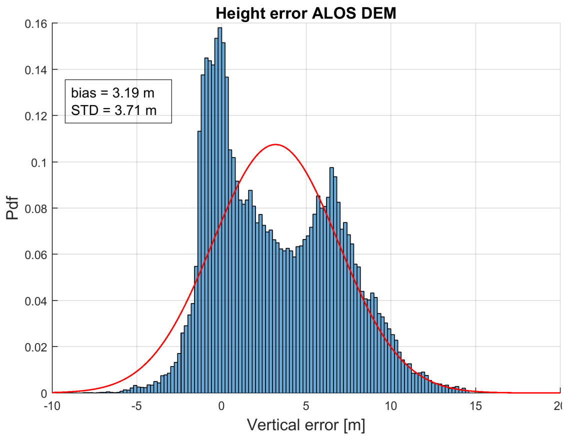


Figure B.139: Histogram DEM error ALOS, Aunuu

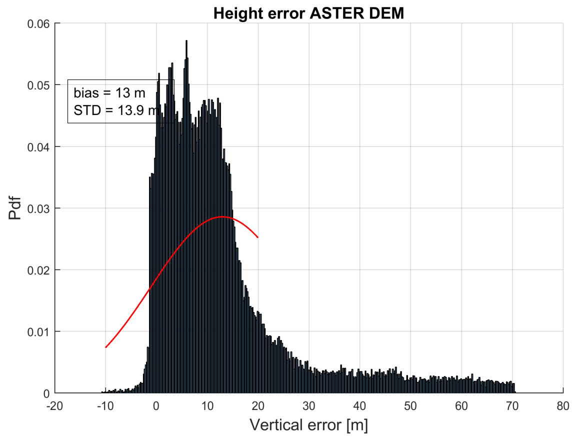


Figure B.140: Histogram DEM error ALOS, Aunuu

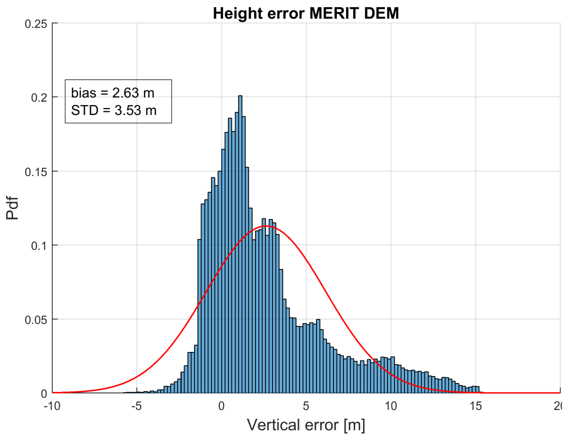


Figure B.141: Histogram DEM error MERIT, Aunuu

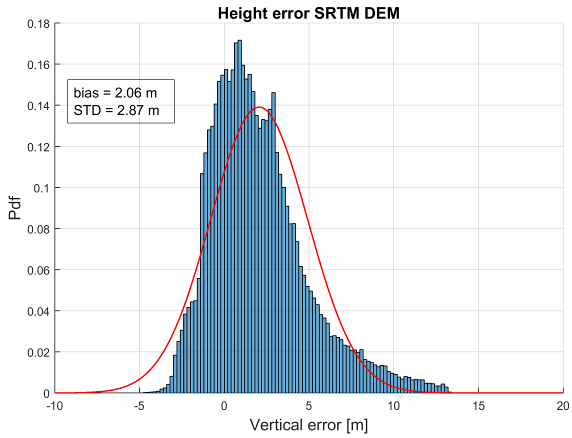


Figure B.142: Histogram DEM error SRTM, Aunuu

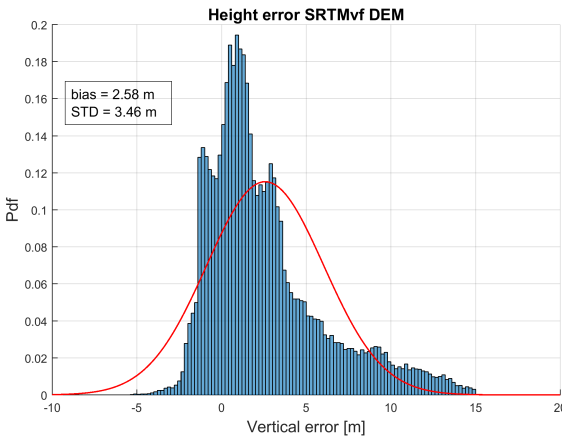


Figure B.143: Histogram DEM error SRTMvf, Aunuu

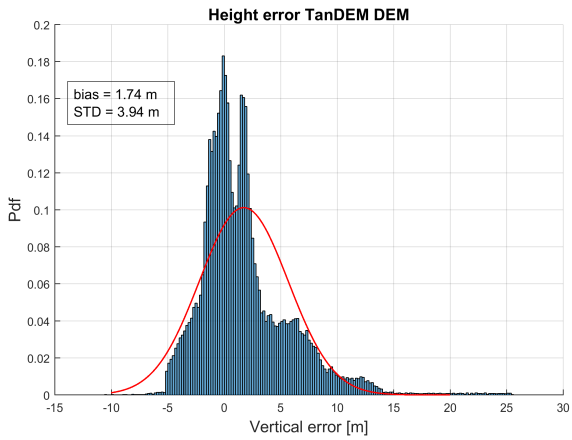


Figure B.144: Histogram DEM error TanDEM-X, Aunuu

Difference plots

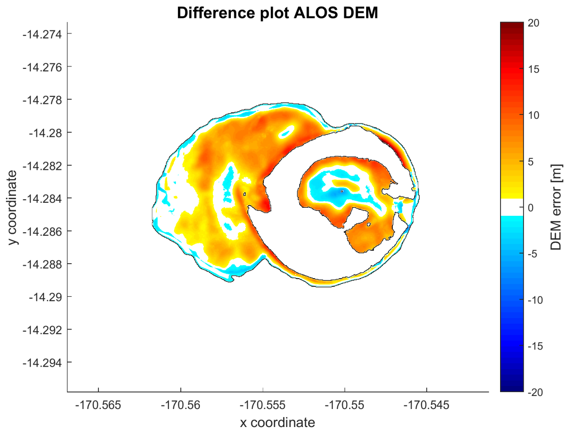


Figure B.145: Difference plot ALOS, Aunuu

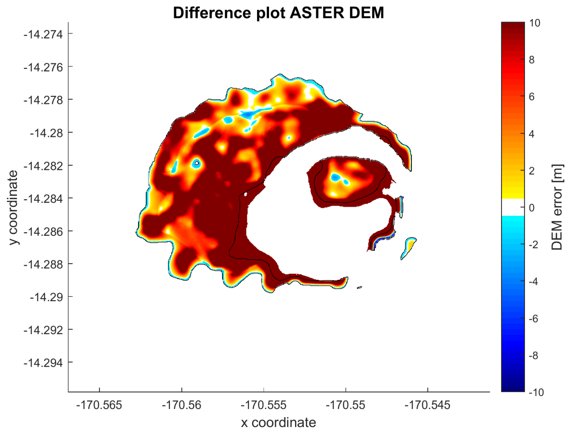


Figure B.146: Difference plot ASTER, Aunuu

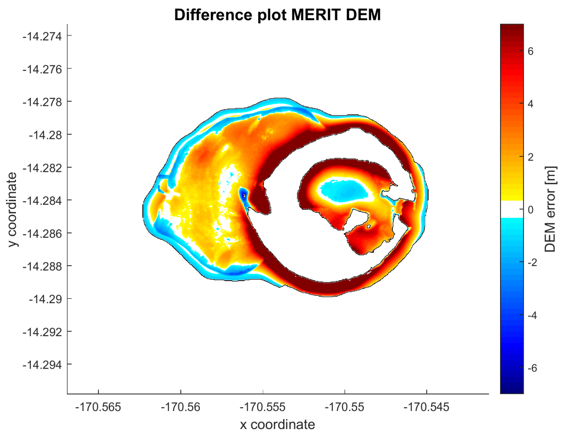


Figure B.147: Difference plot MERIT, Aunuu

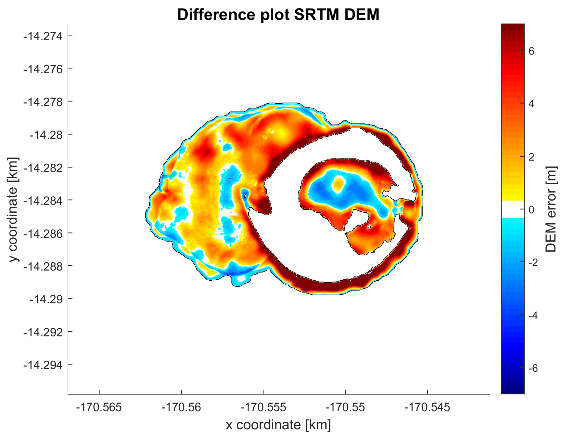


Figure B.148: Difference plot SRTM, Aunuu

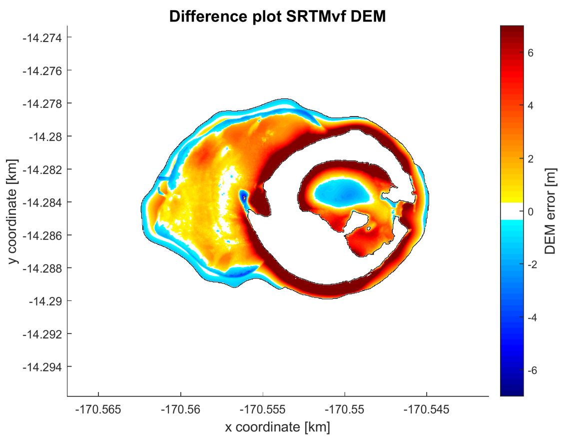


Figure B.149: Difference plot SRTMvf, Aunuu

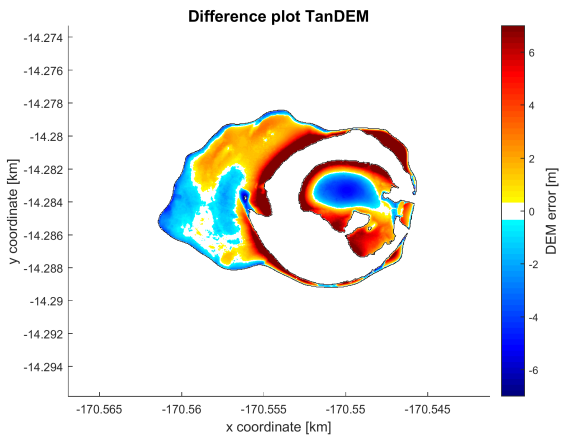


Figure B.150: Difference plot TanDEM-X, Aunuu

Unbiased difference plots

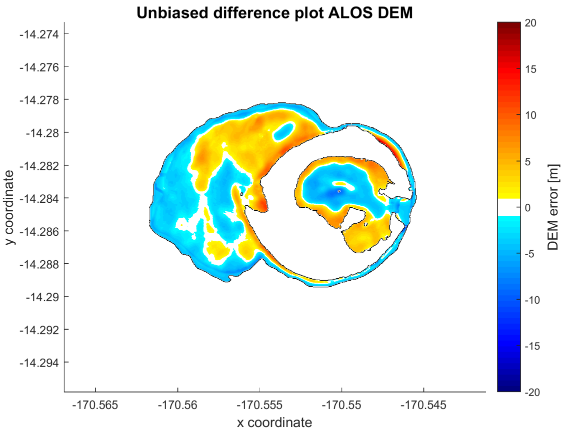


Figure B.151: Unbiased difference plot ALOS, Aunuu

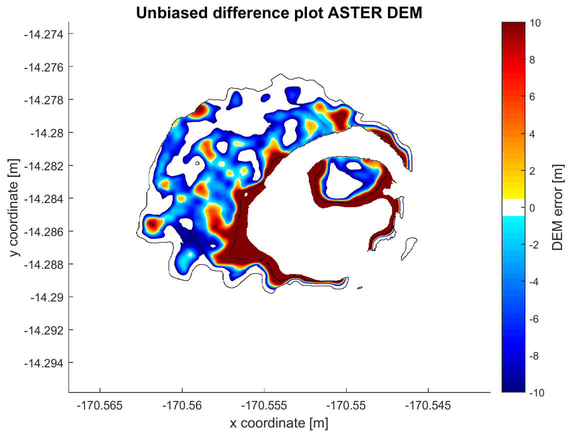


Figure B.152: Unbiased difference plot ASTER, Aunuu

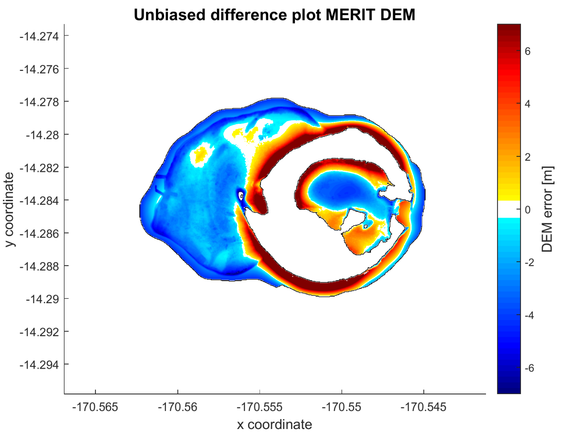


Figure B.153: Unbiased difference plot MERIT, Aunuu

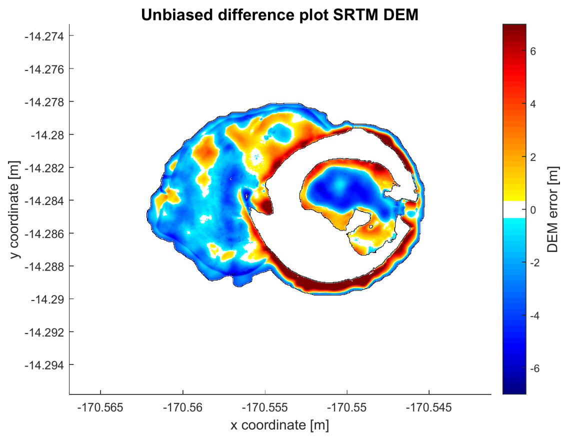


Figure B.154: Unbiased difference plot SRTM, Aunuu

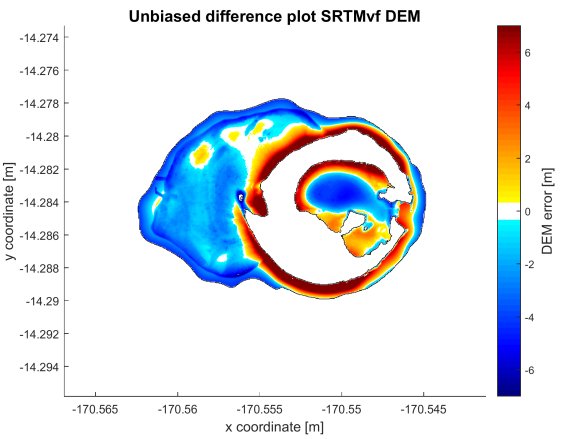


Figure B.155: Unbiased difference plot SRTMvf, Aunuu

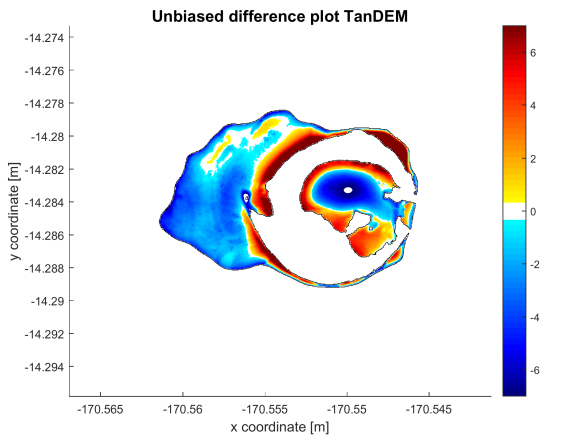


Figure B.156: Unbiased difference plot TanDEM-X, Aunuu

B.4.3. Ofu-Olosega

For the island of Ofu-Olosega, only the error statistics and histograms of the DEM error are included in this appendix. Due to the size and shape of the island, both the difference plots and unbiased difference plots cannot be displayed clearly in a report of A4 size. For these plots, please contact the author (martinerottink@hotmail.com).

Error statistics

Table B.12: Error statistics for the island of Ofu-Olosega

	Bias [m]	MAE [m]	UMAE [m]	RMSE [m]	URMSE [m]	min [m]	max [m]	LE90 [m]
ALOS	3,06	3,91	3,82	5,85	4,99	-10,79	27,86	9,84
ASTER	16,01	16,53	9,53	20,31	12,49	-10,91	62,82	32,42
MERIT	9,79	10,41	7,83	14,04	10,06	-10,80	45,67	23,36
SRTM	4,21	5,04	4,21	6,84	5,39	-10,85	24,10	11,76
SRTMvf	7,85	8,51	6,47	11,17	7,95	-10,78	34,66	19,26
TanDEM-X	8,66	9,46	7,57	13,02	9,72	-10,72	45,29	22,58

Histograms DEM error

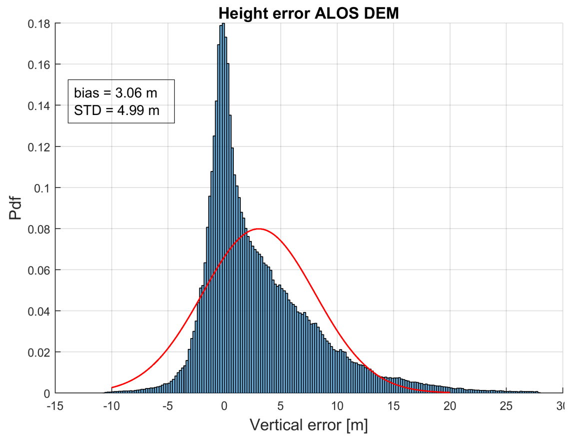


Figure B.157: Histogram DEM error ALOS, Ofu-Olosega

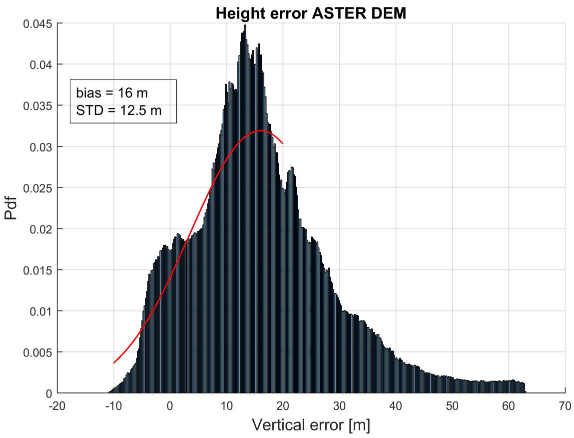


Figure B.158: Histogram DEM error ALOS, Ofu-Olosega

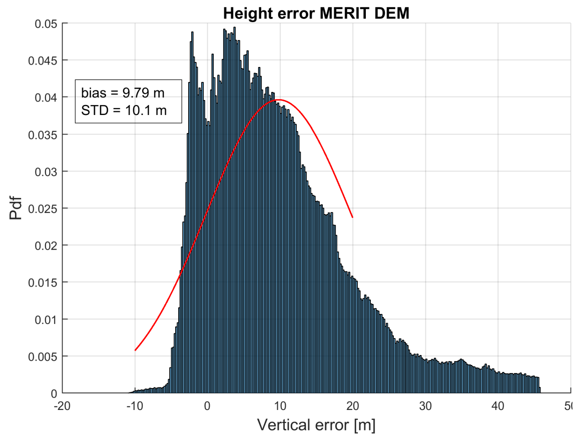


Figure B.159: Histogram DEM error MERIT, Ofu-Olosega

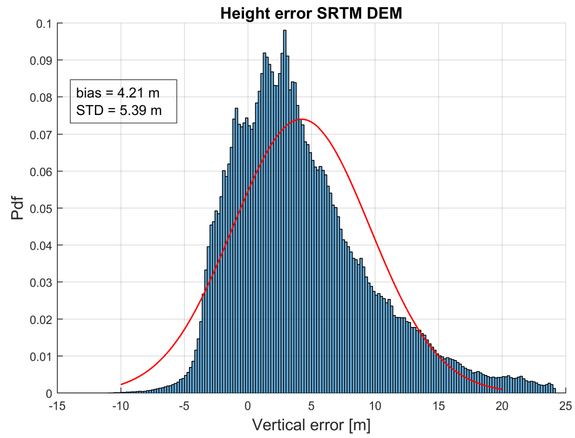


Figure B.160: Histogram DEM error SRTM, Ofu-Olosega

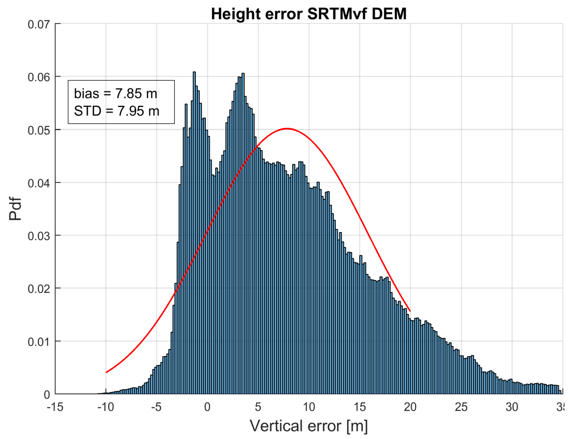


Figure B.161: Histogram DEM error SRTMvf, Ofu-Olosega

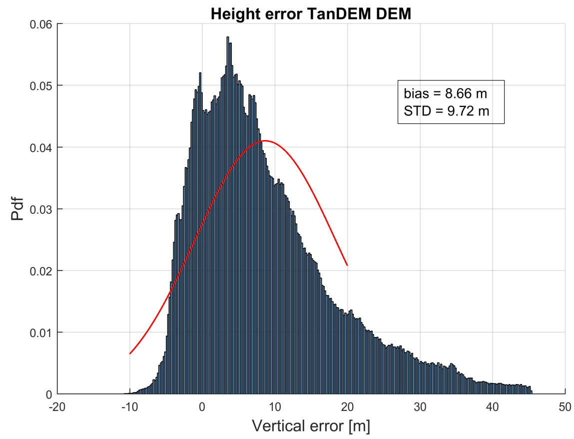


Figure B.162: Histogram DEM error TanDEM-X, Ofu-Olosega

C

Building correction

C.1. Building heights

In this appendix, the different building types for the islands in the Pacific Ocean and for the Wadden islands are listed in Table C.1 and Table C.2 respectively. The assumed amount of floors and floor height per building are listed as well. Not all islands included all building types. The building type 'yes' that was present on all islands is the category that is assigned by OSM to all buildings that did not receive a specific building type tag. This category included most of the buildings on the islands.

