# Beach development in Oranjestad Bay, St. Eustatius

A study of the morphological system and possible coastal solutions for the creation of a beach.

K.A. Adank

Delft University of Technology

TU Delft

Deltares

Rijkswaterstaat
Ministry of Infrastructure and Water Management

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by

K.A. Adank

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday March 2, 2023 at 09:00 AM.

| | | |
|---|---|---|
| Student number: | 4372212 | |
| Project duration: | March 28, 2022 – March 2, 2023 | |
| Thesis committee: | Prof. dr. ir. S.G.J. Aarninkhof, | TU Delft, Chairman |
| | Dr. ing. M. Voorendt | TU Delft |
| | Ir. M. Onderwater, | TU Delft |
| | Ir. M. Ruijter, | Rijkswaterstaat |
| | Ir. P. K. Tonnon, | Deltares |

Cover: Image of Oranjestad Bay taken from Fort Oranje, July 2022
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# Acknowledgements

Throughout my studies, I have learnt the importance of keeping the complexity of the real world in mind while trying to understand problems using numerical models. I am therefore proud to have worked on a coastal project (as my master thesis), which required me to consider both.

Upon the completion of this thesis, I would like to express my gratitude towards the people that supported me during the past months. First of all, I would like to thank Michel Ruijter, who has put this study at my disposal and has allowed me to experience the Caribbean. I have also learnt a lot from you about measuring instruments and how to think critically but out of the box. Thank you, Economy, Nature and Infrastructure team, for welcoming me to St. Eustatius and taking care of me during my stay. My thanks also go to Pieter Koen Tonnon, who took up the challenge with me to build a Delft3D model in a limited time. Not only did you help me build my knowledge from the ground up, but you were also always available for meetings and questions. I would also like to thank Mark Voorendt, for reading my thesis and asking critical questions to improve the final version of my report.

Stefan Aarninkhof, thank you for chairing this graduation committee and for making room for open discussion during the progress meetings. Martijn Onderwater, you have helped shape my research with great suggestions and advice. Thank you for the positive guidance through my research. I hope that many more students will be lucky enough to be supervised by you.

Finally, I would like to give a special thank you to my mum for always being there from the very beginning. Enjoy reading.

*K.A. Adank*
*Delft, February 2023*

# Summary

Sint Eustatius is a Caribbean island located in the north of the Lesser Antilles. The coastline west of the capital, Oranjestad Bay, is of vital importance to the island as it is here where tourism, recreation, the harbour and historical ruins are located. On the other hand, Oranjestad Bay has a heavily fluctuating beach, which is undesirable. The Public Entity of St. Eustatius is investigating the possibility of a coastal solution that could preserve and extend this beach. However, there is insufficient knowledge of the hydrodynamic processes and morphology available to design a solution. By analysing the morphological system, this study aims to advise the Public Entity of St. Eustatius on the decision for a coastal solution to create a beach in Oranjestad Bay.

A literature study was performed to obtain basic knowledge of the coastal system of Oranjestad Bay. A two-dimensional numerical Delft3D model was then developed to gain more in-depth knowledge of the wave, current and sediment patterns. The result of both findings is combined in a conceptual model, where the cause of the beach fluctuations along Oranjestad Bay was analysed. Based on the system knowledge and stakeholders' demands and regulations, three alternatives to create a beach at Oranjestad Bay are proposed. The alternatives are qualitatively verified and evaluated with a multi-criteria analysis and cost-value ratio.

The literature review shows that Oranjestad Bay has the characteristics of a wave-dominated coast. The seasonal wave climate has a strong influence on the beach fluctuations that occur in Oranjestad Bay. The influence of tides and wind on sediment dynamics is expected to be minimal.

The modelling study concluded that the wave climate can be described by three main wave conditions, namely a sea condition, a storm condition and a swell condition. The different hydrodynamic and morphodynamic characteristics of these conditions provide a reasonable simulation of the coastal processes in Oranjestad Bay. The model results give an impression of the seasonal wave climate and a net northward sediment transport capacity is found. These results are consistent with the expected coastal morphodynamics found in the literature study. The effect of a storm is less well represented in the modelling study. This limitation is caused by the modelling approach. In addition, there are some uncertainties in the model due to the lack of detailed coastal data in the nearshore.