Building type	**Amount of floors (m)**	**Height per floor (m)**
Apartments	1	3
Cathedral	1	10
Church	1	10
Commercial	1	3
Construction	1	3
Garage	1	3
Government	1	3
Hospital	2	4
Hotel	3	3
House	1	3
Industrial	1	3
Office	1	3
Public	1	3
Residential	1	3
Restaurant	1	3
Retail	1	3
Roof	1	3
School	2	3
Service	1	3
Shed	1	3
Storage tank	1	3
Warehouse	2	3
Yes	1	3

Table C.1: Building types and assumed amount of floors and height per floor for PICs

Building type	Amount of floors (m)	Height per floor (m)
Apartments	2	3
Bunker	1	3
Church	1	10
Civic	1	3
College	2	3
Commercial	2	3
Construction	2	3
Detached	2	3
Farm	2	3
Garage	1	3
Greenhouse	1	4
Hangar	1	3
Hotel	2	3
House	2	3
Hut	2	3
Industrial	2	3
Lighthouse	1	10
Museum	2	3
Office	2	3
Public	2	3
Pumphouse	1	3
Retail	2	3
Roof	2	3
School	2	3
Service	2	3
Shed	1	3
Static_caravan	1	3
Supermarket	1	3
Terrace	0	0
University	2	3
Yes	2	3

Table C.2: Building types and assumed amount of floors and height per floor for the Wadden islands

C.2. Results

C.2.1. Texel

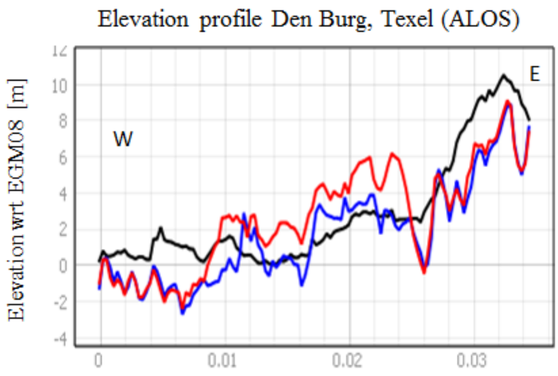


Figure C.1: Cross section Den Burg, ALOS

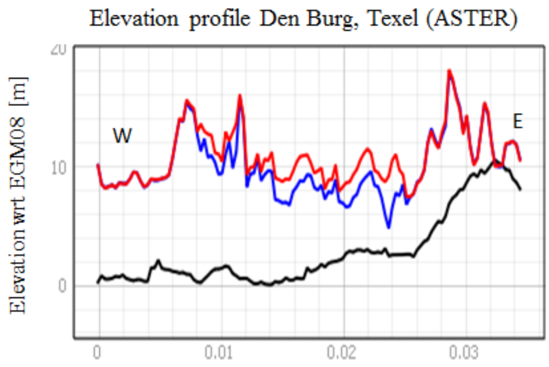


Figure C.2: Cross section Den Burg, ASTER

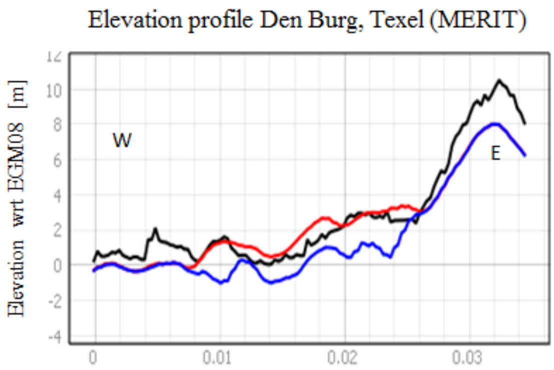


Figure C.3: Cross section Den Burg, MERIT

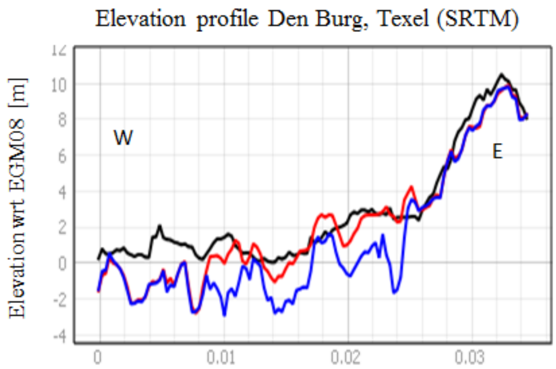


Figure C.4: Cross section Den Burg, SRTM

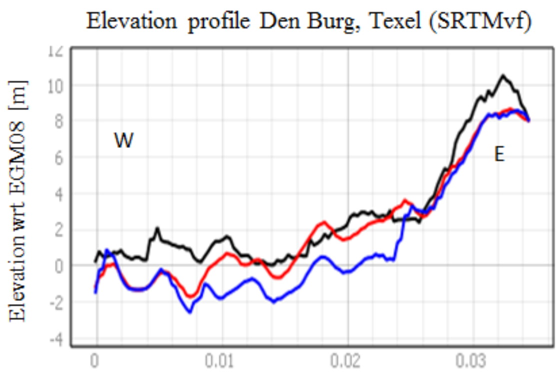


Figure C.5: Cross section Den Burg, SRTMvf

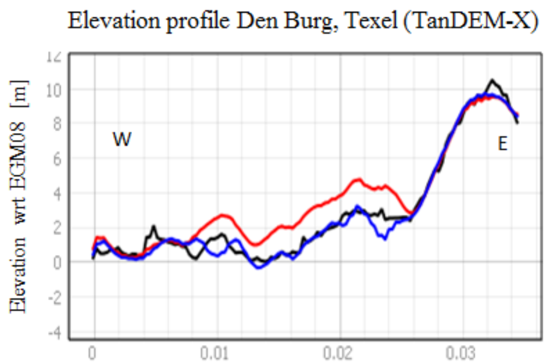


Figure C.6: Cross section Den Burg, TanDEM-X

D

Simple flood model

D.1. Wave breaking formulations

There exist different parametric wave breaking formulations in literature. In order to develop the simple flood model as described in Chapter 5, different parametric wave models were reviewed from literature. In this section, these different models are shortly described.

D.1.1. Battjes and Janssen

Many parametric wave breaking models are based on the model by Battjes and Janssen (Battjes and Janssen, 1966). In this model, the transformation of short waves in the surf zone is modelled using a short wave energy balance including energy dissipation due to wave breaking. this dissipation is modelled using the analogy of a turbulent bore. In this model, the wave height is assumed to be Rayleigh distributed with a cutoff function for the maximum possible water depth, see equation D.1. All broken waves are assumed to have a height H_b; this is depicted in Figure D.1.

$$P(H) = \begin{cases} 1 - exp\left(-\frac{1}{2}\frac{H^2}{\bar{H}^2}\right), & \text{for } 0 \leq H < H_b \\ 1 & \text{for } H_b \leq H \end{cases} \tag{D.1}$$

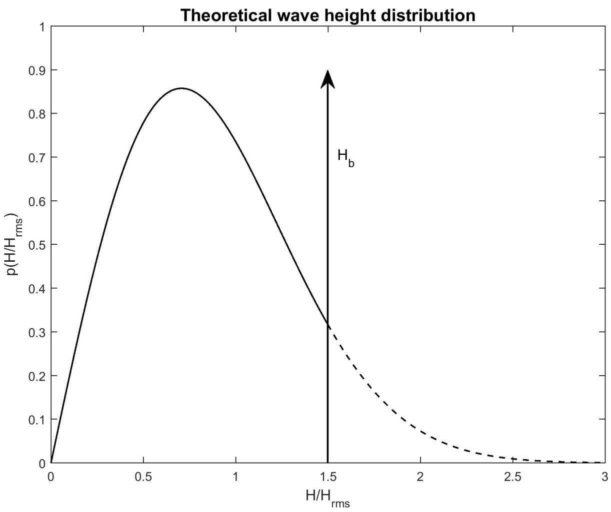


Figure D.1: Theoretical wave height and breaking wave height distributions. Adjusted from (Thornton and Guza, 1983)

The analogy with a turbulent bore leads to equation D.2 for the energy dissipation due to wave breaking. As can be seen, the energy dissipation in a breaking wave is assumed to depend on the mean frequency f and the breaking wave height H_b. In order to calculate the total energy dissipation, this expression needs to be multiplied with Q_b, a parameter representing the fraction of broken waves. This parameter can be calculated with the implicit function given in equation D.3.

$$\langle \epsilon_b \rangle = \frac{\alpha}{4} Q_b f \rho g H_b^2 \tag{D.2}$$

$$\frac{1-Q_b}{lnQ_b} = -\left(\frac{H_{rms}}{H_b}\right)^2 \tag{D.3}$$

There exist various expressions to calculate the breaking wave height H_b. In the orginal model developed by Battjes and Janssen, an adjusted version of the Miche wave breaking criterion was used. The model was validated with flume experiments carried out on plane beach slopes and beaches with a bar-trough profile. Different experiments with a slope of 1:20 and different offshore forcing conditions were carried out. The model was shown to work quite well for the estimation of water levels and wave heights on mildly sloping beaches.

D.1.2. Thornton and Guza

The model developed by Battjes-Janssen (Battjes and Janssen, 1966), assumes a truncated Rayleigh distribution for the short waves inside the surfzone; the offshore Rayleigh distribution is truncated at the breaking wave height H_b. Thornton and Guza conducted field experiments and showed that also in the surf zone, the short wave height distribution was almost Rayleigh (Thornton and Guza, 1983). Furthermore, they concluded that the distribution of breaking wave heights can be expressed as a weighting of the Rayleigh distribution for all waves:

$$P_b(H) = W(H)p(H) \tag{D.4}$$

For the weighing function, they defined an expression based on their observations, see equation D.5. The distribution of wave height and breaking wave height are depicted in Figure D.2.

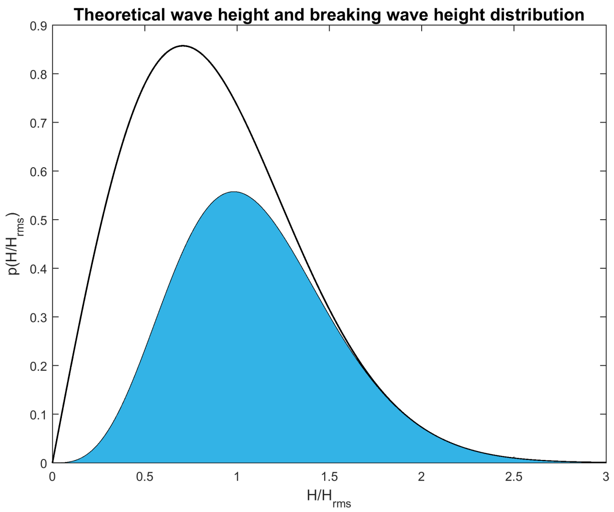


Figure D.2: Theoretical wave height and breaking wave height distributions. Adjusted from (Thornton and Guza, 1983)

$$W(H) = \left(\frac{H_{rms}}{\gamma h}\right)^n \left[1 - exp\left(-\left(\frac{H}{\gamma h}\right)^2\right)\right] \leq 1 \tag{D.5}$$

This weighting function is somewhat skewed to the higher waves, since a greater proportion of the larger waves contribute to the breaking process. Elaboration of this breaking wave height distribution in the formulation for breaking wave dissipation yields equation D.6.

$$\langle\epsilon_b\rangle = \frac{3\sqrt{\pi}}{16}\rho g \alpha^3 \bar{f}\frac{H_{rms}^5}{\gamma^2 h^3}\left[1-\frac{1}{(1+(H_{rms}/\gamma h)^2)^{5/2}}\right] \tag{D.6}$$

The Thornton-Guza model was tested against the laboratory data from (**?**) and observations from field experiments. Both comparisons showed that the Thornton-Guza model is well able to predict the short wave transformation in the surf zone. However, the model skill was not compared to results of other parametric wave models.

D.1.3. Baldock

The model developed by Battjes and Janssen assumes a saturated surf zone, which means that the wave height or wave energy in the inner surf zone is independent of the incident wave height or energy. However, on steep beaches, the surf zone is very narrow and there is insufficient time for all the incident short wave energy to dissipate. In this case, the inner surf zone is unsaturated. Baldock reformulated the original Battjes Janssen model to improve its prediction skills in shallow water on steep slopes.

Based on observations by Thornton and Guza, the waves in the surf zone are assumed to be Rayleigh distributed, instead of the truncated Rayleigh distribution proposed by Battjes and Janssen (Thornton and Guza, 1983).

$$P\left(\frac{H}{H_{rms}}\right) = 2\left(\frac{H}{H_{rms}}\right) exp\left[-\left(\frac{H}{H_{rms}}\right)^2\right] \tag{D.7}$$

Adopting the usual criterion that a wave is breaking when its height exceeds some fraction of the water depth, the proportion of breaking waves is obtained directly from the Rayleigh distribution, as depicted in Figure D.3. This assumption is more simplistic than the one in the model developed by Thornton and Guza, where an empirical weighting function is proposed. The proportion of broken waves, Q_b is obtained from integrating the Rayleigh distribution over all waves for which $H/H_{rms} \geq H_b/H_{rms}$, which results in an explicit expression for Q_b and ϵ_b.

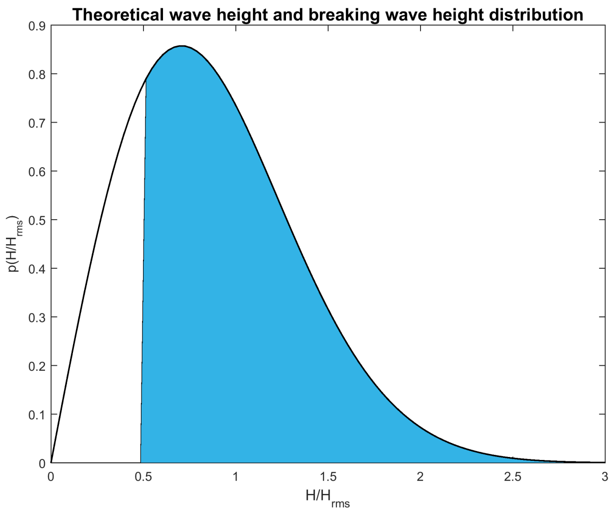


Figure D.3: Theoretical wave height and breaking wave height distributions. Adjusted from (Baldock et al., 1998)

$$Q_b = exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right] \tag{D.8}$$

$$\langle\epsilon_b\rangle = \frac{\alpha}{4} f\rho g exp\left[-\left(\frac{H_b}{H_{rms}}\right)^2\right](H_b^2 + H_{rms}^2) \tag{D.9}$$

The Baldock model was validated using the results of experimental flume tests on a 1/10 beach profile. Comparison with these experimental results showed that the Baldock model is indeed better able to predict the water levels and wave heights in the inner surf zone on steep beaches. Also, it was shown that the wave heights in the inner surf zone are Rayleigh distributed and do not follow the truncated Rayleigh distribution as proposed by Battjes and Janssen (Baldock et al., 1998).

D.1.4. Janssen and Battjes

Janssen and Battjes revisited the derivation of the parametric surf zone model developed by Baldock, after observing a shoreline singularity when the model is applied in very shallow water. The identified an algebraic inconsistency and propose an improved (explicit) expression for the wave breaking process:

$$\langle \epsilon_b \rangle = \frac{3\sqrt{\pi}}{16} \alpha f \rho g \frac{H_{rms}^3}{h} \left[1 + \frac{4}{3\sqrt{\pi}} \left(\left(\frac{H_b}{H_{rms}} \right)^3 + \frac{3}{2} \left(\frac{H_b}{H_{rms}} \right) \right) exp \left[- \left(\frac{H_b}{H_{rms}} \right)^3 \right] - erf \left(\frac{H_b}{H_{rms}} \right) \right] \tag{D.10}$$

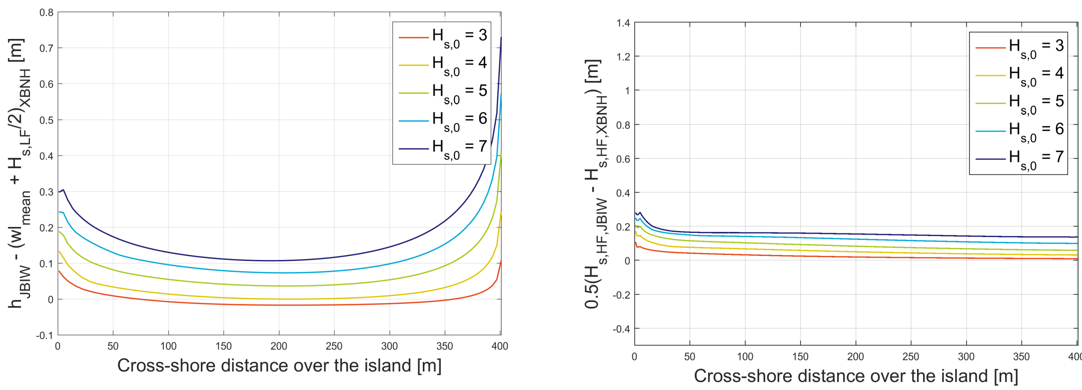
The Janssen-Battjes model was applied on beach slopes of 1/10, 1/20 and 1/100. For the 1/10 beach slope, the Janssen-Battjes model was shown to be more robust; the shoreline singularity present in the Baldock model is solved. On the 1/20 and 1/100 beach slopes, be model performed similar to the Baldock model (and to the Battjes-Janssen and Thornton-Guza models). Furthermore, the model was compared to observations on a 1/10 beach slope reported by (Baldock et al., 1998). This comparison showed good agreement between observations and predictions of wave height in the inner surf zone (Janssen and Battjes, 2007).

D.2. Analysis of the accuracy of the JBIW model for different parameters

D.2.1. downslope profile

In order to analyse how the error in maximum water level predicted with the JBIW model depends on the different parameters (i.e. the offshore wave height, the fore reef slope, the reef flat width, the beach slope, the height of the island and the slope on the island), the mean error is calculated for different values of all parameters. The results are depicted in Figure D.10 and will be discussed below.

Figure D.10a indicates that the error increases for increasing offshore wave heights, both at the start and at the end of the island. From the figure it can be seen that for larger offshore waves $H_{s,0}$, the maximum water level at the start of the island is underestimated more (this is most clear around x = 40). This is caused by the combination of the underestimation of the maximum water level by the use of equation 5.19 and the overestimation of both the water depth (including a long wave component) and the short wave height in the JBIW model, as discussed above. In Figure D.4a and D.4b, it can be seen that the overestimation at the start of the island of the both the water depths and the short wave heights increases for higher offshore wave heights $H_{s,0}$. However, in Figure D.5, it can be seen that the underestimation of the maximum water level calculated with equation 5.19 also increases for higher offshore wave heights, which indicates that the contribution of waves is underestimated in equation 5.19.



(a) Overestimation water depth (including a long wave component), for different $H_{s,0}$

(b) Overestimation $H_{s,HF}$, for different $H_{s,0}$

Figure D.4: Figure (a) and (b) show the overestimation of the water depths (including a long wave component) and the short wave heights in the JBIW model respectively, for different offshore wave heights.

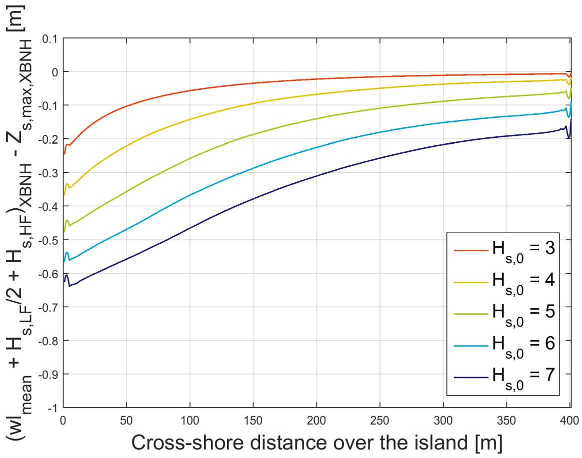
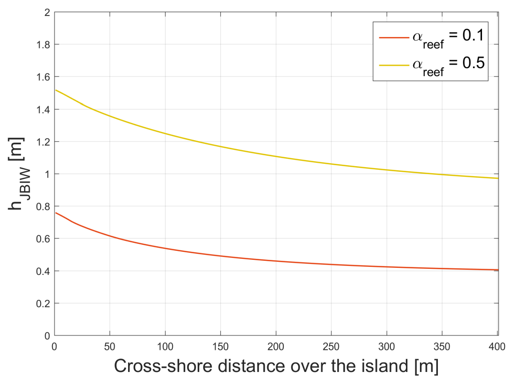


Figure D.5: Difference between the maximum water level calculated with equation 5.19, with the mean water level, short and long wave heights obtained from XBNH+ and the maximum water level from the XBNH+ runs.

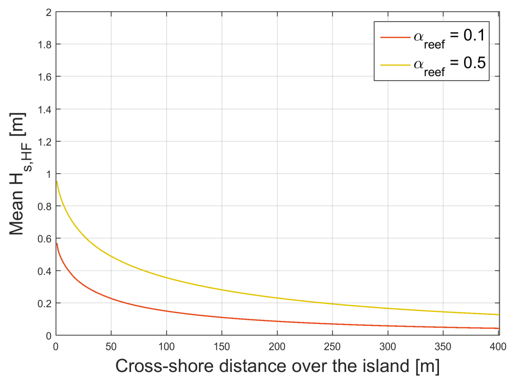
At the start of the island, the underestimation of the maximum water level by the use of equation 5.19 and the overestimation of the water depth (including a long wave component) and $H_{s,HF}$ result in a mean error which is approximately equal for all offshore wave heights. It can be seen from Figure D.4a that the overestimation of the water depth decreases faster for higher offshore waves. The underestimation of the maximum water level by equation 5.19 decreases at approximately the same rate for different offshore wave heights (see Figure D.5). Therefore, the underestimation of the maximum water level at the start of the island is larger for larger offshore wave heights $H_{s,0}$.

Furthermore, it can be seen that for larger waves, the overestimation of the maximum water level at the end of the island also increases. This is caused by the boundary effect from the end of the island, as was described above. For higher offshore waves, the waterdepths over the island are larger and the error introduced by the boundary effect is also larger. This is also depicted in Figure D.4a; in this figure it can be seen that the overestimation of the water depth at the end of the island is larger for larger offshore waves.

Figure D.10b suggests that the error over the island increases for steeper fore reef slopes, both at the start and at the end of the island. This can be explained by the fact that for steeper forereef slopes the amount of long wave energy generated in the breakpoint mechanism is much larger (Baldock et al., 2000), which results in both higher long waves and short waves at the beach foot. The water depth (including a long wave component) and therefore the short waves over the island will thus be higher for steeper fore reef slopes. This can be seen in Figure D.6a and D.6b. Similar to what was concluded from Figure D.10a, this results in a larger underestimation of the maximum water level at the start of the island and a larger overestimation of the maximum water level at the end of the island.



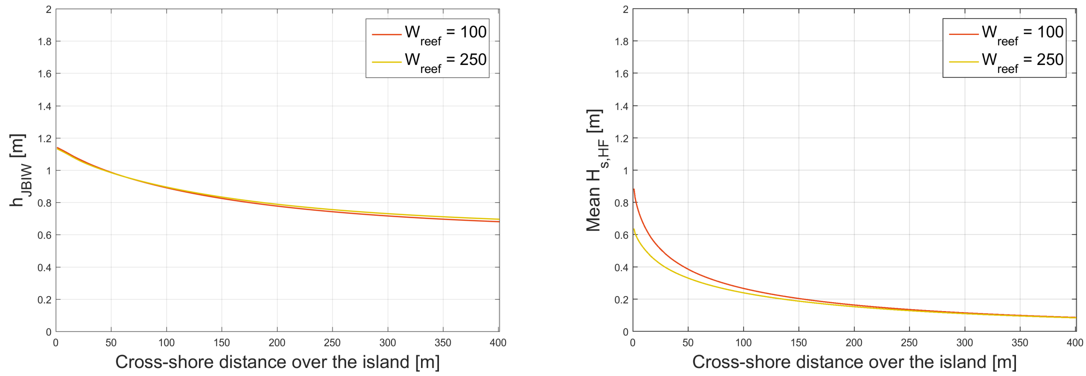
(a) Mean h_{JBIW} for different forereef slopes



(b) mean $H_{s,HF}$ for different forereef slopes

Figure D.6: Mean long and short wave heights for different forereef slopes

From Figure D.10c it can be seen that the error is larger for shorter reef flats. This can be explained by the fact that the longer the reef flat, the more wave dissipation (mainly due to bottom friction) takes place over the reef flat. This means that for longer reef flats, the amount of short wave energy at the beach foot is less. The difference in long wave energy is expected to be small; therefore the difference in water depth over the island calculated with the JBIW model is also expected to be small. This is confirmed in Figure D.7a. Similar to what was concluded from Figure D.10a, larger wave heights lead to a larger underestimation of the maximum water levels at the start of the island. The error at the start of the island is therefore larger for shorter reef flats. Since the short wave energy dies out over the island under the influence of bottom friction, the difference in error decreases over the island.

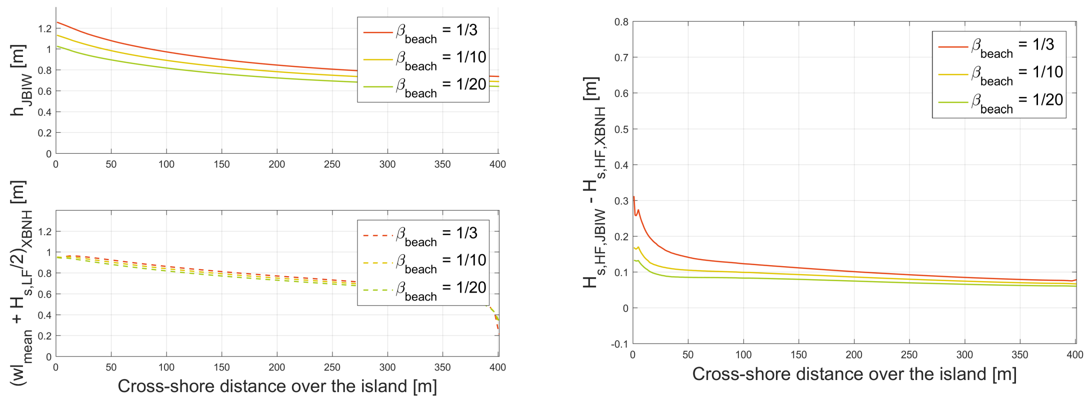


(a) Mean h_{JBIW} for different reef flat lengths

(b) mean $H_{s,HF}$ for different reef flat lengths

Figure D.7: Mean long and short wave heights for different reef flats, calculated with the JBIW model

In Figure D.10d, it can be seen that the underestimation of the maximum water level at the start of the island increases for milder beach slopes. This can be explained by Figure D.8a and D.8b. These figures show that the overestimation of both the water depth (including a long wave component) and the short waves increases for steeper beachslopes. It can be observed that the mean water depth (including a long wave component) as calculated with XBNH does not differ that much between the different beachslopes. However, the water depths calculated with the JBIW model differ quite a lot for different values of the beachslope. This behaviour of the JBIW model is expected, since the equation to calculate the long wave dissipation due to breaking does not assume a saturated surf zone: the long wave dissipation due to breaking only depends on $H_{rms,LF}$ and not on the water depth (see equation 5.17). For steeper beachslopes, a larger long wave and therefore larger water depth is thus expected. This higher water depth subsequently also results in a larger short wave height (see Figure D.8b).



(a) Mean $H_{s,LF}$ for different beachslopes

(b) mean $H_{s,HF}$ for different beachslopes

Figure D.8: Mean errors in the long and short wave heights for different beachslopes

Since the maximum water level is underestimated by equation 5.19, the larger overestimation of the wave heights for steeper beach slopes causes the errors at the start of the island to be smaller for steeper slopes. Since the wave energy decreases over the island, the difference in error between the different beach slopes becomes less towards the end of the island.

In Figure D.10e, it can be seen that the error at the end of the island increases for lower island heights. This is caused by the boundary effect from the end of the island, which is larger for larger water depths over the island (i.e. for lower island heights). At the start of the island, no clear relation between the island height and the error in the JBIW model can be found. It is expected that this is caused by the fact that the island height was not the only parameter that was changed between these runs; the offshore water level was different as well (see Section 6.1.2).

Lastly, from Figure D.10f, it can be seen that the error at the end of the island decreases for increasing island slopes. This can be explained by the fact that the value for λ in Equation 5.23 depends both on the slope and the roughness. For larger island slopes, λ increases and thus the water level decreases faster. The difference in water level at the end of the island then decreases and the boundary effect from the end of the island becomes less.

Furthermore, it can be seen that at the start of the island, the mean error is somewhat larger for milder island slopes. This was not expected, but might be explained by Figure D.9. This figure shows the mean difference between the maximum water level calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+, calculated for different island slopes. From this figure, it can be seen that at the start of the island, the underestimation of the maximum water level calculated with equation 5.19 is somewhat larger for milder island slopes. This might explain the difference in mean error for different island slopes at the start of the island. However, the reason for this is not clear.

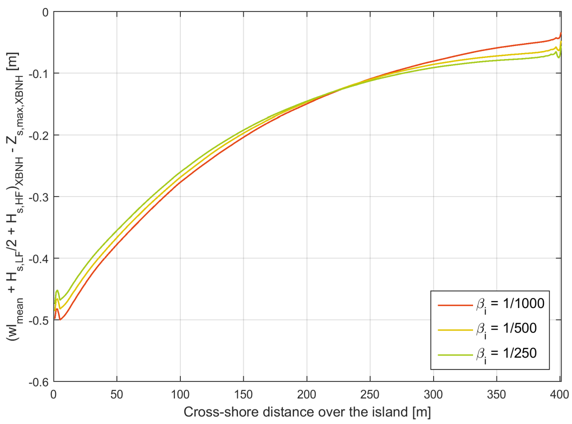
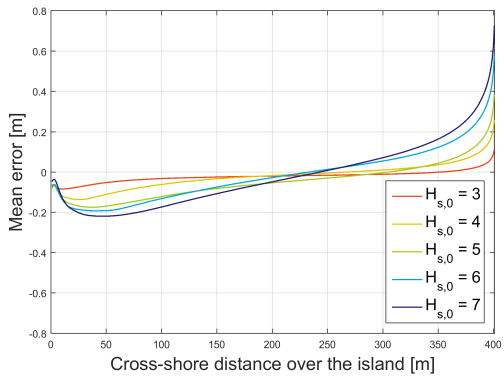
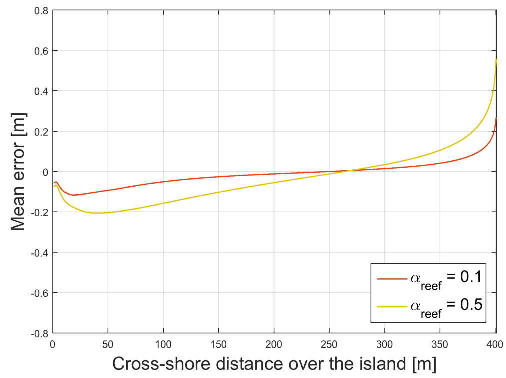


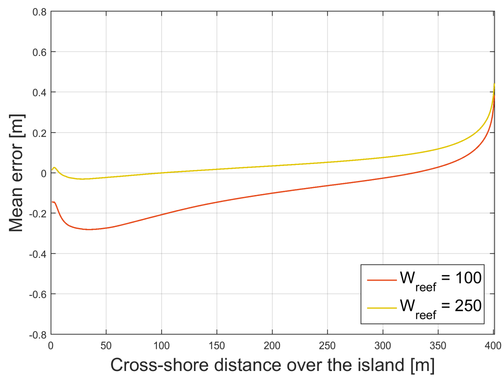
Figure D.9: $(Z_{s,mean} + H_{s,LF}/2 + H_{s,HF})_{XBNH}$ - $Z_{s,max,XBNH}$ for different island slopes



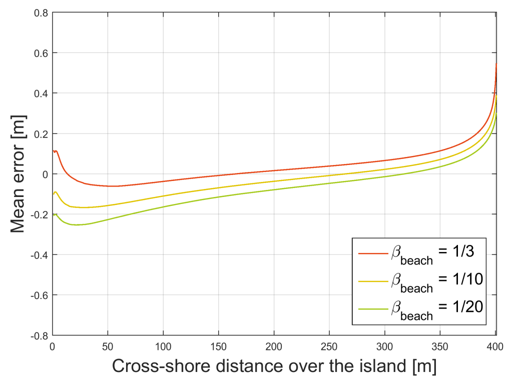
(a) Different $H_{s,0}$



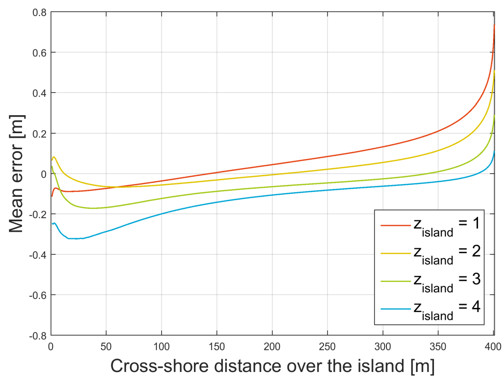
(b) Different β_f



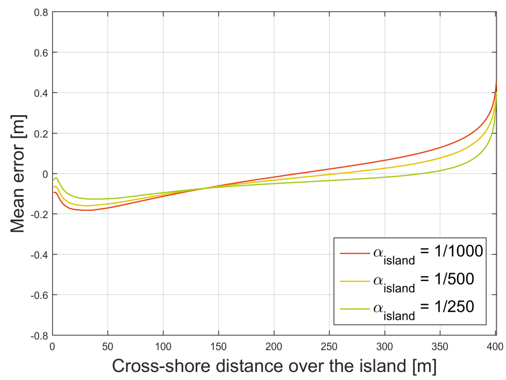
(c) Different W_{reef}



(d) Different β_b



(e) Different z_{island}



(f) Different β_i

Figure D.10: Mean errors in the maximum water levels for the conceptual tests on the downslope profile. The mean error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the JBIW model ($Z_{s,max,JBIW} - Z_{s,max,XBNH}$)

D.2.2. Upslope profile

Similar to the downslope profile, the error in maximum water levels calculated with the JBIW model is analysed for different values of the offshore wave height, forereef slope, reef width, beach slope, island height and island slope. In this way, the influence of these parameters on the error can be analysed. The results are depicted in Figure D.12.

Figure D.12a shows that the dependence of the error in maximum water level on the offshore wave height for the upslope profile is comparable to the downslope profile. For higher offshore wave heights, the error increases both at the start and at the end of the island. A difference with the downslope profile is that the underestimation of the maximum water levels at the start of the island is somewhat larger for the upslope profile than for the downslope profile, especially for higher offshore wave heights. This can be explained by

Figure D.11, which shows that the underestimation of the maximum water level by equation 5.19 does differ between the two profiles. The figure shows the difference between the maximum water levels calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+. The solid lines represent the upslope profile and the dashed lines the downslope profile. As can be seen from the figure, the underestimation is larger for the upslope profile compared to the downslope profile (especially for higher offshore waves). This indicates that the waves have a larger effect on the maximum water levels for the upslope profile, compared to the downslope profile. This might be explained by the reflection of waves on the upslope profile, which also adds to the maximum water levels in the XBNH+ runs, but is not incorporated in the JBIW model.

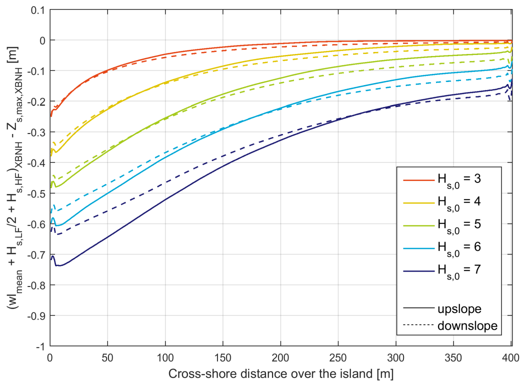


Figure D.11: The different lines represent the difference between the maximum water levels calculated with XBNH+ and the maximum water levels calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs. The differences are averaged over all runs belonging to a certain offshore wave height $H_{s,0}$. The dashed lines (−−) represent the downslope profile, and the solid lines (–) represent the upslope profile. The x-axis represents the cross-shore distance over the island.

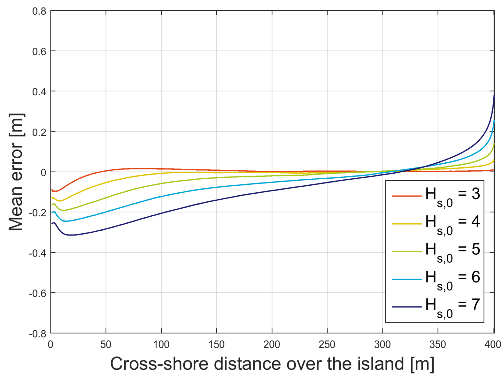
Another difference with the downslope profile is that the 'switch' from negative to positive errors occurs later on the island, compared to the downslope profile. This is caused by the fact that for the upslope profile, the waterdepths at the end of the island are smaller compared to the downslope profile. Therefore, the boundary effect from the end of the island is smaller and extents over a smaller distance.

In Figure D.12b, the mean error for different forereef slopes is similar to the downslope profile. Again, the underestimation of the maximum water level at the start of the island is a bit larger compared to the downslope profile. This can be explained in the same way as for Figure D.12a. The same is true for the position of the 'switch' from negative to positive errors in Figure D.12b.

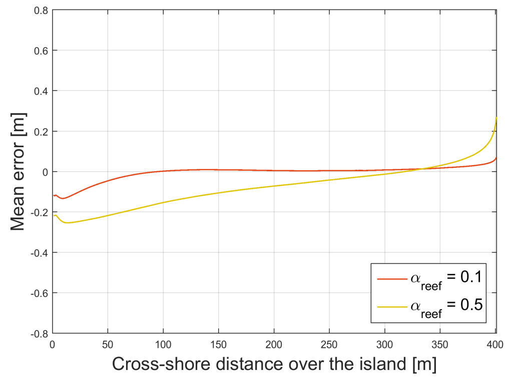
Figure D.12c looks again similar to the upslope profile. The underestimation at the start of the island is a bit larger compared to the downslope profile, which is expected to be caused by the reflection of waves on the upslope profile which adds to the maximum water level, but is not included in the JBIW model. Furthermore, the error at the end of the island is smaller compared to the downslope profile. For the upslope profile, the waterdepths at the end of the island are smaller compared to the downslope profile and therefore the effect of the boundary is smaller and extents over a smaller distance.

Figure D.12d shows a similar trend compared to the downslope profile: milder beachslopes result in a larger underestimation of the maximum water levels at the start of the island and a smaller overestimation of the maximum water levels at the end of the island. From Figure D.12d, it can be seen that the underestimation of maximum water levels at the start of the island is larger compared to the downslope profile, which can again be explained by reflection of waves on upslope island slopes, which adds to the maximum water levels but is not included in the JBIW model.

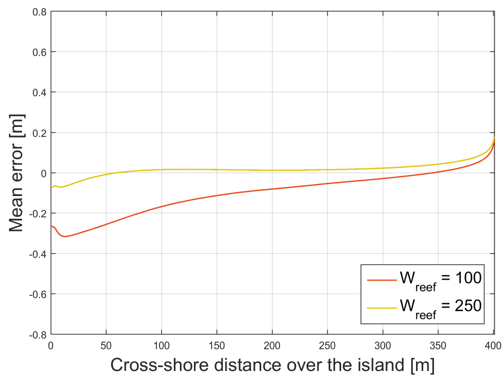
Figure D.12f shows that the mean error at the start of the island increases for steeper island slopes. This is expected, since for steeper upslope island slopes, reflection is expected to increase (and therefore the maximum water levels at the start of the island calculated with XBNH+). Since reflection is not included in the JBIW model, the underestimation of the maximum water level calculated with the JBIW model is expected to be larger for steeper island slopes, where reflection is larger. Furthermore, Figure D.12f indicates that the error at the end of the island increases for milder island slopes. This is also expected, since the waterdepth at the end of the island, and therefore the error introduced by the boundary, is larger for milder island slopes.



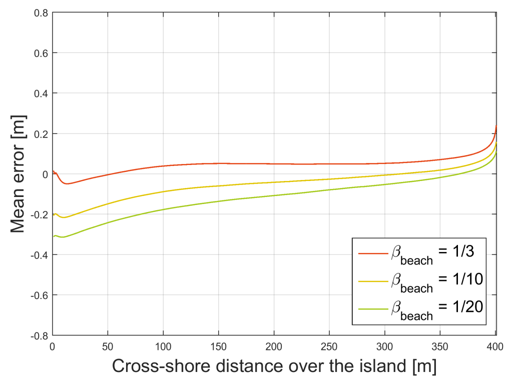
(a) Different $H_{s,0}$



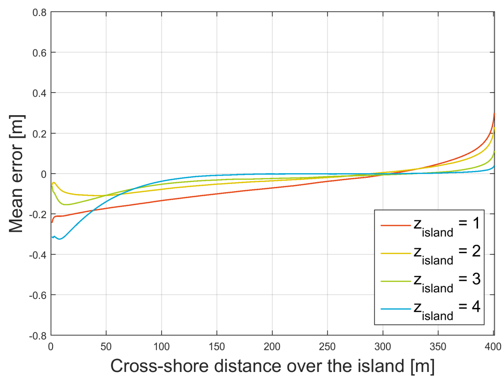
(b) Different β_f



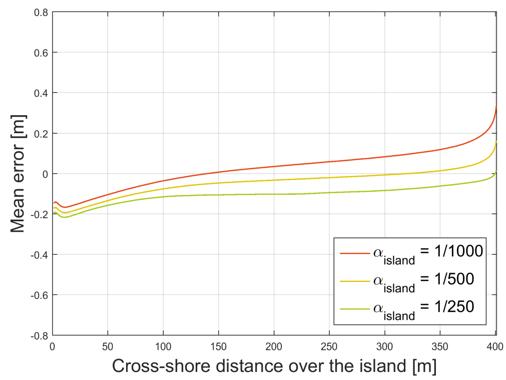
(c) Different W_{reef}



(d) Different β_b



(e) Different z_{island}



(f) Different β_i

Figure D.12: Mean errors in the maximum water levels for the conceptual tests on the upslope profile. The mean error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the JBIW model ($Z_{s,max,JBIW} - Z_{s,max,XBNH}$)

D.2.3. Bathtub profile

Similar to the downslope and upslope profiles, the error in maximum water levels calculated with the JBIW model is analysed for different values of the offshore wave height, forereef slope, reef width, beach slope, island height and island slope. In this way, the influence of these parameters on the error can be analysed. The results are depicted in Figure D.14.

The errors over the island look somewhat differently for the bathtub profiles compared to the downslope and upslope profiles. From the different plots in Figure D.14, it can be seen that the maximum water levels at the start of the island are in almost all cases too high, while both for the upslope and downslope profiles, the maximum water levels at the start of the island are too low. This can be explained by Figure D.13. This figure shows the difference between the maximum water levels calculated with Equation 5.19, with the mean water level, $H_{s,LF}$, and $H_{s,HF}$ obtained from the XBNH+ runs and the maximum water levels calculated with XBNH+. The solid lines represent the bathtub profile and the dashed lines the downslope profile. As can be seen from the figure, the underestimation of the maximum water level at the start of the island is smaller for the bathtub profile compared to the downslope profile. However, the overestimation of the water depths (including a long wave component) and the short wave height at the start of the island are the same for the bathtub and downslope profiles. This results in an overestimation of the maximum water levels at the start of the island for the bathtub profiles.