The conceptual model indicates that the coast of Oranjestad Bay may experience seasonal gradients in alongshore sediment transport leading to beach fluctuations. From April to September, beaches are likely to erode due to net northward sediment transport. In addition, beaches erode due to periodic storm conditions that occur from June to November. It has been found that the recovery of beaches after a storm varies along Oranjestad Bay. Scubaqua beach recovers much faster than the beach at Smoke Alley. This is due to the larger sediment transport capacity in the alongshore direction at Smoke Alley beach, the amount of larger cobbles on the shoreline of Smoke Alley and the lack of sediment north of Smoke Alley. From September to March, beaches increase due to long (swell) waves from the Southwest to the western direction. The resulting longshore transport brings sediment into the coastal system. Finally, the widest beach is observed in April.

The coastal solutions considered in this study consist of beach nourishment combined with a groyne. Alternative I is a small-scale nourishment that is located in the harbour area and makes use of the existing structures in the area. Alternative II is a small-scale nourishment in combination with a groyne and is located around Scubaqua beach. Alternative III is a long-stretched nourishment covering the area from Scubaqua to Smoke Alley in combination with a groyne. Each alternative is successfully verified. The results of the MCA provided an overview of scores and criteria that can be used as a tool in the decision-making process for a coastal solution in Oranjestad Bay. In this study, Alternative I had the highest MCA score at the lowest cost. Therefore, the most suitable solution for Oranjestad Bay is Alternative I. This study is limited to an initial inventory of alternatives. Therefore, a refinement of the proposed solutions is still necessary in order to decide on the coastal solution for Oranjestad Bay.

In conclusion, this study contributes to the understanding of the coastal morphodynamics in Oranjestad Bay. A first indication of alternatives is presented and evaluated with an MCA and cost-value ratio. The results can be used by the Public Entity of St. Eustatius in the decision-making process for a coastal solution in Oranjestad Bay for the creation of a beach.

**Keywords: Coastal morphology, St. Eustatius, Delft3D-4 modelling, Beach fluctuations**

# Contents

# 1 Introduction

## 1.1. Problem description

Sint Eustatius is a Caribbean island located in the north of the Lesser Antilles. It is part of the Leewards Islands and lies between Saba, approximately 27 kilometres (km) northwest, and St. Kitts, 12 km southeast. Figure 1.1 illustrates the location of St. Eustatius in the Caribbean. The coastline west of the capital, called Oranjestad Bay, is important for the island as tourism, recreation, the harbour, and historical ruins are situated here. Figure 1.2 presents Oranjestad Bay. This study focuses on the area between Smoke Alley and the harbour.

In 2017 St. Eustatius was hit by hurricanes, Irma, and Maria, and in 2018 by a heavy swell that concerned the inhabitants about their coastal safety. Especially the heavy swell of 2018 had a severe impact because it flooded the vital road of the island. This motivated the Public Entity of St. Eustatius to improve the coastline of Oranjestad Bay.

In Oranjestad Bay, a fluctuating beach is present which can build up to 30 m wide. This is illustrated in Figure 1.3 by historical pictures. According to Esteban and MacRae (2007) particularly during the months December to April, a substantial sandy beach builds up, of which most is eroded again in the months' May to November. These beach fluctuations are undesirable for the important elements that are located in Oranjestad Bay. For this reason, the Public Entity of St. Eustatius wants to develop the coastline of Oranjestad Bay with the creation of a (stable) beach. The presence of a more permanent beach may have a positive impact on weak spots that are prone to coastal erosion but also be beneficial for tourism. In addition, it may protect the historical ruins from eroding in the sea.

To design a coastal solution for Oranjestad Bay understanding these beach fluctuations, or in general, an understanding of the coastal system is necessary. However, currently, insufficient knowledge of the hydrodynamic processes and coastal morphology is available to make a suitable design. Therefore, the goal of this research is to contribute to the understanding of the morphological system and to advise the Public Entity of St. Eustatius on the decision-making for a coastal solution to create a beach in Oranjestad Bay.


**Figure 1.1:** Location of Sint Eustatius (red) on the world map using Google Earth (24/4/2022). Oranjestad Bay is highlighted in yellow.


**Figure 1.2:** Oranjestad Bay using Google Earth (24/4/2022). The study area is between Smoke Alley and the harbour.

**Figure 1.3:** Beach fluctuation in Oranjestad Bay, data unknown (Esteban & MacRae, 2007)

## 1.2. Knowledge gap

Since 2018 several studies have been conducted to gain knowledge of the characteristics of the coastal zone of Oranjestad Bay. Ruijter (2019) explained that no coastal retreat is expected at the coastline of Oranjestad Bay. Results were based on a comparison between historical maps and a drone survey in 2018. His conclusion is in agreement with historical satellite imagery of Google Earth, which shows hardly any shift in the coastline from 2004 to 2022. Additionally, the studies by Gautier and Doeleman (2022) and Bos et al. (2018) give insight into the nearshore wave characteristics at Oranjestad Bay using a SWAN wave model. Both studies show the existence of a seasonal wave climate, where the dominant wave direction is South South-East during most of the year. During the period from September until mid-April, however, the waves approach the coast from a more westerly direction. In addition, a measuring campaign from 2020 to 2021 supported the modelling study of Gautier and Doeleman (2022) regarding local wind, wave, and sediment characteristics (Gautier, 2022). Lastly, de Vroeg (2022a) conducted a desk study on the coastal morphology based on a literature study and an evaluation of the longshore sediment transport with the help of a one-dimensional shoreline model (UNIBEST-CL+). de Vroeg (2022b) argued that most of the year there is a longshore transport capacity in the northward direction, assuming a fully sandy beach. However, a reversal of the transport capacity is seen in the months from September until April. This longshore transport reversal, caused by a seasonal wave climate, could be an explanation for the fluctuating beach at Oranjestad Bay.

These studies help to gain insight into the hydrodynamic processes and sediment dynamics of Oranjestad Bay yet a complete understanding of the dominant processes in the coastal system is still lacking. The knowledge on the coastal system is incomplete because the shoreline model focuses only on longshore sediment transport. For the design of a suitable solution for Oranjestad Bay, the influence of cross-shore transport is also necessary. Therefore, it is important to study both the effect of the longshore and cross-shore sediment transport in the coastal zone of Oranjestad Bay to acquire a thorough understanding of the coastal system. By filling in this knowledge gap, advice on a suitable solution for a beach at Oranjestad Bay can be given.

## 1.3. Research Questions

### Research objective and main research question

This research aims to advise the Public Entity of St. Eustatius on the decision-making for a coastal solution to create a beach in Oranjestad Bay by analysing the morphological system. The following research question is formulated:

*What is a suitable coastal solution to create a sandy beach at Oranjestad Bay, St. Eustatius?*

### Sub-questions

Four sub-questions are formulated to answer the main question and are as followed:

1. What are the morphodynamic characteristics of the coastal zone in Oranjestad Bay?
2. To what extent can a numerical model simulate the coastal processes at Oranjestad Bay?
3. Based on the system knowledge, what is causing the variation in beach fluctuations along the coastline of Oranjestad Bay?
4. What alternatives are suitable to create a sandy beach at Oranjestad Bay based on system knowledge and the stakeholders' requirements and regulations?

*Sub-question 1* addresses the hydrodynamic conditions and sediment dynamics of the coastal zone. With this question, an understanding of the characteristics and dynamics of the environment is obtained which forms the basic knowledge of the coastal system. By evaluating individual processes in a numerical model, *Sub-question 2* helps to obtain a thorough insight into the coastal system of Oranjestad Bay. The aim of *Sub-question 3* is to combine the knowledge of Sub-question 1 and 2 to describe the morphological changes on the coast of Oranjestad Bay. Based on this information, regulations and stakeholders' wishes, the focus of *Sub-question 4* is to identify conceptual designs and evaluate various coastal solutions for the creation of a beach at Oranjestad Bay. Based on findings from these sub-questions, an answer is given to the main question.

## 1.4. Methodology

In this study, an understanding of the coastal system is obtained (Research Question 1,2 and 3), after which possible coastal solutions are identified and evaluated in a qualitative manner (Research Question 4). Table 1.1 presents an overview of the methods for each sub-question.

| Sub-question | Method |
|---|---|
| 1 | Studying literature & visiting the project site |
| 2 | Setting up a numerical model: Delft3D-4 |
| 3 | Creating a conceptual model |
| 4 | Evaluating multiple solutions and choosing the most suitable solution |

**Table 1.1:** An overview of the methodology per sub-question

To identify coastal solutions, the Building with Nature (BwN) design philosophy will be used (See Figure 1.4). This approach initiates a creative design process, where an integrated solution is developed that seeks to enhance the system's potential (societal and economical) while safeguarding or improving sustainability (Van Eekelen & Bouw, 2020). The BwN approach can be applied in this research since the coastal solution should serve multiple purposes such as tourism and heritage protection, while not harming the environment. This study relates to the first three steps of the BwN cycle. Step 1: Understanding the system (Chapter 2 - 4); Step 2: identifying alternatives and Step 3: evaluating alternatives to select an integral solution (Chapter 5). An elaboration of each step and how it relates to the research questions are provided below.