Furthermore, moving from the start of the island towards a distance of about 60 m, the maximum water levels as calculated by the JBIW model are underestimated. This is expected to be caused by the fact that the decrease in mean water level depends on the value for λ in the IW-method. In this method, the value for λ depends on the bottom roughness and the slope. At the start of the island, the slope is quite steep; therefore the water level decreases quite strongly. Apparently, this decrease in mean water level is too strong and leads to an underestimation of the maximum water level.

Furthermore, the dependence of the error on different values for the different parameters is similar to the downslope and upslope profile, and will thus not be repeated here.

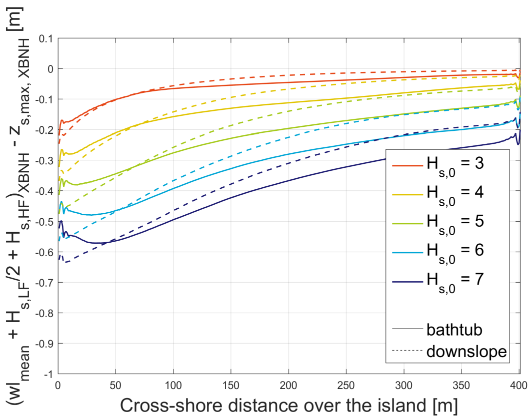
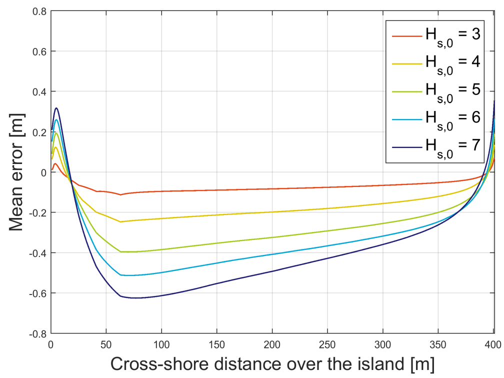
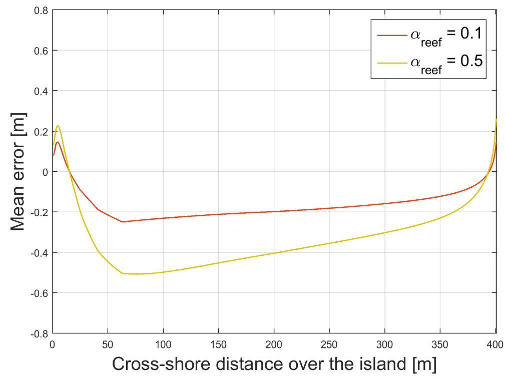


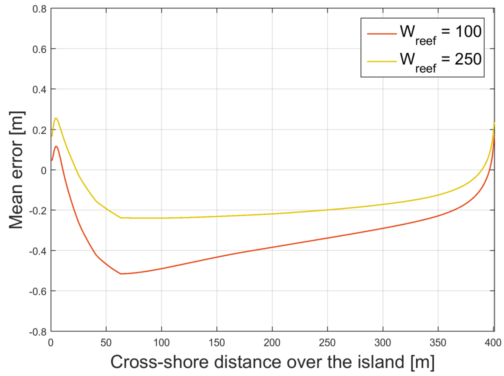
Figure D.13: The different lines represent the difference between the maximum water levels calculated with XBNH+ and the maximum water levels calculated with equation 5.19, with the mean water level, $H_{s,LF}$ and $H_{s,HF}$ obtained from the XBNH+ runs. The differences are averaged over all runs belonging to a certain offshore wave height $H_{s,0}$. The dashed lines (−−) represent the downslope profile, and the solid lines (–) represent the bathtub profile. The x-axis represents the cross-shore distance over the island.



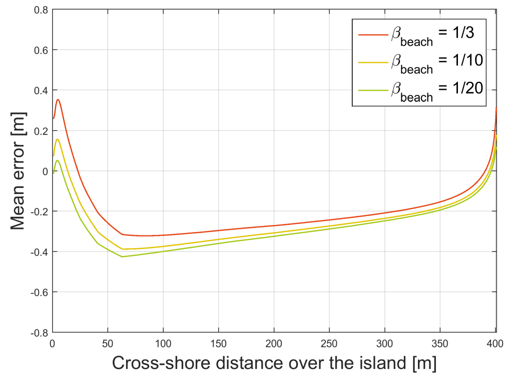
(a) Different $H_{s,0}$



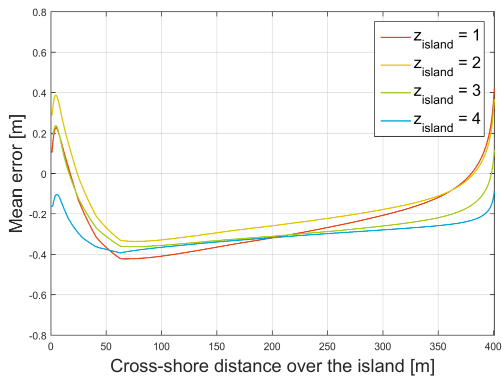
(b) Different β_f



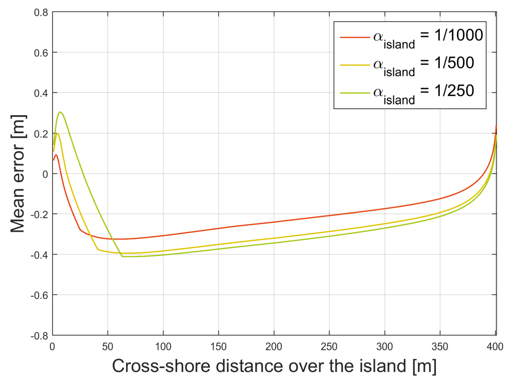
(c) Different W_{reef}



(d) Different β_b



(e) Different z_{island}



(f) Different β_i

Figure D.14: Mean errors in the maximum water levels for the conceptual tests on the bathtub profile. The mean error is calculated by subtracting the maximum water levels calculated with the XBNH+ model from the maximum water levels calculated with the JBIW model ($Z_{s,max,JBIW} - Z_{s,max,XBNH}$)

E

Set-up XBNH+ and SFINCS models for conceptual tests

E.1. Model set-up

In this section, the model set-up of the XBNH+ and SFINCS models is described in more detail. First, the set-up of the XBNH+ model is described. Secondly, the set-up of the SFINCS model runs is described. For both models, attention is paid to the computational grid, the modelled topography, the boundary and initial conditions of the model runs.

E.1.1. XBNH+ model

XBeach is an advanced process-based model that can be used to model processes close to the shore. Multiple studies have tested the application of this model in coral reef environments and found good results (Quataert et al., 2015) (REF). The model can be run in different modes. It can be run in the surfbeat mode, where the short wave variations on the wave group scale and the long waves associated with them are resolved. Furthermore, the model can be run in the non-hydrostatic mode, additionally modelling the propagation and decay of individual (short) waves (REF). The hydrostatic mode was extended with a reduced 2-layer non-hydrostatic model (XBNH+). In this model an added hydrostatic layer improves the dispersive behaviour of the model, so that the non-hydrostatic model can start in larger water depths (up to kh = 5) (de Ridder, 2018). For the conceptual tests, the reduced 2-layer non-hydrostatic model was used, since this is expected to give the most accurate results that can be used as a reference to compare the outcomes of the other flood models to.

Computational grid

The optimal grid size was based on a short discretization analysis, in which the results of XBNH+ model runs with different grid sizes were compared. In Section 5.1, it is described that the water level time series at the location of the beachfoot in the XBNH+ model runs is used to obtain the input for the bathtub, BJIW and SFINCS model runs. Therefore, the water levels and wave heights at the beachfoot are compared between the different model runs.

Grid sizes varying from 0.1 m til 1.5 m were modelled. For a grid size of 0.1 m, it is assumed the model does not require further optimization and therefore the results of this run are used to normalize the results of the other model runs. In Figure E.1, the normalized significant wave height H_s, the different normalized wave height components ($H_{s,HF}$ and $H_{s,LF}$) and the normalized mean water level $\bar{\eta}$ at the beachfoot are depicted. The split between low and high frequency waves is at a frequency of 0.04 s^{-1} (i.e. corresponding to a wave period T = 25 s). All waves with a higher frequency are high frequency waves and all waves with a lower frequency are low frequency waves.

From these figures, it can be seen that the deviations from the model run with dx = 0.1 m are still small ($\approx O(5\%)$) for a grid size of 1 m. In Figure E.2, the wave spectrum at the beachfoot is depicted for different grid sizes. This figure shows that the differences in wavespectrum are not that large. The largest deviations are present for lower frequencies, which can also be observed in Figure E.1, where for the model run with grid size dx=1.0 m the low frequency wave height $H_{s,LF}$ shows a larger deviation from the reference run than the high frequency wave height $H_{s,HF}$.

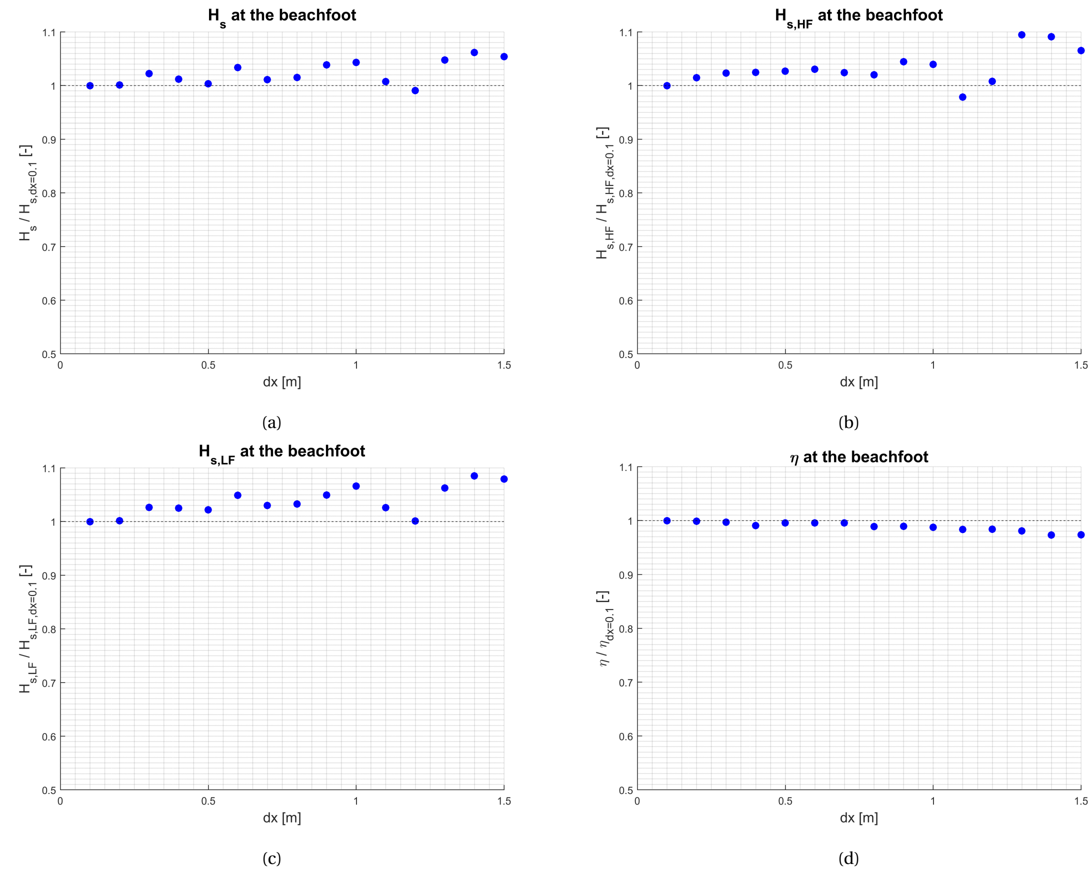


Figure E.1: Normalized wave heights and water levels at the beachfoot. The results for the minimum grid size $\delta x = 0.1$ m is used to normalize the results of the other runs.

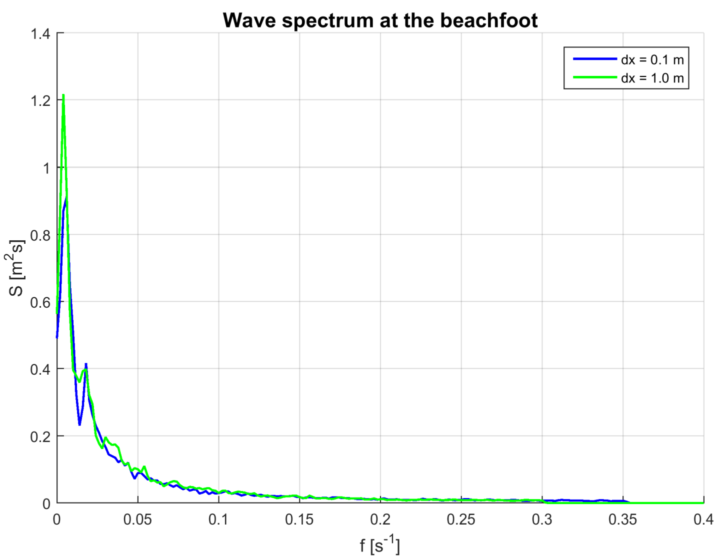


Figure E.2: Figure (a) shows the normalized water level at the beachfoot. Figure (e) shows the wave spectrum at the location of the beachfoot for runs with a grid resolution of 0.1 and 1.0 m.

In Figure E.3, the transformation of the different wave height components over the model domain is depicted for different grid sizes. In this figure, the high-frequency wave height $H_{s,HF}$, the infragravity wave height $H_{s,IG}$ and the very low frequency wave height $H_{s,VLF}$ are depicted for model runs with two different grid sizes (0.1 and 1.0 m). It can be seen that the differences are very small. The difference between the two model runs is most apparent for the very low frequency waves, which corresponds to the results in Figure E.1 and E.2. A grid size dx of 1.0 m is chosen for the different model runs, since the deviations from the model run with dx = 0.1 m are small and a grid size of 1.0 m leads to significantly shorter run times compared to model runs with a grid size of 0.1 m.

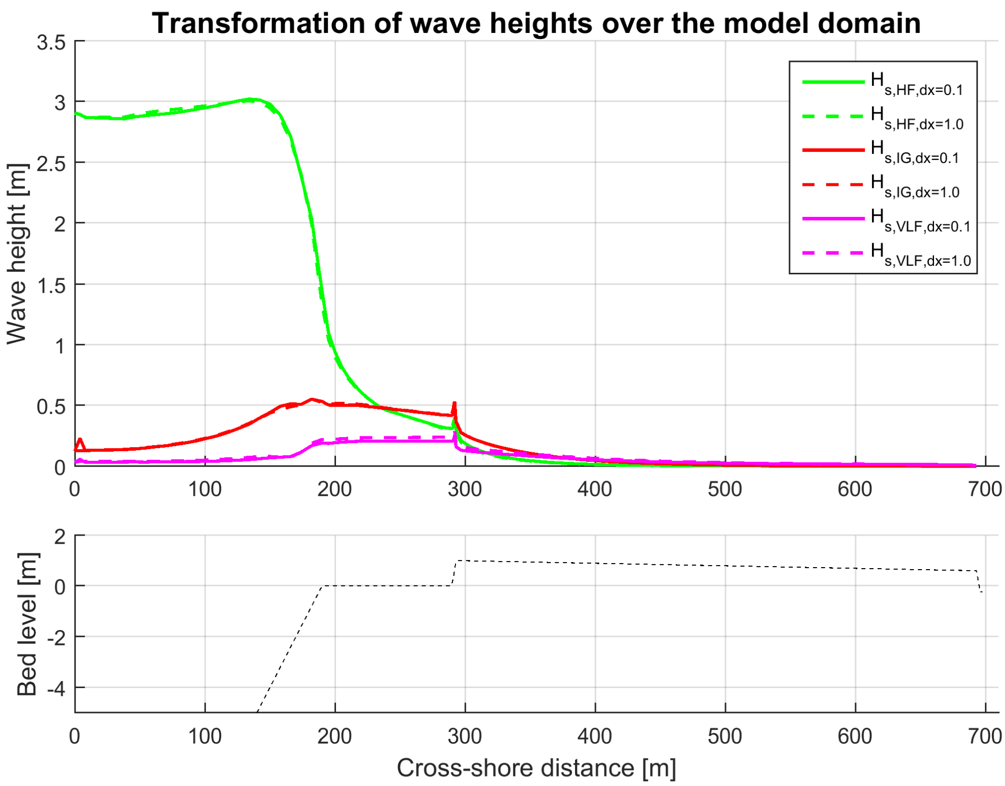


Figure E.3: Figure (a) shows the wave spectra at the beachfoot for a grid size of 0.1 and 1.0 m. Figure (b) shows the transformation of wave heights over the model domain. The straight lines indicate the model run with a grid size of 0.1 m and the dotted lines indicate the model run with a grid size of 1.0 m.

Topography

The location of the offshore boundary is dependent on the hydrodynamic forcing conditions for a given model run. The waterdepth h at the boundary is set such that $kh < 5$, $n < 0.8$ and $h > 4 * H_{s,0}$. The condition $kh < 5$ must be met such that the dispersive behaviour is modelled accurately enough (de Ridder, 2018). The waterdepth h must be larger than 4 times the incoming significant wave height $H_{s,0}$, to avoid the occurance of wave breaking at the model boundary and n must be smaller than 0.8 to ensure that the offshore boundary is located in sufficiently deep water for realistic long wave boundary conditions. For the different offshore significant wave heights, this results in offshore water depths as listed in Table E.1.

$H_{s,0}$ [m]	$z_{b,0}$ [m]
3	-16
4	-22
5	-27
6	-32
7	-38

Table E.1: Bed level at offshore boundary for different offshore significant wave heights $H_{s,0}$

A short flat step of 40 m is modelled before the fore reef starts sloping upwards in every model run. Consequently, the fore reef is modelled as a planar slope (not including the coral ridges that can be present in practice(REF?)). The flat coral reef extends over a distance of W_{reef} horizontally until the start of the beachslope. The beach is modelled as a planar slope and extends til the first islandpoint, after which the island has a downslope, bathtub or upslope shape (as described in Section 6.1). The width of the island is set at 400 m in every model run. This is assumed to be a realistic width for most coral atolls (which are generally very small) and a realistic length for the shallow coastal part of more vulcanic islands (i.e. the fringing reef islands). At the end of the island, the topography is sloping down again until the rear model boundary. This slope ensures that the flood water drains from the model domain, avoiding filling up at the rear boundary of the model.

Throughout the model domain, different observation points are defined. For every model run, observation points are defined at the offshore boundary, around the breakpoint at the fore reef, over the reef flat, at the location of the beachfoot, over the beach slope and over the island. At these observation points, high-frequency output is obtained (every 0.5 s).

Boundary conditions

The offshore water levels, significant wave heights and peak periods vary over the different model runs as described in Section 6.1.2. These conditions are held constant over the duration of each model run (i.e. a varying tide and varying wave heights are not included in the model runs). In each model run, random waves are generated at the offshore boundary according to a fixed wave spectrum for twelve 30 minutes periods (i.e. the total model run time is 6 hours for each model run).

In all runs, the model is forced with a JONSWAP spectrum at the offshore model boundary. Although multimodal spectra are highly prevalent in the Pacific Ocean, a simplified, unimodel, unidirectional JONSWAP spectrum is assumed for simplicity. The wave direction of the incident waves is shore-normal, which leads to conservative flood water levels over the island. Furthermore, the directional spreading s is set to the default value 10. Since it is a 1D model, the directional spreading won't influence the direction of the waves in the model domain, however it does effect the groupiness of the waves on the model boundary and therefore the infra-gravity wave generation (REF: XBeach manual). For higher s values, the directional spreading is less. The groupiness is then expected to be higher leading to higher infra-gravity waves. The effect of directional spreading on the wave height components and water levels at the beachfoot is not further investigated. The peak enhancement factor γ is set to the default value 3.3.

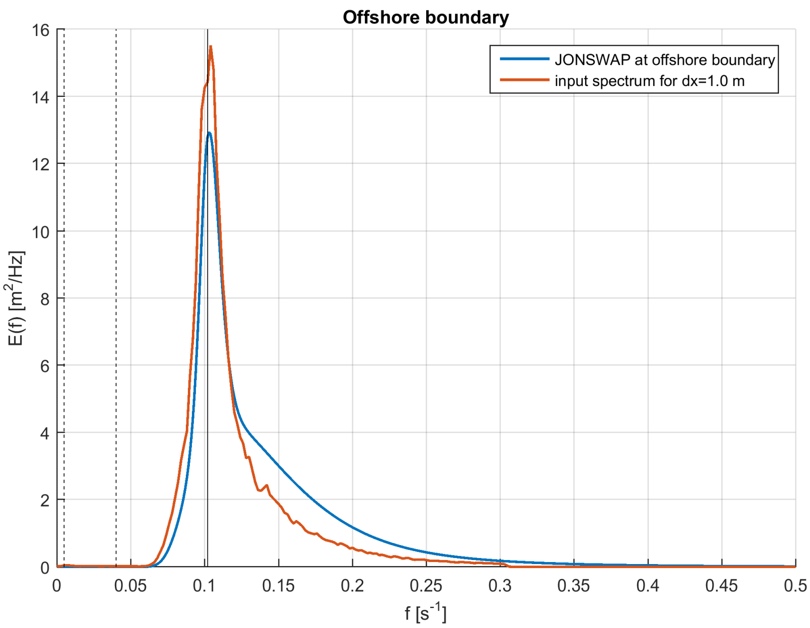


Figure E.4: Wave spectrum at the offshore model boundary

The wave spectrum at the offshore boundary is depicted in Figure E.4. From this figure, it can be seen that the wave spectrum at the offshore boundary does not entirely correspond to the theoretical JONSWAP spectrum. Especially for the higher frequencies deviations from the theoretical JONSWAP spectrum are observed. However, the total amount of wave energy is the same, leading to a more peaked spectrum with more wave energy around the peak frequency.