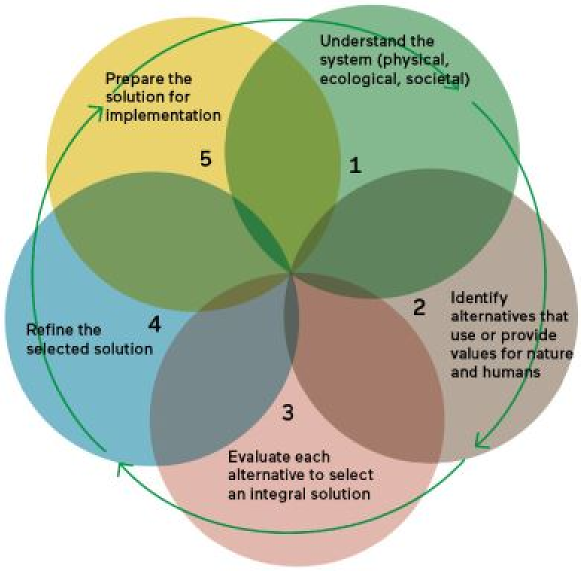


**Figure 1.4:** The five steps of the BwN design circle (Van Eekelen & Bouw, 2020)

*Methodical step 1*
The first step is to gain a better understanding of the coastal morphodynamics in Oranjestad Bay, which is related to BwN design Step 1. The approach for this step is threefold.

At first a basic understanding of the coastal system of Oranjestad Bay is acquired through a literature study on the morphodynamic characteristics of the coast as well as a site visit to St. Eustatius. The most important sources for the literature study are a combination of regionally available data, such as information on weather patterns and the tidal systems, and locally available information from reports and nearby measurement stations. In 2017 and 2018, several studies were performed to fill the information gap related to coastal morphology, waves, water levels and currents (Gautier and Doeleman (2022), de Vroeg (2022a), de Vroeg (2022b), Gautier (2022)). The collected information in these researches is also used in the literature study. Besides the literature study, a site visit extends the knowledge of the local wave climate and sediment dynamics. During the visit, a nearshore wave measurement was performed and the beaches of Oranjestad Bay were inspected during the storm season. Based on the findings, Research Question 1 is answered and a basic understanding of the coastal system is acquired.

Subsequently, more in-depth knowledge on the individual coastal processes in Oranjestad Bay is gathered with a numerical model (Delft3D-4). A Delft3D-4 model simulates two-dimensional and three-dimensional flows, sediment transport and morphology to support decision-making in complex natural environments like coasts, rivers, and estuaries. In this study, the Delft3D-4 model is applied in 2D mode and a coupled Flow Wave model is set up. The 'WSO' wave buoy data as well as the knowledge from Research Question 1 serve as model input. The output of the Delft3D-4 model will, among others, be wave directions and heights, velocity fields and sediment transport patterns. The model is validated with the nearshore observation obtained during the site visit. Besides that, the validation process is mostly based on expert judgement and the basic system knowledge obtained by Research Question 1. To conclude, a modelling study is carried out to obtain more in-depth knowledge about the coastal processes of Oranjestad Bay and to answer Research Question 2.

At last, a conceptual model is created to explain the coastal morphodynamics in Oranjestad Bay. The obtained knowledge of the coastal system in Research Questions 1 and 2 serves as the basis for the conceptual model. Using sketches of the coastline and different symbols for wave direction, velocities magnitudes and sediment transport the conceptual model is visualized. With this conceptual model, an explanation of the variation in beach fluctuations along Oranjestad Bay is given. This answers Research Question 3.

Based on the literature study, site visit, modelling study and the conceptual model, enough information on the understanding of the coastal system of Oranjestad Bay is obtained in order to create coastal solutions.

*Methodical step 2*
Step 2 is to identify realistic alternatives based on the obtained knowledge on the coastal system and stakeholders' wishes and regulations. This related to design Step 2 of the BwN design cycle. The wishes for the coastal solution are collected by conversations with relevant stakeholders, like the Public Entity of St. Eustatius and STENAPA. Furthermore, regulations- and laws of the Caribbean Netherlands (the so-called BES laws) are the most relevant rules to consider and are obtained from the literature. Inspiration for realistic alternatives is gathered through the site visit and example projects in the Caribbean. Based on these findings, an answer to Research Question 4 is provided.