Initial conditions

Since all model runs start with still water conditions, it takes time for the model to reach stationary conditions (i.e. the spin-up time). In order to obtain accurate statistics for the different wave height components and mean water levels at the beachfoot, the waves must first propagate from the offshore boundary across the model domain and reach the shoreline. Also, the wave setup on the reef flat must reach steady state. Mainly depending on the width of the reef flat and the water depth over the reef, it may take quite some time before the waves have transported enough water onto the reef flat to balance the radiation stresses imposed at the reef crest.

In Figure E.5 the water level time series at the beachfoot for one of the model runs is depicted, for the first hour only. The spin-up time for this model run is about 6 minutes. For model runs with wider reef flats and/or higher island elevations (corresponding to higher offshore water levels), the spin-up time is expected to be somewhat longer. In order to make sure only stationary model results are used for the calculation of the different wave height components and mean water levels, the first hour of water level is discarded in every model run. The wave height components and mean water levels that are used as input for the BJIW and bathtub flood models, are based on the last 5 hours of each model run.

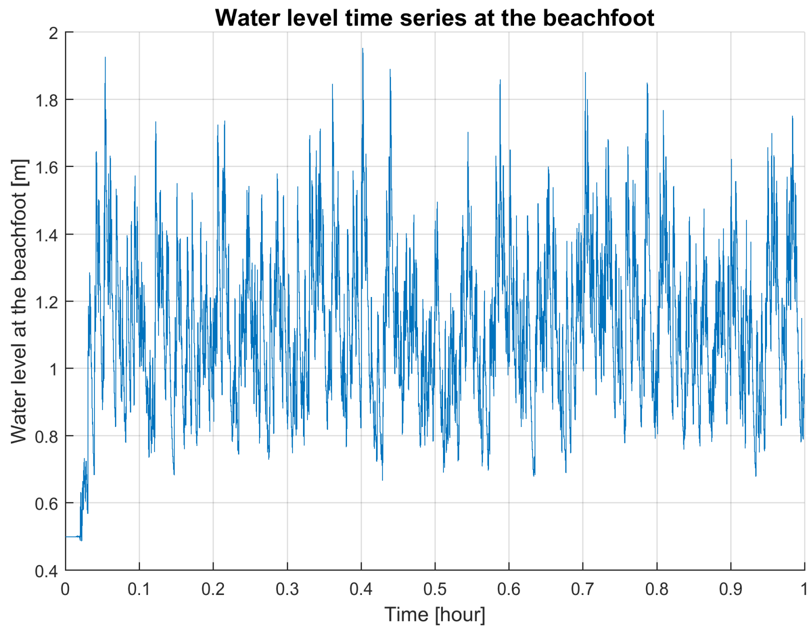


Figure E.5: Water level time series at the beachfoot for model run with $H_{s,0}$ = 3 m, β_f = 0.1, W_{reef} = 100 m, β_{beach} = 1/3, z_{island} = 1 m and β_{island} = 1/1000. For this run, the spin-up time is about 6 minutes. For model runs with wider reef flats and or higher island elevations (corresponding to higher offshore water levels), the spin-up time is expected to be somewhat longer.

Fixed parameters

Other parameters in the XBNH+ model runs were set at the default values. An example of a params-file for the XBNH+ runs is depicted below:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                                     %%%
%%%                                                                          %%%
%%% date:     26-Feb-2019 10:55:02                                           %%%
%%% function: xb_write_params                                                %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Flow boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

front        = nonh_1d
back         = abs_1d

%%% Flow parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bedfriction  = manning
bedfricfile  = bedfricfile.txt

%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

nonhq3d      = 1
tidelen      = 2

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

depfile      = bed.dep
posdwn       = 0
nx           = 698
ny           = 0
alfa         = 0
vardx        = 1
xfile        = x.grd
yfile        = y.grd
xori         = 0
yori         = 0
thetamin     = 0
thetamax     = 360
dtheta       = 180
thetanaut    = 1

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

tstop        = 21600
CFL          = 0.700000

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

morfac       = 1
morstart     = 0

%%% Physical processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

sedtrans     = 0
morphology   = 0
nonh         = 1

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

zs0file      = tide.txt
tideloc      = 2

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

instat       = jons_table
```

```
%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bcfile       = jonswap.txt

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

outputformat = netcdf
tintm        = 1800
tintp        = 0.500000
tintg        = 100
tstart       = 0

nglobalvar   = 5
zb
zs
hh
qx
qy

nmeanvar     = 6
zs
u
v
hh
qx
qy

npointvar    = 6
zs
zb
u
v
qx
qy

npoints      = 140
c@FancyVerbLinee40
```

The jonswap.txt file is used to specify the wave boundary conditions for each model run. An example of this file is depicted below:

```
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
 3.0  9.8 270  3.3 10  1800 1
```

E.1.2. SFINCS model

The SFINCS model is a computationally efficient, semi-advanced process-based model that can be used to model flooding in coastal areas. It only includes the swash zone and hinterland. By default, the model solves the Linear Inertial Equations (LIE), which are obtained from the shallow water equations after neglecting the horizontal viscosity and advection terms. To obtain a higher accuracy in the modelling of wave-driven flooding, advection can be included in the model. The inclusion of the advection term only adds a little to the computational time; therefore this term was included in the SFINCS model runs for the conceptual tests. For an elaborate description of the SFINCS model, the reader is referred to (Leijnse, 2018).

Computational grid

For the SFINCS runs, the same one-dimensional (1D) grid with idealized island profile as used for the XBNH+ model runs is used. The computational grid for the SFINCS model runs was taken directly from the XBNH+ runs. The grid resolution was thus 1 m. In contrast to the XBNH+ model runs, the SFINCS model runs start in shallow water depths of around -2 m (Leijnse, 2018). Therefore, it was chosen to start the SFINCS model runs at the location of the beachfoot. The waterdepth at this location varied between the different model runs, depending on the height of the island z_{island} (since the offshore SWL is linked to the height of the island) and the offshore wave height $H_{s,0}$ (the higher the offshore wave height, the more wave energy is dissipated through wave breaking, leading to more wave setup). A maskfile was used to 'mask' out the first part of the computational grid as used for the XBNH+ runs.

Boundary conditions

The SFINCS model can have different boundary conditions as input. Generally, the model is run with a water level time series as input. The water level time series are obtained directly from the XBNH+ model runs. As was described in Section E.1.1, high-frequent output was obtained at different observation points in the XBNH+ model runs. For each XBNH+ run, an observation point was placed at the location of the beach foot. This location is defined as the last point in the model before the beach starts sloping upwards. Since the grid of the SFINCS model is exactly similar to the XBNH+ grid, the water level time series are input at the exact same location in the SFINCS model.

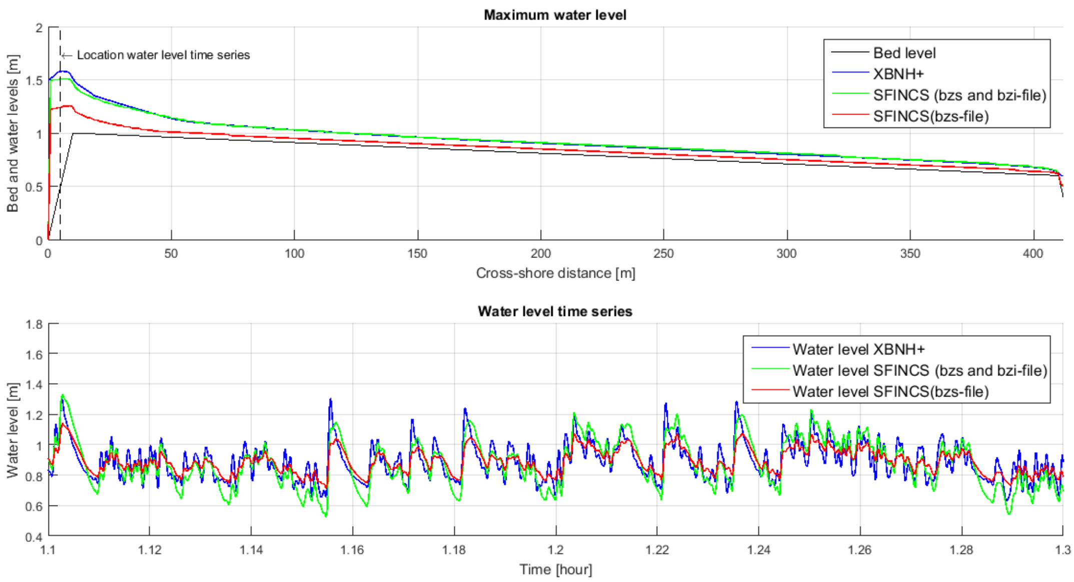


Figure E.6: Results SFINCS model with different boundary conditions

Since the beach slopes in the different model runs are quite steep, a certain level of reflection of wave energy is expected for the different runs. Therefore, the water level signal from the different XBNH+ runs is filtered to obtain only the incoming waves. The filtered water level time series is split in a mean water level component (the bzs-file) and a deviation from this mean value (the bzi-file). It is also possible to have one water level time series as input, however the results were found to be less accurate in this case (see Figure E.6). When one water level time series was used as input, the results were found to systematically underestimate the maximum flood levels. When looking at the water level time series at a certain location (see figure E.6), it can be seen that the water level in the SFINCS model (the red line) does not capture the maximum and minimum water levels. The peaks and therefore the maximum water level is therefore underestimated. When the water level time series is split in a mean component and deviations from this mean, the SFINCS model is better able to capture the maxima and minima (the green line), although the results still deviate from the XBNH+ water levels (the blue line).

When only one boundary condition was defined at the start of the computational grid, the model was found to fill up because no water was flowing out at the end of the model grid. In order to avoid this filling up of the model, leading to unrealisticly high water levels on the island, the last point in the model is also defined as a boundary point; the water level here is set equal to the SWL throughout the entire model run. As is described in Section E.1.2, the SWL is linked to the height of the island z_{island} in the different model runs.

Initial conditions

The initial water level can be defined with a zsini-file. The initial waterlevel in the model is spatially varying. The water level till the island is initially set to the mean water level as defined in the bzs-file. In this way, the spin-up time of the model was found to be as short as possible. For initial water levels equal to the SWL, the modelled water levels in the beginning of the model were much too high, see Figure E.7. This is expected to occur because in the SFINCS model the velocities are calculated based on the (initial) water depth and the water level time series. If the initial water depth is too low, this will result in unrealistic high water velocities and high water levels on the island at the start of the model run and thus a longer spin-up time.

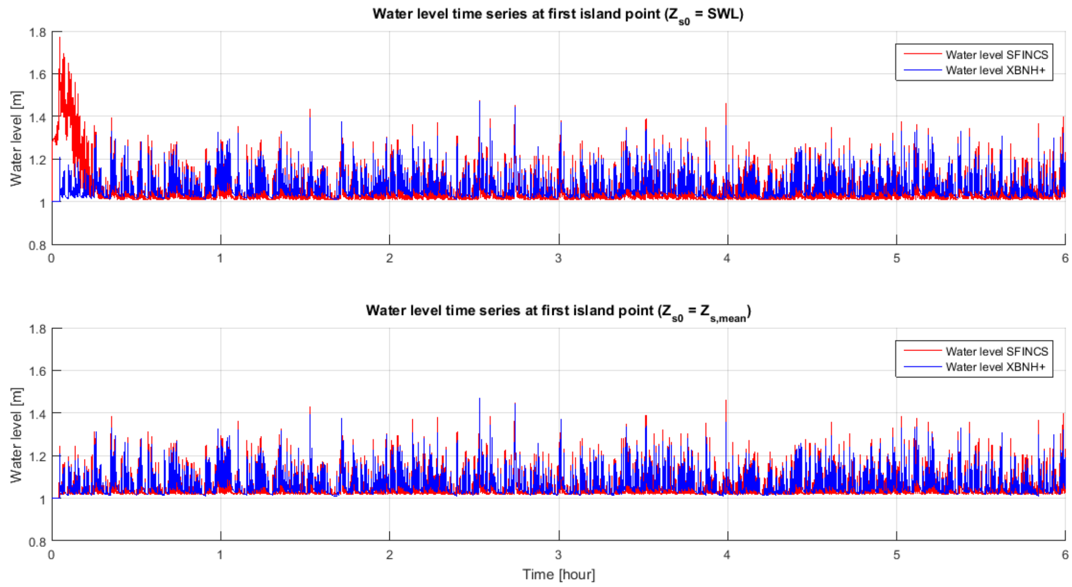


Figure E.7: Spin-up time SFINCS model with different initial water levels

The initial water level on the island is set equal to the bed level (i.e. zero water depth) and the water level behind the island is equal to the SWL.

Fixed parameters

Different parameters were held fixed over the different SFINCS model runs. The manning value was set to 0.06 over the entire computational grid, similar to the XBNH+ model runs. Furthermore, the limited flow depth huthresh is taken as 0.02 m. Alpha, the CFL-condition reduction, is taken as 0.25. All other parameters in the SFINCS model are taken as the default value. An example of an input file for the different SFINCS runs is depicted below.

```
input          = asc
output         = asc
```

```
depfile        = sfincs.dep
mskfile        = sfincs.msk
hmaxfile       = hmax.txt
zsfile         = zs.txt
bndfile        = sfincs.bnd
bzsfile        = sfincs.bzs
bzifile        = sfincs.bzi
dtout          = 1
tstart         = 20171124 000000
tref           = 20171124 000000
tstop          = 20171124 060000
advection      = 1
alpha          = 0.25
bndtype        = 1
manning        = 0.06
theta          = 0.9
huthresh       = 0.02
inifile        = sfincs.ini
dy             = 1
x0             = 0
y0             = 0
dx             = 1
mmax           = 715
nmax           = 1
c@FancyVerbLinee 1
```

F

Case study Sao Tome

A first prototype of the flood tool was developed and used as input for the interviews and questionnaires at the island of Sao Tome. For this first prototype, flood calculations with the BJIW model were performed and the results used as input for the flood tool prototype. Therefore, the BJIW-model was implemented at one of the research locations at Sao Tome.

The Deltares project carried out at the islands of Sao Tome and Principe encompassed 6 different coastal communities. For one of these locations, Praia Abade at the island of Principe, the research results indicated that coastal flooding had a significant effect (while coastal flooding was less severe at the other locations). Therefore, this location was chosen to calculate flood levels with the BJIW model.

In this appendix, the case study for Sao Tome is described in more detail. First, the general modelling set-up as applied by Deltares is shortly described. Next, the results of a comparison between the XBNH+ runs and a Battjes-Janssen approach to obtain the input for the flood models are described. Subsequently, the results of the flood modelling, both with the BJIW and with a simple bathtub approach, are compared to the reference SFINCS runs. Lastly, the link between the flood maps and exposure maps for Praia Abade is described.

F.1. General model set-up

One of the objectives of the Deltares project was to calculate the risks associated with compound flooding (i.e. both pluvial and coastal flooding) and coastal erosion for 6 different coastal communities located at the islands of Sao Tome and Principe. In order to calculate the risks associated with coastal flooding, a modelling framework as depicted in Figure F.1 was applied.

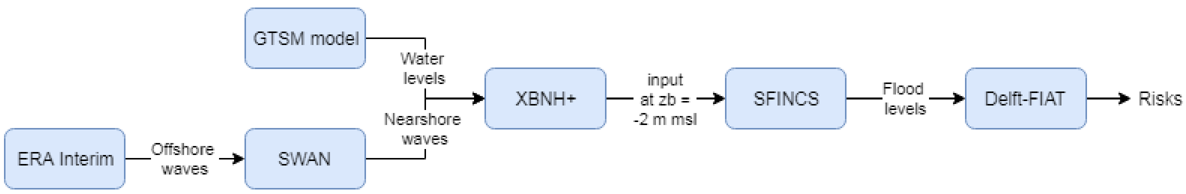


Figure F.1: General model set-up of the Deltares Sao Tome project, to calculate coastal flood risks

The extreme water levels associated with different return periods were directly obtained from the GTSM model developed by (REF: Muis et al. 2016). This global reanalysis of extreme sea levels includes contributions to offshore waterlevels from the tide, wind and inverse barometric effects. The offshore extreme wave conditions were obtained from the ERA Interim database and translated to nearshore wave conditions (i.e. at the -20 m MSL depth contour) using a SWAN model. Subsequently, these waterlevels and nearshore wave conditions were used as input for different 1D XBNH+ models, corresponding to measured transects of the nearshore bathymetry. From these 1D XBNH+ models, the waterlevel time series at a depth of -2 m MSL were obtained. These timeseries were subsequently used to force a 2D SFINCS model to calculate the waterdepths in the coastal areas corresponding to different return periods. Lastly, the resulting flood maps were used as input for the Delft-FIAT model to calculate coastal flood risks. For a more detailed description of the modelling study, the reader is referred to (REF).

In the context of this thesis research, the translation from nearshore waterlevels and significant wave heights (i.e. at the -20 m MSL depth contour) to the -2 m MSL depth contour was also calculated with a simple Battjes-Janssen model and the results compared to the XBNH+ model results. This is described in the next section. Subsequently, the flood waterdepths associated with different return periods were also calculated with the BJIW-model as described in Section 5.1 and with a simple bathtub approach on water levels. The results are compared to the output of the SFINCS model. This is described in Section F.3.

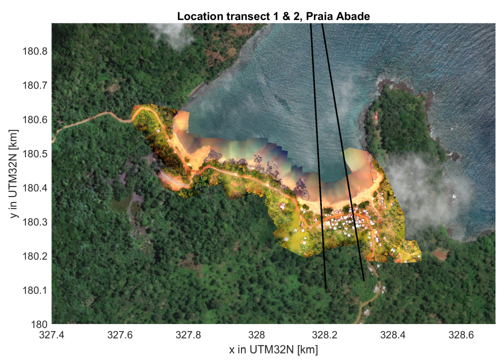
F.2. Comparison XBNH+ and the Battjes-Janssen model

In this section, the results of a comparison between the XBNH+ model runs and the Battjes-Janssen model are described. Both models are used to calculate the transformation of water levels and significant wave heights from an offshore depth of -20 m wrt MSL to an onshore depth of -1.5 m wrt MSL. This is done for two measured transects of the nearshore bathymetry for Praia Abade. The location of these two transects is indicated in Figure F.2a.

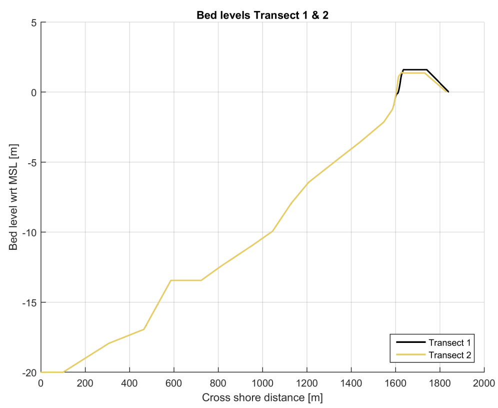
The XBNH+ model runs are not obtained directly from the Deltares project at Sao Tome. For these original model runs, the offshore water levels and wave heights varied over the model run. Since it is expected that the combination of highest offshore water levels and waves will lead to maximum floodlevels, the XBNH+ models are re-run with constant water levels and wave heights at the offshore boundary, corresponding to the maximum water levels and wave heights from the original runs. Instead of 24 hours, the models were now run for 6 hours. Also, the output location is changed from the -2 m MSL bed level to the -1.5 m MSL bed level, since the 2D elevation map for Praia Abada starts approximately at -1.5 m MSL. The params file for one of these runs is depicted below.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file                                    %%%
%%%                                                                          %%%
%%% date:     01-Feb-2019 13:57:47                                           %%%
%%% function: xb_write_params                                                %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Flow boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

front      = nonh_1d

%%% General %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

nonhq3d    = 1

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

depfile    = bed.dep
posdwn     = 0
nx         = 1147
ny         = 0
alfa       = 0
vardx      = 1
xfile      = x.grd
yfile      = y.grd
xori       = 0
yori       = 0
thetamin   = 0
thetamax   = 360
dtheta     = 360

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

tstop      = 21600

%%% Physical processes %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

swave      = 0
```

```
sedtrans    = 0
morphology = 0
nonh        = 1

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

zs0file     = tide.txt
tideloc     = 2

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

instat      = jons_table

%%% Wave-spectrum boundary condition parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

bcfile      = jonswap.txt

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

tintm       = 3600
tintp       = 0.250000
tintg       = 600

nglobalvar = 5
H
zs
zb
u
qx

nmeanvar    = 5
H
zs
zb
u
qx

npointvar   = 2
zs
u

npoints     = 3
328098 181939 point1
328100 181917 point2
328187 180388 point3
```



(a) Location transect 1 & 2



(b) Bed levels transect 1 & 2

Figure F.2: figure (a) shows the location of the two transects, and figure (b) shows the bed levels of the two transects. As can be seen from figure (b), the transects are very similar.

The Battjes-Janssen model is implemented as described in Section 5.1. Energy dissipation due to bottom friction and wave breaking are taken into account; energy dissipation due to vegetation is not included in the model. The offshore water level and significant wave height are the same as for the XBNH+ model runs. The offshore wave period differs for the different offshore conditions (corresponding to different return periods) and is taken from the XBNH+ runs as well.

The mean water level and the significant wave height are calculated at the -1.5 m MSL bed level in both models. The water level signal obtained at the -1.5 m MSL bed level from the different XBNH+ runs is filtered to obtain only the incoming waves. The results are depicted in Table F.2 and F.1. The errors are calculated with Equation F.1 and are also listed in the tables.

$$error = \frac{|BJ - XBNH+|}{XBNH+} \tag{F.1}$$

First of all, it can be noted that the results along the two different transects for the location of Praia Abade are very similar. This is to be expected, since the two transects are very similar to each other, as can be seen in Figure F.2b, where the two bottom profiles are plotted in one graph.

Furthermore it can be seen that the water levels at the -1.5 m MSL depth contour vary only sligtly between the XBNH+ model runs and the Battjes-Janssen model. The relative difference is less than 1% in all cases. Since even in the most extreme scenario of wave heights corresponding to a return period of 100 years, the wave height is only 1.20 m at the offshore boundary of the model (i.e. the -20 m MSL depth contour), the effect of setdown and setup is expected to be small. Therefore, the difference in water levels between the different models is expected to be small as well. The difference in the calculated significant wave height is larger. The relative difference of the Battjes-Janssen model compared to the XBNH+ runs is between 10 and 15% in all cases, where the Battjes-Janssen model systematically overpredicts the significant wave height compared to the XBNH+ model.

		RP = 1	**RP = 2**	**RP = 5**	**RP = 10**	**RP = 50**	**RP = 100**
Transect 1	XBNH+ [m]	0.89	0.97	1.02	1.05	1.12	1.15
	BJ [m]	0.90	0.97	1.02	1.05	1.12	1.15
	Error [%]	0.06	0.05	0.06	0.06	0.06	0.05
Transect 2	XBNH+ [m]	0.89	0.97	1.02	1.05	1.12	1.15
	BJ [m]	0.90	0.97	1.02	1.05	1.12	1.15
	Error [%]	0.03	0.04	0.05	0.04	0.07	0.03

Table F.1: Water levels and related errors. For both models, the water levels are obtained at the -1.5 m MSL bed level.

		RP = 1	**RP = 2**	**RP = 5**	**RP = 10**	**RP = 50**	**RP = 100**
Transect 1	XBNH+ [m]	0.75	0.80	0.86	0.93	1.05	1.09
	BJ [m]	0.86	0.91	0.98	1.04	1.16	1.20
	Error [%]	15.3	13.87	12.96	12.34	10.69	10.30
Transect 2	XBNH+ [m]	0.75	0.81	0.87	0.93	1.04	1.08
	BJ [m]	0.86	0.92	0.98	1.04	1.15	1.20
	Error [%]	14.97	13.97	12.50	12.34	10.80	11.00

Table F.2: Wave heights and related errors. For both models, the significant wave height is obtained at the -1.5 m MSL bed level. To obtain the significant wave height from the XBNH+ runs, the water level signal was filtered to obtain only the incoming waves.

F.3. Comparison of different flood models: SFINCS, BJIW and bathtub

In the coastal flood risk assessment carried out as part of the Deltares project, the flood levels associated with different return periods are calculated with the SFINCS model. In the context of this thesis, the flood levels were also calculated with the BJIW model and with a simple bathtub approach on water levels.

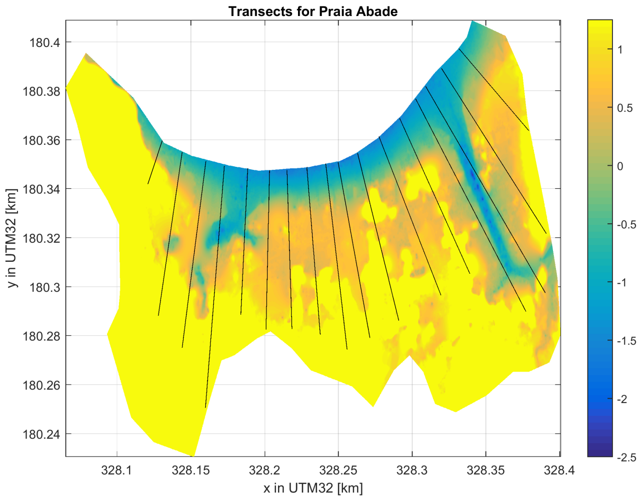
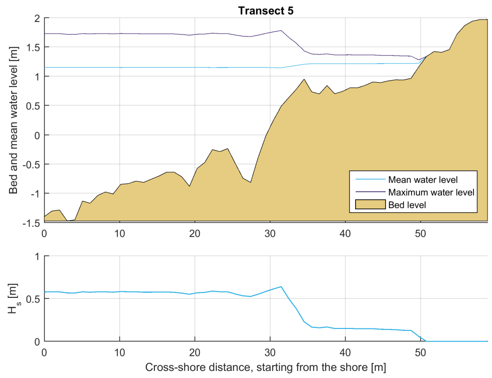
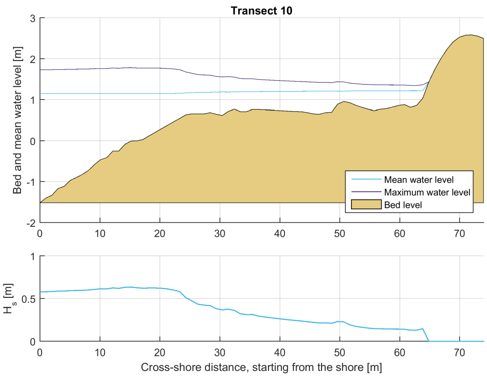


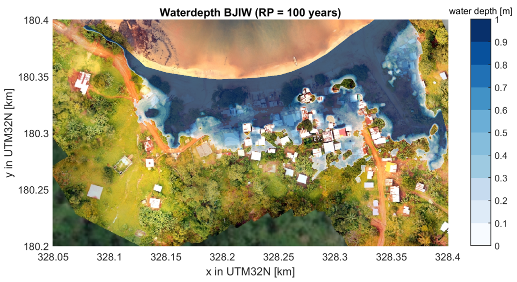
Figure F.3: Location of the different cross-sections for Praia Abade



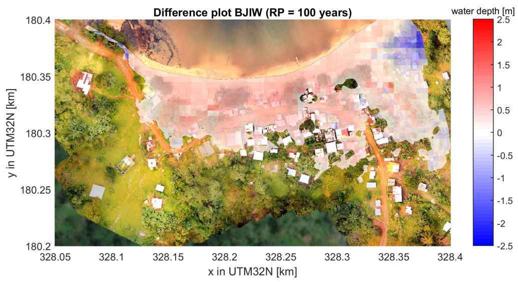
(a) Maximum water levels calculated at transect 5



(b) Maximum water levels calculated at transect 10



(c) Flood map PA, calculated with the BJIW model for a 100 year return period



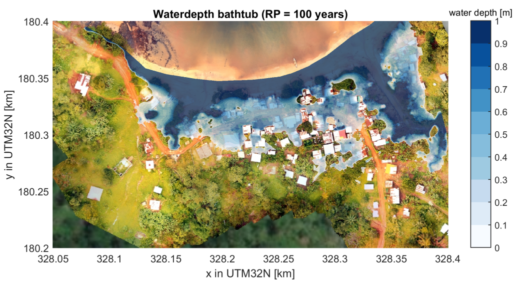
(d) Differences in waterdepths calculated with the BJIW model compared to the SFINCS model, for a 100 year return period

Figure F.4: Results of the BJIW model at Praia Abade

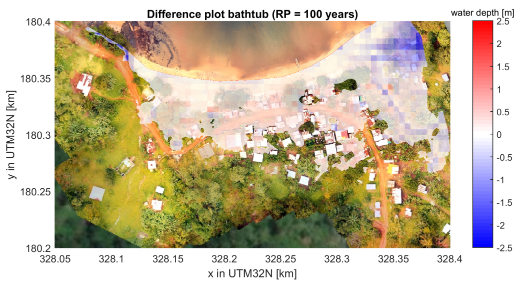
Similar to the approach described in Chapter 6, different transects perpendicular to the shoreline were defined. For the location of Praia Abade, 17 different transects were defined (see Figure F.3). Each of these transects starts approximately at a depth of -1.5 m MSL. Along each of these transects, the maximum water levels were calculated with the BJIW model. The input water levels and significant wave heights are obtained from the XBNH+ model runs at the -1.5 m MSL depth contour. Since the results at the -1.5 m MSL depth contour were very similar for the two transects, as was described above, the average waterlevel and significant wave height of these two transects is used as input for all 17 transects. The calculated maximum waterlevels at the different transects are interpolated using linear interpolation and nearest value extrapolation. The elevation map of the area is subtracted from the resulting water level map to obtain the water depths. Negative waterdepths are replaced with zero values. The maximum water levels in transect 5 and 10 associated with a 100 year return period and the resulting water depths are depicted in Figure F.4c.

The calculated waterdepths with the BJIW model were compared with the model outcomes of the SFINCS model. The differences between the outcomes of the two models were calculated by subtracting the waterdepths obtained from the SFINCS model from the waterdepths calculated with the BJIW model. The resulting difference plot is depicted in Figure F.4d. From this figure it can be seen that the BJIW model generally overestimates the maximum flood levels with respect to the SFINCS model, except for a small area at the Eastern border of the community. The reason for this underestimation is not entirely clear. From the elevation map of the community it can be seen that this part is actually quite high, so based on the elevation map waterdepths are expected to be quite small here.

Next to the BJIW model, also a simple bathtub approach was used to calculate the flood levels associated with different return periods. The waterlevel was taken as the average waterlevel from the two XBNH+ 1D models at the -1.5 m MSL depth contour. For every grid cell the elevation value is subtracted from this waterlevel to obtain the waterdepths everywhere. Negative waterdepths are replaced by zeros. Waves are not taken into account. The difference map for the waterdepths calculated with this simple bathtub approach compared to the SFINCS model results is depicted in Figure F.5b. As can be seen from the figure, the bathtub model leads to quite accurate results for the waterdepths, except for the area at the Eastern side of the community. For this area, similar to the BJIW model, the waterdephts are underestimated by the bathtub approach compared to the SFINCS model.



(a) Flood map PA, calculated with the bathtub approach for a 100 year return period



(b) Differences in waterdepths calculated with the bathtub approach compared to the SFINCS model, for a 100 year return period

Both the BJIW and bathtub approaches lead to larger inundated areas compared to the SFINCS model. This is depicted in Figure F.6. This is also to be expected, since bathtub-based approaches often overpredict inundation areas (REF). Since the community is quite small, the difference is not very large. For larger areas, the difference in inundated area between bathtub-based approaches and SFINCS is expected to be larger.

In Table F.3, the MAE and the absolute 90% error, LE90, are listed for the BJIW model and the simple bathtub approach for offshore conditions associated with different return periods. It can be seen from these values that for the location of Praia Abade, the simple bathtub approach closer approximates the results from the SFINCS model. This indicates that the BJIW model overestimates the effect of waves on local maximum flood levels.

F.4. Combining flood and exposure maps

Since the prototype of the tool is an early warning system, the waterdepths associated with different offshore waterlevels and significant wave heights have to be linked to certain indicators that can be used to inform and warn the people locally. There are different possible indicators. For the first prototype of the tool, the maximum waterdepth is linked to the different buildings of the community. A color scale is used to indicate the danger to different buildings. The color scale is applied in a very simple manner in the first prototype:

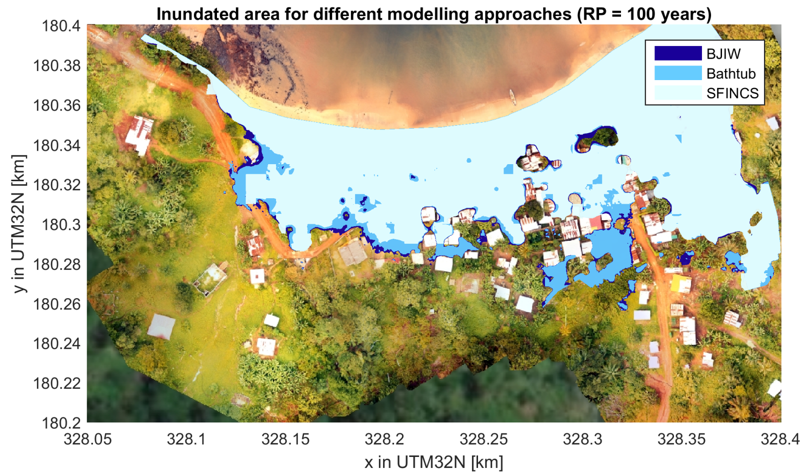


Figure F.6: Inundated area for different modelling approaches

		RP = 1	RP = 2	RP = 5	RP = 10	RP = 50	RP = 100
MAE	BJIW [m]	0.38	0.41	0.41	0.43	0.45	0.43
	Bathtub [m]	0.27	0.26	0.27	0.27	0.27	0.26
LE90	BJIW [m]	0.64	0.70	0.68	0.73	0.76	0.74
	Bathtub [m]	0.58	0.51	0.61	0.58	0.56	0.50

Table F.3: MAE and LE90 associated with different return periods for the BJIW model and the simple bathtub approach compared to the SFINCS model outcomes

green indicates there is no flooding (no risk), yellow indicates a water level between 0 and 0.5 m (low risk), orange indicates a water level between 0.5 and 1 m (medium risk) and red indicates a water level higher than 1 m (high risk). Of course, the color scale can be adjusted in later version of the tool.

The exposure map for Praia Abade (which indicates the location of the buildings and the boats) was produced as part of the Deltares project. It is based on aerial pictures made during a field trip for the project. The exposure map is combined with the flood water levels as obtained from the BJIW method to produce the risk map to the houses.

G

Interactive session

In this appendix, the interactive session held with Alienor de Haan is described in more detail. The aim of this interactive session was to discuss the design process of the tool, taking into account the determinants for the effective use of support tools as found in literature (see Section 14.1.2) and to come up with a first draft for the tool interface.

The set-up of the session was simple. I first introduced the project and the aim of the session. Next, we discussed the different research steps that I intended to make in order to come up with a design for the tool interface in the end. Lastly, we brainstormed about what the tool could look like and came up with a first draft. These two subjects will be described in more detail below.

G.1. Design approach

I explained that, based on the outcomes of the literature search as described in Section 14.1.2, I wanted to focus on the determinants 'relevance to the user' and 'user friendliness' in the design of the tool (interface). Furthermore I explained that for the initial design of the tool I wanted to focus on 'user friendliness'. The relevance to the user could be included/enhanced later, based on interviews with the different potential users during the field trip.

Alienor agreed that these are both important aspects to take into account. She suggested to use the interviews during the field trip to write down the user story or stories of the potential user or users of the tool in Sao Tome. The general form of such a user story can be summarized as follows:

As a <user>, I want to <goal> so that <benefit>

The advantage of such a user story is that it forces you to summarize what the tool should accomplish in order to benefit the potential user. This is directly linked to the relevance to the user.

Furthermore, she suggested that it would be better not to show the initial design of the tool immediately at the beginning of the interviews. She mentioned an example from the design classes she teaches to clarify this point. During these classes, she once asked the participants to improve the existing funda-app (i.e. to look for houses that are for sale). Many participants started by showing different people the existing app and asking them how this app could be improved. However, in this way you strongly limit the space for improvement, because the people are already strongly guided by the design of the existing app. In this way, the existing app (or, in my case, the first design of the app) is the starting point of the design, while actually the (potential) user should be the starting point. In her opinion, it would be better to ask people for their needs when they are looking for a new house (without showing them the app).

Furthermore she mentioned that it is good to remember that people do not always know what they want. As an extreme example she mentioned the famous quote from Henry Ford:

"If I had asked people what they wanted, they would have said faster horses"

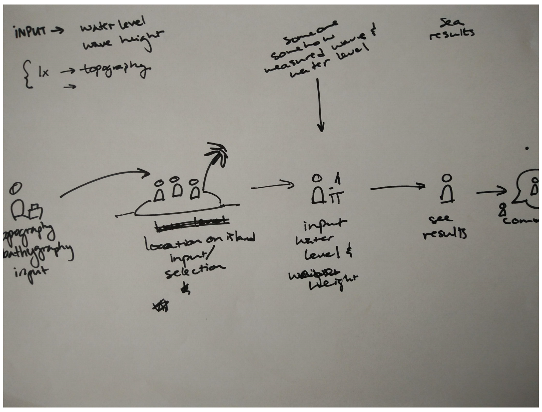


Figure G.1: Visualisation of different steps in the tool

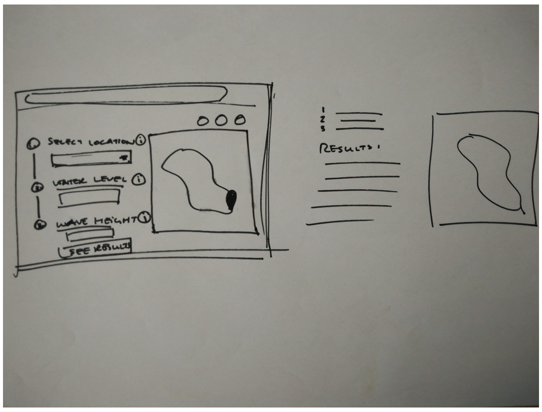


Figure G.2: First design of the input screen in the tool

Of course, this is an extreme example, but it is good to remember that sometimes people can propose solutions or a certain way of doing things that does not really adress their problems or issues. Therefore, it might be useful to focus during the interviews on the problems that the different potential users are facing, and not (only) ask them what they would want. Or, if you ask them what they want, ask them also why they want this; in that way you can indirectly adress their problems.

Regarding the user friendliness of the tool however, this does require the potential user to comment on an existing app or first design of a tool interface. By asking them specific questions relating to the functions of different elements in the screen, you can check if they are clear. This can for example be done by asking questions like 'What do you think happens if you push this button?' or 'What should you fill in here?'.

She suggested that if I wanted to get input on the relevance to the user and on the user friendliness of the tool during one interview, it would probably be best to focus first on the relevance to the user (without showing the first design yet). During the second part of the interview, you can show the initial design and ask specific questions relating to user friendliness.

G.2. First draft for the tool interface

We discussed different aspects regarding the first draft for the tool interface. We discussed the medium of the tool, the required input, the output and the layout. Furthermore, Alienor showed me an online program that I can use to build a prototype (i.e. Figma) and she showed me different websites for inspiration and more information regarding userfriendly design. In Figure G.1 and G.2, visualisations of the brainstorm are depicted.

First, we discussed the type of tool. The main choices here are a (telephone) app, tool or a website. For my application, we thought that a tool would be best. Related to this, we discussed the medium for the tool. The main two choices here are offline (e.g. excel-based) tools and web-based tools. One of the advantages of online web-based tools is that it is much easier to carry out updates. If the tool is an offline tool, all users should download a new version after every update if they want to use the newest version; with a web-based tool, these updates can be carried out automatically without requiring any action from the user. Secondly, with a web-based tool, it is much easier to track and store user data which can be used for further development of the tool. A disadvantage of a web-based tool is that it requires a stable internet connection. Especially for developing countries like Sao Tome and Principe, such a stable internet connection is not always available. However, since the direct users of such a tool in the context of Sao Tome will be people working at one of the central institutions, it is expected that they will have access to a stable internet connection most of the time. Also, if the tool is to be used as an early warning system, an internet connection will be required to obtain predictions on the water levels and waves.

Next, we discussed the required input for the tool. Alienor explained that it is best only to include those parameters that (1) are understandable to the potential user and (2) for which it can be assumed that the user can put in a realistic value. I explained that the tool needs different input data: the topography and bathymetry, roughness values (i.e. indicating the bottom roughness) and hydraulic boundary conditions. The topography, bathymetry and roughness values can be assumed constant for a certain location. For these parameters, it is probably best if they are measured once and then put in the model. However, the hydraulic boundary conditions change all the time. These parameters could be entered manually or be obtained by linking the tool to a global prediction model for offshore water levels and waves. This choice should be incorporated in the tool.

Subsequently, we discussed the output of the model. I explained that I made a distinction between 3 different output types. The first type is the maximum water levels that are calculated with the simple model. These can be visualized in different ways, for example in the form of a flood map or a cross-section. Secondly, these maximum water levels can be related to exposure maps for the specified location. The maximum water levels and exposure maps can for example be combined to give an estimation of the risk to individual houses. Lastly, the tool could output actions that are coupled to either the maximum water levels or risk maps, for example to evacuate the houses that are most at risk. We concluded that for an initial design of the tool, different visualisations of maximum water levels and an example of a risk map can be included. The link to different actions is more difficult at this point, since it is not known which actions are feasible and accepted in the context of Sao Tome. Therefore, actions are not included in the initial design of the tool.

Lastly, we discussed the layout of the tool extensively. Alienor gave many suggestions regarding the layout design, for example:

- Use different screens for the different steps in the tool. For example, one screen to introduce and explain the tool, one screen to give the input and one screen to see the output.
- Make a colorscheme and use this consistently throughout the different screens of the tool.
- Regarding the text on the different buttons: make sure it is very clear what happens if you push that button.
- If the user needs to type something in a input field, it is nice to include what the user should type, for example ’insert water level’. This text dissappears as soon as the user starts typing.
- Include flood maps for a location at Sao Tome (instead of some other location), this will make the tool more relatable for the different people you will interview during the field trip.
- Look at other apps/tools that you think are well-designed. You can use their designs for inspiration.
- Tool tips can be very useful; in this way you can give more explanation regarding certain aspects of the tool without putting too much on the screen.

H

Feedback session

H.1. Set-up feedback session

The feedback session was held when a first version of the tool interface was finished. The goal of this session was to obtain feedback on the tool interface from people with a water background. Based on this feedback, the initial design of the tool interface will be finalized. The finalized interface can subsequently be used in the interviews that will be held with people at different institutions related to coastal flood events in Sao Tome.

The participants of the feedback session, Anna Waque and Anna Goense, both have a background in water treatment and watermanagement, are especially interested in the communication aspect of water and have experience with water-related projects in developing countries. Since the first interactive session was held with someone with an industrial design background, it was expected that organizing this second session with people with another background will lead to different feedback and therefore eventually to a better initial design.

The set-up of the feedback session was very simple. I prepared a short presentation with a few slides to introduce the project in general. Next, I focused on the tool and the aim of the tool. Lastly, I showed them the different screens of the tool interface so far (and asked them not to give feedback yet) and asked them for feedback on a few specific points:

- **Graphical interface** what could be improved visually to make the tool interface more clear and attractive?
- **Visualisation results** how should I improve the visualisation of the results?
- **Content** after a short explanation of the simple flood model, I asked them what elements of the model they thought I could include in the model (for example, should I include some roughness measure that can be adjusted by the user, or should I just provide the model with a value)
- **Content** to what extent do they think I should explain the model (for example at the first page)?

The feedback session lasted approximately 2 hours and resulted in a lot of useful feedback. Mainly regarding the first point, the graphical interface, the participants had many useful suggestions. Also regarding the visualisation of the results and the question to what extent I should explain the model, we had very interesting discussions.

The feedback regarding the first two points is visualized in Figure H.1 and H.2 in the next section. Regarding the elements that should be included in the model, the participants found it hard to give an opinion since they are not really familiar with the flood model and flood models in general.

Regarding the extent to which I should explain the flood model in the tool, the final conclusion of the discussion was that this really depends on the user group of the tool. If the tool will be used by a more scientific user, it would be nice to include an explanation of the model. However, if the user is more practically orientated, an explanation might be unnecessary.