*Methodical step 3*
After the identification of alternatives, the next step is to verify and evaluate the different alternatives (Step 3 in the BwN design cycle). In this study, a qualitative approach is used for the verification and the evaluation. A MCA is carried out to evaluate the coastal solutions proposed. This is a decision-making tool, which is useful to evaluate solutions from various perspectives. A MCA helps to organize criteria and scores, which allows the decision-making entity to make thought-out and defensible choices. Finally, the alternative with the highest score and lowest cost (cost-value ratio) is determined as the most suitable coastal solution for Oranjestad Bay.

## 1.5. Thesis outline

This report consists of eight chapters. First, the coastal system is analyzed in Chapter 2 through a literature study and information gained in the project visit. The findings of this chapter provides answers to Research Question 1. Subsequently, more in-depth knowledge of the coastal system is gathered in Chapter 3, through the modelling study. After which, an answer can be given to Research Question 2. Chapter 4 describes the conceptual model which is a synthesis of the knowledge acquired in Chapter 2 and Chapter 3. By means of the conceptual model, an in-depth understanding of the coastal morphodynamics at Oranjestad Bay is provided and Research Question 3 can be answered. Chapter 5 concerns the design and evaluation of alternatives. The outcomes in this chapter, answer Research Question 4. Subsequently, the results and limitations of the research are discussed in Chapter 6. The research finalizes with Chapter 7 and Chapter 8, where conclusions on the research questions are drawn and recommendations for future research are given. In Figure 1.5 an overview of the thesis outline and how this relates to the steps in the BwN cycle is presented.

In Figure 1.5 an overview of the thesis outline is presented.

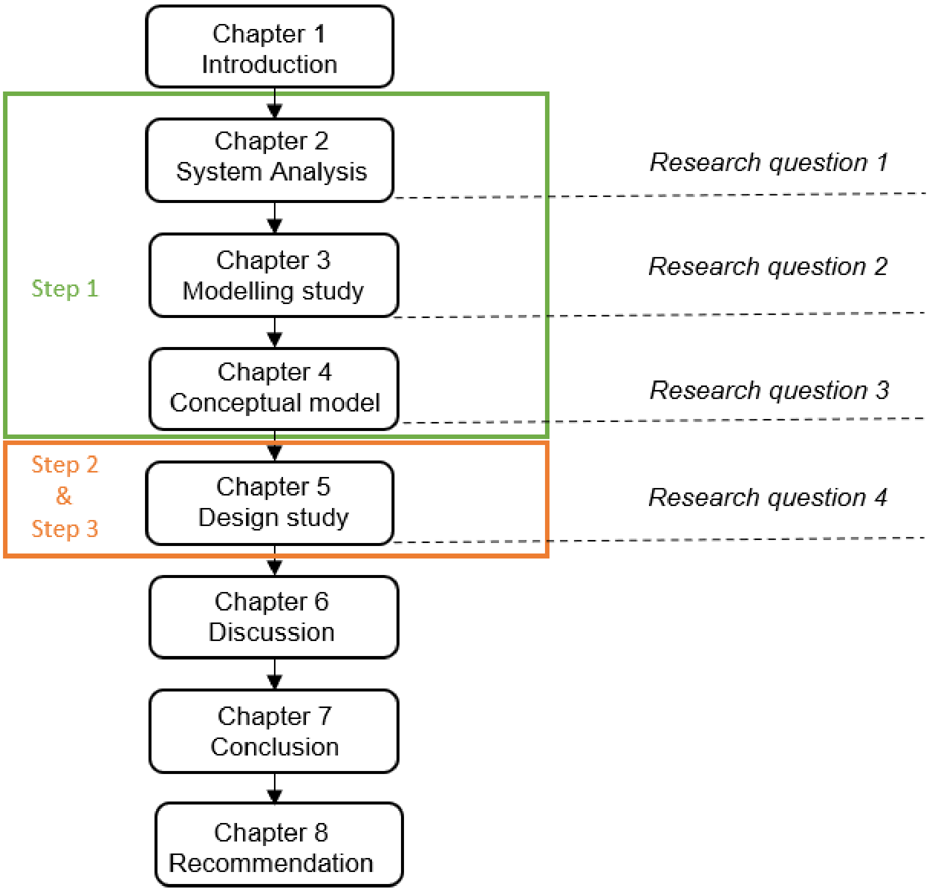


**Figure 1.5:** An overview of the thesis outline, indicating the content per chapter and the related BwN design step.

# 2

# Analysing the coastal system

In this chapter, basic knowledge of the coastal system is obtained through a site visit (July - mid October 2022) and a literature study. The system means in this sense the hydrodynamic- and morphodynamic characteristics of the study area as well as environmental components and stakeholders. The findings of the system analysis are used as input or validation data for the modelling study in Chapter 3. Furthermore, the environmental and stakeholder analysis will help to establish a program of requirements in Chapter 5. Based on the results of this chapter, an answer to Research Question 1 can be given:

*What are the morphodynamic characteristics of the coastal zone in Oranjestad Bay?*

## 2.1. Geology

The island arc where St. Eustatius is part of is formed due to the convergence of the South American and the Caribbean plate. St. Eustatius is situated on the latter, the Caribbean plate. According to Blewitt et al. (2018) the plate is moving approximately 10-12 mm/yr eastward and 14-16 mm/yr northward, considering global Earth-centered frame of reference (IGS14). Moreover, a subsidence of approximately 1-3 mm/yr of the island is expected based on measurements since 2018. Seismic activity is daily monitored by the Royal Netherlands Meteorological Institute (KNMI) and so far no extreme events were measured. The effect of plate tectonics or subsidence is further not included in the scope of this study.

## 2.2. Bathymetry

In 2006 the bathymetry of the west coast of the island was mapped by the Dutch Royal navy, as is illustrated in Figure 2.1. The bathymetry chart covers an area of 33 $km^2$ and includes the depth from -10 m up to 100 m. Figure 2.1 shows that the bathymetry is alongshore uniform in the first ten meters. In areas deeper than MSL -20m, the average slope in the northern part is steeper compared to the southern part, which starts south of the oil terminal. Oranjestad Bay is located in the southern part and characterized by a relatively flat area. This means that the 30 m depth contour is measured at a distance of 3 km from the coast.

Several nearshore measurements by Harris and Cimaglia (2005) and Gautier (2022) were conducted to provide insight into the beach profiles and bathymetry above MSL-10 m depth. In addition, nearshore measurements of the ocean depth were carried out during the site visit in August 2022.

Harris and Cimaglia (2005) conducted a beach profile survey from Smoke alley to the first groyne. The survey showed an average slope of 1:20 to 1:30 between 0 and -3 m depth. Gautier (2022) performed three measurements north and south of the Scubaqua diving centre and in front of the Old gin house. The results showed an average slope of 1:25 to 1:40 between MSL -1 m and MSL -3 m. Both measurements by Gautier (2022) and Harris and Cimaglia (2005) are in fair agreement. Furthermore, Gautier (2022) found an average slope of 1:35 to 1:40 from Smoke Alley to the Scubaqua diving centre between approximately MSL -1 m and MSL -10 m. During the site visit, fairly the same result was measured. From Smoke Alley to Scubaqua diving centre an average slope of 1:30 to 1:35 is found between MSL -2 m and MSL - 10 m. The measurement locations as well as the result of the surveys are presented in Appendix A.

Furthermore, the shoreline orientation of Oranjestad Bay is concave shaped. North of the project site the orientation is 250 °N, after which it slowly decreases to 210 °N. At the southern boundary of the project site, in front of the harbour, the orientation is 270°N. An overview of the shoreline orientation is presented in Figure 2.2.

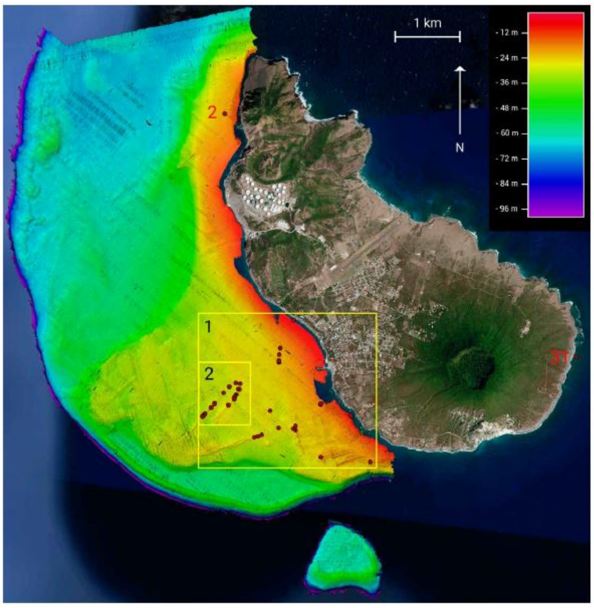


**Figure 2.1:** Bathmetry map of the west coast of St. Eustatius, colours indicate the water depth in meters. The red dots are archeological sites by Stelten (2020)