H.2. Feedback per screen

During the discussion of the different screens of the tool interface, multiple comments and suggestions were made. In Figure H.1 and H.2 below, the different comments are depicted visually.

Figure H.1: Feedback input screen

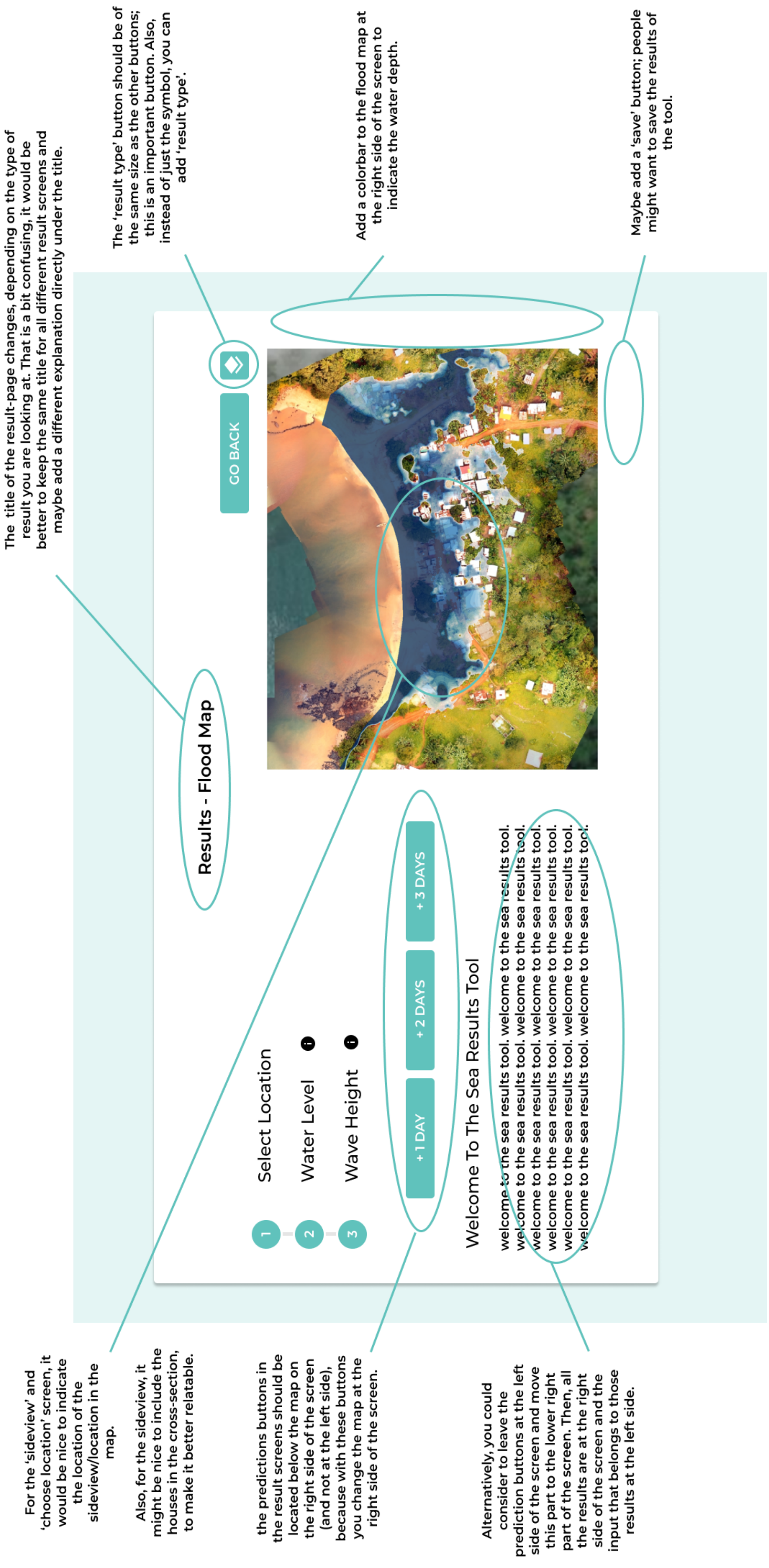


Figure H.2: Feedback results/output screen

I

Questionnaire

In this appendix, the questionnaire that was used in the different coastal communities at the island of São Tomé is explained in more detail. This questionnaire was used to gather information from the people living in the different coastal communities regarding the current warning system that is in place for storm events and what information would be useful to them. In Section I.1, the different questions are listed (in english). Here, the rationale behind the different questions is shortly explained. In Section I.2, the layout of the questionnaires and the questions in Portugues is depicted. In Section I.3, the results of the questionnaire are listed.

I.1. Explanation per question

In this section, the different questions that were included in the questionnaire are listed in English. Where appropriate, the rationale behind the question is elaborated.

1. When was the last big flood event you can recall?

Generally speaking, the people living in the different coastal communities of Sao Tome are not highly educated and many of them cannot read and write (however, this trend is changing as many children are going to school and most coastal communities have a primary school (BRON: Arlindo)). Most of the people living in these communities have to struggle everyday to provide in their basic necessities (i.e. food and clean drinking water) and as a consequence have a very practical attitude. I was warned in advance that these people find it difficult to answer questions related to something that is abstract to them. Also, these people are often not involved in projects regarding their communities (i.e. many projects, usually financed by foreign institutions, do not involve the people living in these communities). Therefore, most people in these communities are not used to be asked to give their opinion and might be a bit shy to do so (BRON: Andres and Tony).

Therefore, it is expected that it is difficult for these people to answer general questions about an early warning system for coastal flood events. To address this difficulty, the questions are related to the latest big flood event that the person answering the questions can remember. By linking the questions to this flood event, the aim is to make the questions more concrete and therefore more easy to answer.

2. How high (approximately) did the water get during this flood event?

In order to get an idea of the severity of the coastal flood events that the community is facing, the people are asked to give a measure of the maximum water level during the flood event that they mentioned in answer to the first question. It is expected that many people might not be able to give this measure in meters, therefore a picture of a person was included in the questionnaire, see Figure I.1. The people can give a measure in meters, but can also indicate in the picture how high the water got (approximately).

3. What problems did this flood event cause for the community?

As was described above, one of the goals of the questionnaire was to gain more insight into the problems that are caused by coastal flood events in the different coastal communities. This question is directly related to that goal. As can be seen in Appendix I this question was first formulated differently: 'What damage did this flood event cause?'. However, the answer to this question would depend very much on the person answering

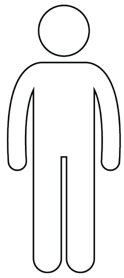


Figure I.1: Figure included in the questionnaire

the question. For example, a fisherman might focus mainly on the damage to his boat, while a woman might focus on the damage to her house. In order to obtain a more broad picture of the problems occuring in the entire community, this question was later changed. In this way, the choice of persons answering the questionnaire is hoped to be less important in order to obtain a general idea of the problems caused by coastal flood events. Also, 'damage' was replaced by 'problems', since problems is assumed to be a broader term. For example, a coastal flood event might cause nuisance because it might be more difficult to enter the houses. This is not necessarily damage, but it is a problem.

4. The problems that were caused by this flood event, did they occur during other flood events as well?

This question was included to check whether the flood event is a representative flood event in the context of the community. It might be that the flood event is much larger (or smaller) that the average flood event that occurs in the community. If the flood event much more severe than the average flood event, this might mean that the problems that were mentioned during question 3 do not occur during other flood events.

5. Did you know in advance that the flood event would occur?

At first this question was formulated differently: 'Did you receive a warning that this flood event would occur?'. Since the CONPREC organisation is active in all the coastal communities that are visited during the field trip, it is possible that the people in the community were warned for the flood event mentioned in answer to question 1. However, the people living in these communities live very closely together with nature; it is therefore very well possible that even when they did not receive a warning, they are able to interpret certain signs that a storm is coming (e.g. by looking at the behaviour of birds). The question was reformulated to include this second option as wel. This question is not an open question and can only be answered by yes or no. Depending on the answer, the person answering the questionnaire is directed to a different question (i.e. to question 6 if the answer is no and to question 10 if the answer is yes).

6. If you would have known in advance that the flood event would occur, what could you have done to decrease the problems caused by the flood event? (for example: get the boats off the beach, bring the cattle to higher areas, abandon the houses close to the coast)

As was mentioned above, one of the goals of the questionnaire is to gain insight in the actions that could be taken to address the problems caused by coastal flood events in the different coastal communities. This question is directly related to that goal. The people working at he different institutions related to coastal flood events in Sao Tome will probably have some ideas on this, which will be addressed during the different interviews (see Section 14.2). However, the people living in the communities may have conflicting (or aligning) ideas on this, which might also be important information for the final design of the tool.

7. If in the future you would get a warning in advance that a flood event will occur, what information would you like to receive? (for example: how long the flood event will last, how deep the water will be, how large the inundated area will be)

This question is directly related to the design of the tool. It is important that the information obtained from the tool can be used effectively by the people living in the different coastal communities. As is described in Section 14.2, this topic is also discussed during the interviews with people at different central institutions related to coastal flood events in Sao Tome. However, since the people living in the communities are the 'end users' of the tool, their information needs are important for the final design of the tool.

This question is deliberately asked after question 6, since it might be easier to answer this question if the person answering the questions has the actions that could be taken freshly in mind. Which information is useful will (partly) depend on which actions the people in the coastal communities could possibly undertake. For example, if they want to evacuate the houses that might get flooded, it is useful to know how large the inundated area will be.

8. How long in advance should a warning be given in order to be properly prepared?

This question was reformulated in the final version. At first, the question was formulated as follows: 'How long in advance would you like to receive the warning?'. However, this might be longer than strictly needed in order to be prepared. By formulating the question as above, the focus is on te time that is really needed to prepare.

This question is also deliberately placed after question 6. When the person answering the questions has the actions that could be taken freshly in mind, it might be easier to give a good approximation of the time needed between the warning and the flooding event.

9. Who should give the warning?

There are multiple people within the coastal communities at Sao Tome who could give a warning for coastal flood events. In (BRON) it is mentioned that every community that is visited during the field trip has a community leader, a leader of the fishermen and several local CONPREC members. Each of these people could spread a warning for coastal flooding among the rest of the community. As many people in these communities do not own communication devices like telephones or computers, it is important that it is someone who is trusted by the people and who has the ability to reach the largest part of the community within a short time span. This is assumed to be especially important within the larger communities. It is expected that not everybody will agree on who should give the warning and that, in a certain community, there might be multiple persons that could be assigned with this task.

10. How did you know the flood event would occur?

This question was added in the final version of the questionnaire. As was explained at question 5, it is assumed that even when the people living in these coastal communities do not receive an official warning, they might still know a storm (possibly leading to flooding) is coming by interpreting signs in nature.

11. How long in advance did you know the flood event would occur?

From different reports (BRONNEN) and conversations with participants of the first fieldtrip to Sao Tome, it was clear that CONPREC is not always able to correctly predict the occurence and timing of flood events. When CONPREC is able to send out a warning, this is usually not that long in advance (sometimes even up to 15 minutes before a storm begins).

12. Would it have made a difference if you would have known it earlier?

If a warning for a flood event is send out only 15 minutes in advance, there is not much that the people in the coastal communities can do to prepare for the event. Depending on the timing of the warning with respect to the event, and the timespan of the activities that the people in the communities might undertake to decrease the negative consequences, it might make a difference if the warning would be given earlier. This is not an open question and can only be answered by yes or no. Depending on the answer, the person answering the questionnaire is directed to a different question (i.e. to question 13 if the answer is yes and to question 15 if the answer is no).

13. How much earlier would you have liked to know the flood event would occur?

14. What difference would it have made?

15. What information about the flood event did you have in advance?

16. What extra information would have been useful? (for example: how long the flood event will last, how deep the water will be, how large the inundated area will be)

This question is deliberately asked after question 15, since it might be easier to decide what extra information would have been useful when the person answering the question has the information that he or she had about the flood event freshly in mind.

17. What would you have done to adress the problems caused by the flood event if you had the information in question 16?

I.2. Questionnaire in Portugues

In this section, the final questionnaire is given. For the field trip, the English questions as listed in Chapter 14 were translated into Portugues and printed. During the field trip, in every community several people were asked to answer the questions (in Portugues). Back in the Netherlands, the answers were translated to English and summarized in a table (see Section I.3).

1. Qual é a última grande inundação que você pode se lembrar? Que data?

2. Qual foi a altura (aproximada) que a agua atingiu na cheia?

   [Por favor desenhe ou descreba]

3. Quais foram os problemas que a inundação causou em sua comunidade?

4. Aqueles problemas acontecem com outras inundações tambem?

5. Você, sabia de antemâo que haveria uma inundação?
   (a) Não → por favor continue com a pergunta 6
   (b) Sim → por favor continue com a pergunta 10

6. Se você soubesse que haveria uma inundação, o que você poderia ter feito para limitar a dano? (Por exemplo: levar as embarcações/ animais para um local seguro, retirar pertenças das casas, nao morar perto da costa, etc.)

7. No futuro, se você fosse avisado que haverá uma inundação, que tipo duração da cheia, que altura a água pode atingir, quais serão as áreas afetadas?

8. Com quanto tempo de antecedência você gostaria de receber o aviso?

9. Quem deve dar o aviso?

10. Como você sabia que haveria uma inundação?

11. Com quanto tempo de antecedência você sabia?

12. Teria feito a diferença se você soubesse antes?
    (a) Não → por favor continue com a pergunta 15
    (b) Sim → por favor continue com a pergunta 13

13. Com quanto tempo de antedecencia você gostaria de saber?

14. Que diferença isso faz?

15. O que você sabia de antemão sobre a inundação?

16. Que informação que você não tinha de antemão, teria sido útil para garantir que a inundação causasse menos problemas? (por examplo: quanto tempo dura a inundação, qual é a altura que a agua pode atingir, qual é a área inundada?)

17. O que você teria feito com essa informação extra para garantir que a inundação levaria a menos problemas?

I.3. Results of the questionnaire

In this section, the results of the questionnaire are listed. All respondents only answered the first 9 questions, since everybody answered question 9 with 'no'. Only one respondent filled in all the questions. However, since this respondent also answered question 9 with 'no', the rest of the answers were left out. In Table I.1, the answers to the first 5 questions are listed for 10 respondents. The answers to question 6 to 9 for these respondents are listed in Table I.2. In Table I.3, the answer to the first 5 questions are listed for the other 10 respondents. The answers to question 6 to 9 for these respondents are lsited in Table I.4.

Table I.1: Answers to question 1 to 5 for the first 10 respondents

Name	1	2	3	4	5
(Io grande)	18 July	between the feet and the knees	1. Evacuation of people and animals. 2. the walls of the school broke.	yes	no
(Io grande)	I don't recall	knee height	1. The school fence was damaged. 2. The people and their animals had to be evacuated. 3. Some houses were flooded. 4. The soud of the sea was very load.	yes	no
Catarina des Neves (Io Grande), CONPREC	14 October 2018	above the knees	1. All houses were flooded. 2. The school fence was destroyed. 3. Many animals were lost.	yes	no
young girl (Praia Pantufo)	19 March	knee height	1. The roof of one of the houses was blown off. 2. One house was damaged by the incoming water. 3. Different trees were uprooted.	yes	no
Melo Christobal (Praia Gamboa)	October 2018, 2015 was also rough	between feet and knees	1. The water did not enter the houses (because they were elevated), but they had disturbances to enter and leave the house. 2. Loss of animals. 3. They have to stop fishing.	yes	sometimes, usually people know based on experience
Tome Ramos (Praia Pantufo) CONPREC	March 2019	knee height	The inundation caused problems to the houses close to the coast. It affected the animals and the banana trees.	yes	no
(Io Grande)	16 July	above the knees	1. Loss of animals. 2. Inundation of the community. 3. flooding of the houses. 4. the wall of the school broke.	yes	no
Joana Moreno (Praia Abade) CONPREC	16,17,18 February 2019	knee height	1. The sea entered the houses close to the beach. 2. coconut trees fell on the houses. 3. we had to take the animals inside.	always	no
Miguel	this month	knee height	1. Water entered the houses. 2. 3 boats were lost to the sea.	yes	no
(Praia Pantufo)	11 March	knee height	1. Loss of boats. 2. Houses were damaged. 3. Threes were uprooted. 4. Loss of furniture	yes	sometimes

Table I.2: Answers to question 6 to 9 for the first 10 respondents

Name	6	7	8	9
(Io grande)	I would warn the community and evacuate the people and animals. right now, we evacuate to a higher location, but there is no shelter there.	Which areas are the most affected.	3 days	the chef the Praia
(Io grande)	I would warn the rest of the community, we would evacuate the people and their animals living close to the sea as a prevention, we would ask for help.	Which areas are the most affected.	3 days	leader of the community
Catarina des Neves (Io Grande), CONPREC	We would evacuate the people and the properties that they can carry. And we could already inform the different authorites to take preventions	Which areas are the most affected.	1 day	CONPREC
young girl (Praia Pantufo)	We would warn the different people from the community, tie up the boats.	How high the water will get.	1 day	people in the community
Melo Christobal (Praia Gamboa)	1. Move their animals. 2. They won't abandon their houses, because they are afraid that their properties will be stolen.	1. Level of the water relative to the body. 2. extent of the flooding (till road, beach)	2 days, normally storms occur at night	CONPREC
Tome Ramos (Praia Pantufo) CONPREC	I would not leave my house, because people might steal my properties.	difficult to say.	1 day	suitable people in the community
(Io Grande)	We would warn the community and evacuate the people and their properties.	which areas are the most affected.	1 day	CONPREC
Joana Moreno (Praia Abade) CONPREC		How high the water will get, affected area	2 days	INM, radio, SMS
Miguel	I would spread the message	When the storm will occur	1 day	radio, television
(Praia Pantufo)				

Table I.3: Answers to question 1 till 5 for the second 10 respondents

Name	1	2	3	4	5
Isabel Sacramento (Pantufo)	19 March	knee height	1. water entered 3 houses, because they were not built high enough. 2. Of these 3 houses, also the roofs were damaged due to strong winds during the inundation	yes	no
Egas Quaresma (Praia Melao)	19 March	knee height	1. There was damage to the houses. 2. There was an accident in the sea, one of the fishermen got lost and had to be saved. 3. Some boats were damaged.	yes	no
Alberto Afonso Marcolino (Praia Melao)	6 March	I don't recall	1. Some fishing material was lost. 2. Damage and total destruction of 2 houses. 3. Partial damage to 3 houses.	yes	no
Eufragio Sousa Peieira (Praia Melao)	19 March	knee height	1. 4 boats sank. 2. 2 houses were destroyes.	yes	no
Gilsan Dias (Praia Melao)	19 March	I don't recall	1. 3 houses were destroyed. 2. the electricity cable broke.	yes	no
Maria Auforia Fouseca (Praia Melao)	14 years ago	knee height	This event caused many problems. 1. Many boats were damaged and destroyed. 2. the road was blocked and could not be used anymore.	no	no
Sergio (representative CONPRECC, praia Micolo)	15 May	knee height	1. Roofs were damaged due to the strong winds. 2. The lagoon area was flooded. 3. The community lost many animals. 4. The fisherman could not go to sea. 5. Woman had to stop their market activities and laundry to watch the children and the house.	in general, there are damages to the roofs, damage of houses and loss of animals	yes and no, sometimes we receive a warning via de radio, or we know from experience
Edite Barrares Mendes (Praia Micolo)	18 October	knee height	1. Water was high and I could not enter my house. 2. I had problems to move my animals. 3. The fisherman couldn't go out to the sea for some days and we didn't have fish to sell.	sometimes, some events are stronger than others	no
Aurelio Carmira Ban Jesus	18 March	between feet and knees	1. Problems to the fisherman (because they cannot go out) 2. Loss of material for the boats (fishing nets). 3. Houses were damaged. 4. Rainfall caused disturbances.	yes	no
CONPREC member (Io Grande)	September 2016	knee height, approx. 60 cm	The problems that affected the community were: 1. Destruction of the school fence. 2. Somebody's house was destroyed. 3. The water took some animals, like pig and chicken.	the problems are bigger now, events are more extreme	no

Table I.4: Answers to question 6 t0 9 for the second 10 respondents

Name	6	7	8	9
Isabel Sacramento (Pantufo)	I would go to a safe place. In this community, people leave their houses in case of an inundation event. We go to friends that live at the other side of the road.	I would like to know how long the storm will last.	2 days	TV, radio
Egas Quaresma (Praia Melao)	I would warn the community, and I would remove my boats from the beach, but there is no place [for the boats].	I would like to know how high the water can get, how long the storm will last and how large the affected area is.	2 days	Radio, telephone (already one telephone warning is nice, the information can than be spread around), people from the community
Alberto Afonso Marcolino (Praia Melao)	1. We would prevent the fisherman from going out to sea. 2. We would warn the community so that everybody can take security measures	I would like to know the area that will be flooded and how high the water level will be.	2 days	the leader of the local people (= leader of the community)
Eufragio Sousa Peieira (Praia Melao)	1. Warn the fisherman so that they will not go to the sea. 2. Warn the entire population against flooding.	I would like to know how long the storm will last, which area will be flooded and how high the water will get. Also, I would like to know whether we should remove the boats from the sea.	1 day,	INM (radio/ CONPREC), radio, leader of the community
Gilsan Dias (Praia Melao)	1. I would warn the community. 2. we could prevent the fishermen from going out to the sea.	I would like to know the duration of the bad weather and which places will be affected.	3 days	Capitanaria, radio, leader of the community
Maria Auforia Fouseca (Praia Melao)	I would have taken my animals to a safer place. I would also take my properties and if possible my entire hous.	I would like to have specific information on what I should do in such a situation, especially since I live in a risky area as my house is located next to the river.	Minimum 1 hour in advance, but it would be best to know 2 days in advance.	National radio, television, the people from CONPREC
Sergio (representative CONPRECC, praia Micolo)	Move all belongins to the second floor of the house (if they have a second floor) and collect the animals sooner	The duration of the event is key, but if they tell me the water will be higher than 75 cm I already know I should move all my belongins. Also, it would be good to know which areas will be the most affected, so that we can move things to other (safer) areas.	2 days	radio, CONPREC
Edite Barrares Mendes (Praia Micolo)	I would move my animals to a safer place.	The duration of the event, and whether I should move my animals or not.	2 days	radio, local members of CONPREC
Aurelio Carmira Ban Jesus	We won't go to the sea and take the boats from the beach.	the duration of the event.	1 day in advance	radio, local members CONPREC
CONPREC member (Io Grande)	I would remove the animals and other properties from the risky areas.	Which areas are the most affected.	1 day in advance	the people from the committee [=CONPREC]

J

Interviews

J.1. List of interviews

In the context of the science communication part of this thesis, several interviews were conducted. Most of the interviews were conducted during the field trip to São Tomé, where the interviews were held with the help of a translator. The translator's English was not always correct, but this was not corrected in the transcriptions.