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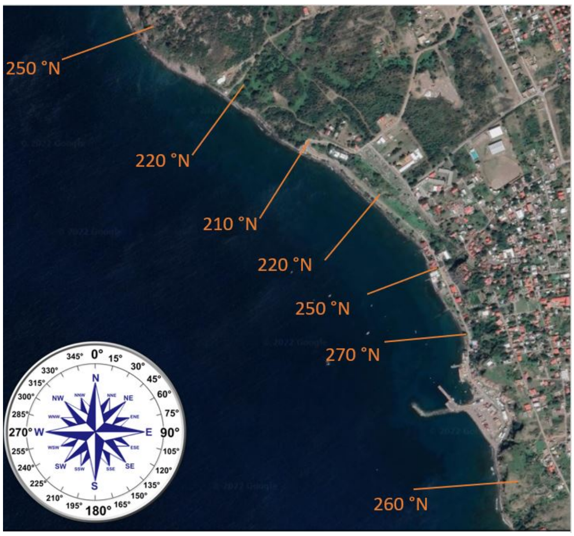



**Figure 2.2:** The shoreline orientation at Oranjestad Bay

**Unique features**

In Oranjestad Bay, two unique features can be found. Firstly, a submerged feature is located parallel to the coast at a depth of MSL -3 m to MSL -4 m. In the report of Harris, the feature is described as a historical wall. However, the definition of the submerged features is under discussion since no clear information is found on a historical wall. Nonetheless, the survey by Harris gives more insight into the dimensions and the distance from the shore to the object. The distance to the submerged feature, called the historical wall by Harris, varies along the coastline, due to the curvature of the shoreline and the position of the wall. Mostly the top of the feature only marginally sticks out above the seabed. Therefore, the effect of the wall on the nearshore waves and sediment transport is expected to be minimal (de Vroeg, 2022a).

Besides that, archaeological sites are present in Oranjestad Bay. These historical elements such as shipwrecks and anchors are a source of biodiversity and a playground for snorkelers and divers. An overview of the site locations is presented with the red dots in Figure 2.1.

## 2.3. Hydrodynamic conditions

### Wind

The latitude and longitude of St. Eustatius are respectively 17.48°N, 63.98°W. Due to its location, the island is mostly affected by the North-East trade winds, which blow from the northeast and easterly direction on the island. Trade winds blow persistent and in the same direction throughout the year, which is reflected in weather measurements at St. Eustatius (Bosboom & Stive, 2015).

Respectively, three sources give information on the local wind speed and direction at the project site based on model simulations and measurements. Firstly, the wind rose of St. Eustatius is illustrated in Figure 2.3. The data is derived from 30 years of hourly global NEMS weather model simulations (Meteoblue, n.d.). The figure shows the amount of hours of wind blown per year from a designated direction. The dominant wind direction simulated by the model is East Northeast and most of the time the wind speed is less than 10.5 m/s. This is in line with the airport weather station which provides local information about various parameters like wind speed and wind direction. This second source is based on measurements from 2005 till April 2022. The airport weather stations delineated a yearly wave direction East North East and an average wind speed of 6 m/s (Windfinder, 2022). Thirdly, a second weather station is located at the harbour of St. Eustatius (17.478°N and 62.987°W), which measures diverse parameters since January 2021. On average, the wind direction at the harbour is East and the average wind speed is approximately 4-5 m/s, as is shown in Figure 2.4. The main wind direction and average wind speed at the harbour weather station vary slightly from the airport weather station and the model simulations because the harbour lies on the lee side of the island. Also, the data available from the harbour weather station represents only one year. Furthermore, in contrast to the model simulations, extreme conditions are not available for both weather stations due to the failure of the instruments at extreme events (Ruijter, 2019).

To conclude, St. Eustatius is mostly affected by the North East trade winds. Most of the year the wind direction comes from ENE and the wind speed is lower than 10.5 m/s. In the harbour, the main direction is more East and the average wind speed is lower due to the lee side location on the island.