The transcriptions of these interviews are not all included in this appendix, but can be requested from the author if needed. A list of interviewees is provided in this section, and an example of the transcription and coding procedure of one of the interviews is provided in the next session. As is described in the main body of this report, the coding procedure entailed four steps. First, the entire interview transcription was read for a general overview. Subsequently, all actors that were mentioned in the interview were marked with green. Third, all information related to the interactions with these actors was marked pink. Lastly, all information regarding the resources needed by the interviewee were marked blue. This information was subsequently used to construct the different actor maps, as described in chapter 13.

List of interviewees:

- Ilse Nederlof (Former intern at HKV, where she worked on a online information platform for SIDS)
- Arlindo de Ceita Cavalho (General director of DGA, the directory of environment)
- Aristómenes Nascimento (General director of the national institute of Meteorology of São Tomé)
- Carlos Diaz (Operational director of CONPREC)
- Abnilde (Working for the observatoire)
- Maria Teresa Mendizabal and Aderito Santana (Working at PNUD in São Tomé)
- Jos'e Bastos Sacramento (General director of the national institute of natural resources in São Tomé)
- Manuel Jorge de Carvalho do Rio (Operational director of MARAPA, an NGO in São Tomé)

J.2. Transcription CONPREC interview

M: First of all, maybe you can tell me a little bit about CONPREC. For example, what are their main tasks, with how many are they and in how many communities are they located?

C: CONPREC is an organ from the government and is installed after the ... law number 16, discrete 12. One of their main competences is of prevention, preparation and national support. It is organized by 7 ministeries:

- defense and internal order
- spatial planning
- foreign affairs
- health
- infrastructure

M: This is all in the central team of CONPREC?

Yes. CONPREC is under the system of civil protection, so they also have representatives of the police, the army, the coast security, national institute of meteorology, institute of hydrology. All of these members, they are nominated based on the ministry of their function.

M: So, all the members in the central team are chosen by the ministry?

Yes.

M: And by whom are they chosen, by the ministry of spatial planning?

No, it depends on each ministry.

M: Okay, so each ministry or institute choose someone that represents them in the central CONPREC team?

Yes. On a every day basis, their main function is as a coordinator. They are, amongst other things, responsible for admin and human resource.

M: what is admin?

The administrative department.

M: oooo, okay.

C: and a meteorologist, there is one permanent member of the CONPREC team who is a meteorologist. The other members whenever there is a plan of activity, they are called.

M: So, those are the people in the communities?

No, not in the communities. They are members of the CONPREC team. All of these names, which are nominated and chosen by the ministries. There is one effective member, which is one meteorologist, the coordinator (who is responsible for administration and human resources) and other members are called whenever there is a plan of activity.

M: Okay, so for example when there is a storm?

Yes, that could be. But they have a daily plan of activity (capacity building in the communities, sensitizing the different communities). Today, for example, they went to sensitize one community. They are now called to come along with that activity. For instance, when they are going to develop a plan they call all of them and work on that. But if there is an emergence case, it depends on magnitude and hat is happening, but they will call some specific members who are going to work on that.

M: Okay, I understand.

So, this [pointing at office and Carlos] is administrative and coordinative aspect. Then there is the operational aspect, which is in the other room with two staff and that works 24 hours per day.

M: Okay, and their job is to see whether a storm or another dangerous event is coming up?

Yes, they are in contact with all the institutions, like the meteorological institute, police and the coast guard. Their job is to collect all the information and to know when something is going on. He said that that operational area is supported by a radio which they call HF, another one is VHF.

M: that is also a radio?

Yes, and the last one is called SMS.

M: So, you mean SMS, the text messages?

Yes, the messages for the mobile phone.

M: Okay, so they send out information via the radio and also via SMS?

Yes. All of these radio stations have the following function:

HF, this is to communicate with the boats on the crisis situation, with the fishermen that are out at sea.

M: So, that is the radio that the fishermen can take with them when they go out fishing and then they can send out a warning. The radio MARAPA told us about?

Yes. And this radio is also in direct connection with the coast guard, they also receive that radio. For VHF, this is the national network, and it is connected with the fire distinguishers, all police stations and also with the coastal guard.

M: So the coastal guard receives a double message?

He said they always have to be in connection with the coast guard. Because apart from their specific mission, they also have to cover the aspect of contingency, for example when a fisherman disappears in the ocean or he gets lost at sea, the community where he is from will inform them for instance: okay, we have a fishermen that left, he didn't come back. Then they now inform the coast guard, especially if he is further out than 35 miles, where there is not network anymore. They cannot communicate. So, the coast guard will now go and find the fishermen.

M: And I also understood that in each community, there are a few members of CONPREC that they train, is that correct?

They have 31 communities, with in total 254 trained elements, 78 of these people are women. Not belonging to the CONPREC team, but these people work for them. The people they train for communication.

M: Okay, so all these people are part of the communities, but they work for CONPREC. They are trained by CONPREC?

Yes, and 78 of them are women.

M: Okay, and these people, are they volunteers or do they get paid?

They are volunteers.

M: okay, and how are they chosen?

[System of selection] He says that in the community to elect the elements, there are some standards, some criteria to elect those elements. For instance, they go to the community and they tell the intention. What they want to do and now the volunteers will present themselves and now the community will have analyse; if it is someone who is always drinking or it is a fisherman who is using the network that is forbidden by the law. All these criteria they will analyse and say for example, okay, for this number of 30 person presented, we want 8 to be selected. And then they take them from the community, bring them to the capital of the district and train them. And for example in Lemba, which is one of the districts, they have a team, they bring them from the community Santa Katharina, which is a town, they select, let's say, about 24 of them, made up of 8 members of each community and they train them. And also from that 24, there is 2 which would be to replace in case somebody is sick.

M: So there are two people, to make sure that someone is always available?

Yes, and based on the law, that decrete he mentioned, local power has to provide somebody that is always part of this training to be a contact person between the instructor they create on this district and the local power. And they also, in that local power, that is the instructor, they also provide some equipment that they will be now using it for these people they train in that part of the community, because all the resources are made available.

M: You mean something like a telephone?

Yes, we have a marine telephone [for communication with the coastal guard] and a communication radio [for communication with the other parties].

M: So, let me summarize it shortly to see if I understand it correctly. In each community they ask people to volunteer. So maybe a group of 30 people and they have certain standards to choose which people they want. In every community they finally choose about 8 people and then they bring these people together, from the different communities of one district and then they train them. And from the 8 people they choose 2 people for every community who are always available, so they are sort of the contact person and they provide them with a telephone and a radio. Is this correct?

Yes.

M: Okay, and what do they learn them in the training? What is the training about and how long does it take?

The training is on several subjects. First, they learn them how to assess the risk, the community risk.

M: But what do you mean? Like to decide which people are vulnerable or..?

Yes, so for example to assess which people are vulnerable and should have more attention.

M: okay

When they learn to assess the risk, for example there is risk if you build very close to the sea or to the rivers as well. For example, there is a risk if you remove sand from the sea, there is risk of erosion. And all this risk, when they learn how to assess it, they will now teach the population [of the community] on how to prevent it.

M: So they teach these people these things you shouldn't do or these things you should do. For example, don't build in these risky areas, don't extract the sand for the beach. And they teach this to the people living in their community?

Yes.

M: okay, and what else?

Within the group, they also train them on how to help people when they are drowning or dying in the water.

M: O, you mean that they teach them how to rescue people that are in trouble in the sea?

Yes. He is saying that apart from it, in that community, the contact person in the community, they will... Even in the community, they are able to find when there is any type of occurrence, which area is not affected. So, whenever there is occurrence, this is the area they should go to. While they are doing it, they are also communicating with CONPREC and CONPREC will also provide certain assistance if there is a need to call the police, the army, it depends on the magnitude of what is happening.

M: Okay, so they learn them where the safe areas are and where they should go in case of an event and they also learn them how to communicate with CONPREC and what help they can ask for.

While they are moving to the safe areas.

While they are moving to the safe areas.

He said the information will go from here to them and from them to here. Because, they have a local team and the local team is provided with enough information on what to do in a certain situation and how to communicate or even the measurements to take. For example, if there is a period of rain, they calculate the speed of rain [intensity of rain?] and the period of rain and they are also able to know what will be the consequences based on the information of the river they have there; if it will be full and if there will be flooding and all this information. And if they only say there is rain: okay, they just take the occurrence of from the register and they cannot yet act on it. But if they can calculate all this information, they now tell them: based on the speed of this rain [intensity?] , taking into consideration the river, they will now tell the population to leave that area. Most of the time, they sent them to the school or the church of that community, which is the safe place. But the only problem is, if the class is going on. If they pupils are in the classroom and they are studying. That is the only problem they are facing now.

M: I'm sorry, what is the problem, they cannot go to the school?

If there are students there and then the population cannot go there because they would have to stop.

M: Okay, but this is all related to river flooding, but do they also send out alerts for coastal flooding/flooding from the sea?

It is global information of the river, wind, the sea, social conflicts. The information is general; it has to do with fire, it has to do with flooding, both from the river and from sea, it has to do with social disturbances. Everything that changes the normal livelihood, both in the community and the country they are informed about, because for instance... and in every community they have a local team that covers this... for instance, there was a place where people went to cut the trees and then the police came and now the police asked them to stop cutting the trees and they wanted to arrest them. And the population all started fighting the police and throwing stones and all that and then someone from their local team will call them; this is a situation, this is a red light. This is a situation of risk. They will now take this information to the police station. Okay, this is the situation in that part of the country and then they will go there to control the situation. Because they are not just giving information related to flood, but it is general.

M: how often approximately do they send out an alert for a storm or an inundation?

Whenever there is a need for any occurrence, they inform them. But the information is also daily.

M: O, so they inform the different communities on a daily basis?

The communities inform them on a daily basis, because they have their local team. Every day in the morning, they will give them an update.

M: So, the communities inform the central CONPREC team on a daily basis and the central CONPREC team sends out an alert whenever it is necessary.

Whenever it is necessary yes. And the central CONPREC team also uses these daily reports to make a monthly report for each community. And then, whenever the communities send him with information, it goes to three different places: here, the fire distinguishers and the coast guard.

M: and is this true only in case of an emergency, or for all the information that the communities send? For all daily updates?

For all the things.

M: okay, so they send a daily report to CONPREC and that also goes to the fire distinguishers and the coast guard. And CONPREC contacts the communities in case of an event or another emergency, and they produce monthly reports for all communities, based on the daily updates they receive from the communities. And are they able to alert all the people in time for storms? Or does it also happen, because of the weather forecast, that they are not able to warn the people in time?

He is saying that this is their wish to give the information, but it is not always possible, for example due to electricity problems. Sometimes they want to communicate to a certain community but if there is no electricity, they may not be able to get the information to them [to the community]. Because the machines went down, because the battery, sometimes they have to move to another community to recharge the battery and all this, so they may not be able to give them the information in time. This is a challenge. Even the institute of meteorology is saying that they stay for two years without light in the centre of their system, because their machine was in another institution and because they couldn't pay the electricity bill, they cut it for two years. But now with the new director, there is a new arrangement and this problem is overcome.

He is saying that another challenge has to do with the hydrological centre, because they have a system there and it is working, but it is not working 24 hours. Because they are reading the information, but there is nobody there to spread or to pass the information.

M: So, that is about the river flooding, they have the information about the rain but there should be somebody to get the information and pass across?

Yes, that is a problem. Because with the new structure, because some of the staff in the new structure they got promoted, to the position of director and all this. Now they have to recruit new staff to go there and get information and now they are starting 24 hour passing of information.

M: So, it is not automatically connected?

Yes, so that is why they now have developed another way of approaching it. They will calculate the quantity of water and the quantity of water per time and they have to know the size of the river to be predicting what the water levels will be. That is what CONPREC does.

M: Okay, so now maybe, it is a good idea to show you my tool. I have a movie that explains the tool and then I would like to know from you what kind of information you think is useful and what extra information would be useful for the people in the communities?

[show movie]

He saw a similar model in Mexico that was presented by the Cuban government, because at this time the best on is from Cuba. He said that on that conference, he attend to, the president of the country and the secretary of the united nations, she adviced that countries of less resources should adopt the system of Cuba, because it is less expensive and is also for their lives.

M: So, do you think something like this could also be useful for Sao Tome?

Yes, very much. He says that it is simple and practical. Also, he asks if it will work with the internet?

M: yes

He says that the only think is, of course you are still developing, but when it is concluded, they can just train somebody to introduce the data and somebody will be seeing the information there who can help to predict.

M: Okay, so imagine we have this tool in Sao Tome. What information from the tool would they use and communicate to the people?

He said that, just as a contribution, you can add the information from the river to this one, it would be spectacular. They have information from the sea, but for certain area where there is a river, normally when the sea water increases, most of the time the river water will also increase. When they meet, there will be flooding of large areas. He said also that they have information that Portugal installed for the . . . countries, which is a group of countries where they speak Portuguese. But this system only tells about the sea level, if it is high or low.

M: it doesn't give a value?

No, but if this system provides information from the river as well, it would be very useful. But with this one also and the information from the river, what they could tell the people: based on the information here, you people should take care because so so place may be affected. And based on that, they will now decide on what to do.

M: because now they only have information qualitatively on the water level from the sea (but no values), but they don't have information on the area. And that would be very useful, to know which areas will be affected?

Yes, exactly. They wanted him to see, if for instance the country will have assets to have this tool, he would be using it.

M: which type of visualisation, or combination of visualisations, does he think are useful and if there is a type of visualisation, which I did not include, but which would be useful?

From what he perceived, each one of them has a different kind of information.

M: yes, a bit, yes.

For them color, they don't have an objection against that. For them, what is more important is the content. If the content of the information is enough for them, it is good. Because it is based on the content of information, for instance, if they are able to predict it for tomorrow, that the sea level will be high, it is okay for them.

But there is a second option. Another option is, if you can provide them these ones [pages with the different visualisations], they can meet their team and then each one of them will maybe have an opinion and if they have a conclusion they can scan it and say for so so visualisation, you can improve on that. And they will send you an email.

M: that would be great. So they want to discuss with the team what information they think is more useful?

Yes, and then they can forward it to you, via email their opinion.

M: Because I think it is important to know that these three all give information about the flood extent, so they give the area and they give the height. But this one there is a translation to risk to the houses. So is it more useful for them to have information on the risk or just on the flood extent?

Flooding is a concern, but habitation is also another concern. A combination of the two is therefore better.

M: Okay, this one is about the risk to the houses. But you could also relate the water depth on the beach to get a warning whether the fishermen should get their boats away or not. Would something like that also be useful?

These are the activities that they normally do, the fishermen, based on experience. Based on the fishermen's experience they also have a misunderstanding with the local government, because when bad weather is coming, they want to tie their boats to the fence. And whenever there is a storm or event, the boats are damaging the fence.

He is saying there are 10 communities which have been ordered to identify and there is already a project to build a park for the boats.

M: I'm sorry, can you repeat that?

Okay, so they have a project which includes 10 communities which they are going to build a park for the boats.

M: you mean like a marina?

Yes, kind of like. So that they can go and put their boats in a safe place. But the importance of this tool is for all other communities where there is no park to put their boats. So, it is important to have this one, so that it will inform them on the safety for their boats. They [the central CONPREC team] are also advising them [the communities] to plant some trees which help the land against erosion and also stop the intensity of the wind, and it can also help them to tie their boat.

M: Okay, so this information would be useful, but apart from that, they are also trying to look for other solutions for the boats?

Yes.

M: I have another question. So, say you have this tool, so you can calculate the inundated areas. But that information is very difficult to communicate to the community because you only have a phone right, so you cannot show them a map. So how would they use this? Would they use it in the trainings to show the people what the risky areas are, or how would they deal with that?

For example, they have a program to capacitize all the community leaders. And in all these fishing communities, they know better than us what are the challenges they are facing. They also know the areas where these incidents occur. As they [the central CONPREC team] send information through the radio or telephone, they also have another way of communicating in the communities over megaphon. The people use megaphones to spread the information, also in the local language. Then, instantly, everybody will know what is coming. They know the consequences and also they cooperate without problem.

M: Okay, so you don't need to show them these maps?

He says that most of the time they take it whenever they are sensitizing people. It is more for the memory. For memorizing and see, okay, when there is a problem and then they communicate, they will know: o, it is based on the image they showed us. This is the risk area and so on.

M: o, so it would be more to use during the training and sensitizing sessions that they would take this to the communities and show them. For example, if the water is this high, this area will flood. So the outcome of the tool would be used in an early warning setting for them and in a training setting for the communities.

Yes, since they don't have access to electricity and all this internet they cannot see this. And again, if they bring it and take it there, it can be destroyed after so, it is only in that specific moment of training and sensitizing that they will show it. But for them [central CONPREC team], is useful to know in early warning as well, because they know which areas are more affected.

M: so that they can identify the most vulnerable communities more efficiently?

Yes, and send help sooner, maybe not only when they ask for it but already in advance.

So, every two months they train them [the people in the communities] to refresh their ideas, and they have daily contact with them.

M: Okay, so I have a few questions in that case. Because this is an early warning system, so related for example to the predictions of tomorrow. But would it then also be useful to have maps that show the inundated area for an event that occurs every ten years, and for an event that occurs every 50 years this is the inundated area. So, it is not really an early warning system, but more showing the affected areas for different offshore conditions?

He is saying that, yes it is similar to what they have already presented on a seminar. He said that they define the line of coast for ten years ago, where was the level of sea, and for 20 years. They did a study for 50 years and all this information they provide to the community, but the problem is, everyone said: yes, this is today, this zone or this area is not a risk area. You are saying ten years after, it is a risk area, but where will we go? So, it means they are still building on this risk area or the 10 years possible risk area, they are still building. This is the challenge.

M: Okay, I understand. But what I meant is, you can have different types of storms. You can have a mild storm, but also a very strong storm and the consequences will be different. So you can calculate the consequences of the different storms with this. That's is what I mean. So, off course, the risk is also increasing in the future, but it also differs per type of storm. I am wondering, if you could calculate this for different kind of storms and show that to the people, would that be useful?

Yes, this is what they call typology of scenarios. He is saying that that is also useful for them.

M: Okay, and then I have another question. Because you can calculate this and show it to the people, but like he just said, the people will still build in the risky areas. So what does he think should be done to make sure people don't build in these risky areas anymore?

He is saying that the main challenge is a conflict between law and hierarchy and also governance. Because we have several institutions that are selling or distributing the land. We have the agriculture ministry, we have coast guard, we have also local power and we have a central institution that is distributing the land. So each one of them, based on the law, if there is interference on the area of order. So now, they identify one area as a risk area, coast guard will say: 18 meters from the sea line, this is our jurisdiction, we are the one in charge. Agriculture also intended, this is the area under our jurisdiction, so they also give for agriculture. Now there is also a local power that is normally, in that district, the distributor of land. And there is the central power also that distribute the land all over the country. So with that, if you receive the land from one of these institutions, you of course pay for that. And now, how will you recover your money, you have to build there. So, this is the problem we are facing now.

But in conclusion, he is saying there is a solution. So, there is an international convention signed that says all the risky area identified by the country [part of the WACA project]. They are supposed to have a law that is against any building in that area. So based on that law, once they receive there is any map of risk area and the law, you give to all these institutions that is sharing the land and they should not give out the land anymore. And if they do it, they will be responsible for that and have to pay.

M: And this law is already there or it is going to be there in the future?

In the future, they are working on that now. But first, they also need to identify the risk areas. They do it based on experience with the different communities, but they also need models for that.

M: Is that also what they are working on in the observatoire? The risk maps that should become part of the online platform?

Yes, exactly.

M: And if he is having the training sessions in the communities with these maps, which visualisations does he think are most understandable to the people there?

He thinks that is up to them to decide. Because he may think one is the best, but that is only his opinion. He thinks the interpretation of information, visualisation of that, and information on what they should do is the best. A combination of that. Based on what they are teaching them, based on a visualisation that is this one, it would explain better.

M: You mean that is would be more easy to convince them to undertake certain actions if you could show them these maps?

Yes, that is what he is saying. But this should also be something in the development of the tool. Go to the communities and see what are the best maps and visualisations to show them.

M: and going back to the training of the CONPREC members in the different communities, how long are these trainings?

He says that they are always 3 days.

M: 3 days, okay, and they are always in Sao Tome [the capital]?

Yes, always in Sao Tome. These trainings are every year and they are always 3 days, 4 times a year. But for the technicians, they are trained as a part of the sanddye (?) project, which runs from 2015 till 2030. These trainings can be longer. For example, there was a team from Italy that came here and trained them for 5 days.

As part of the project, they have multiple trainings. As part of this project, some students (I believe 4) are also sent abroad now to study geography, related to catastrophic risks. They study in Portugal.

The student if they go out to receive the training, when they finish the course, when they finish the university, depending on the result, the project fund will pay for their masters and then they come here as a staff.

M: Okay, I think I get it. Then I have two final questions. The first is related to the tool. If such a tool would be implemented in Sao Tome, who would use it? Would it be CONPREC, or INM or yet another institute?

He says it will be CONPREC, the civil protection and the fire distinguishers. But also the observatoire and INM, because they receive the weather forecast.

M: Okay, and CONPREC is located in 31 communities now, but do they want to extent it to all coastal communities in the future?

He mentioned that he said 31 communities, because this is where their team is working, but they are disseminating information all over the country, both Sao Tome and Principe. The radio messages that they sent are also received in other parts.

They want to have the teams in other communities as well, but the problem is the support. How should they support that? Because they need more people.

M: Alright, thank him very much for his time. And does he have more questions or suggestions for me?

No, he says it is all very clear. If you give him the information, the team will gather and they can contact you via email if needed.