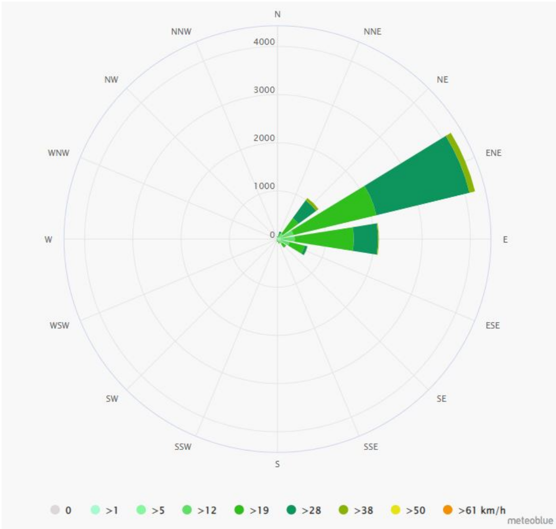
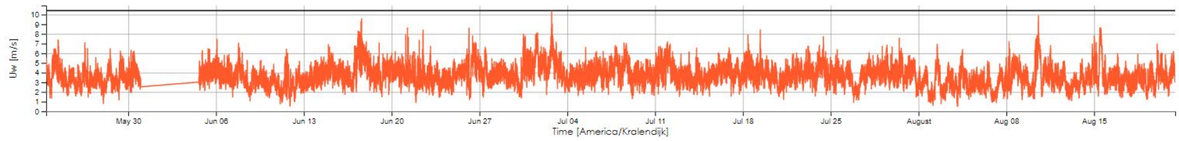
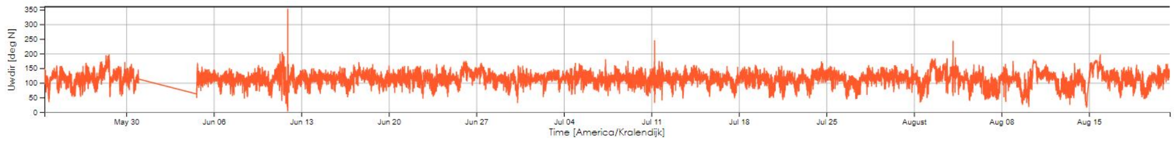



**Figure 2.3:** Wind rose of St. Eustatius, (Meteoblue, n.d.)




**(a)** Wind speed (Uw) in m/s




**(b)** Wind direction (Uwdir) in degrees N

**Figure 2.4:** Wind speed (Uwspeed) and Wind direction (Uw dir) from harbour weather station measurements May till August 2021, https://obscape.com/portal/login

## Waves

A recently performed wave study by Gautier and Doeleman (2022) gives insight into the nearshore wave characteristics at Oranjestad Bay. Gautier and Doeleman (2022) uses a SWAN wave model to transform wave data from offshore data sets to nearshore wave characteristics. The findings conclude that most of the time the significant wave height is below 0.7 m and the peak period between 4 seconds (wind generated) and 13 seconds (swell waves) at the location of the WSO wave buoy ($\sim$13 m depth).

Besides, Oranjestad Bay experience a seasonal wave climate. The dominant wave direction is South-South East. However, during the winter months approximately from September to April swell waves arrive from a Western direction. These waves tend to have longer wave periods than the waves arriving from the South-Southeast (de Vroeg, 2022b). The dominant wave direction varies from the wind direction since waves that travelling from the Atlantic bend around the island. An illustration of the computed significant wave height for two events is illustrated in Figure A.4 (see Appendix A). In this figure, the bending of waves around the island is clearly visible.

Figure 2.6 presents the wave rose for a location in the vicinity of Oranjestad Bay. It shows the nearshore significant wave height and mean wave period during the 42-year hindcast for the location of the wave buoy Smoke alley Offshore 'WSO' (See Figure 2.5). The wave rose shows the nearshore wave direction in a southern and more westerly direction.

In addition, in 2021 a one year measuring campaign started which involved the measuring of offshore wave data in front of Smoke Alley (17.48°N, 62.99 °W). Compared to the model simulations, the mean wave direction measured at Smoke Alley is South while the computed direction is South-South East for most of the time. Despite that, the available measurements from April 2021 till 2022 are fairly inline with the nearshore wave climate found in the model study by Gautier and Doeleman (2022).

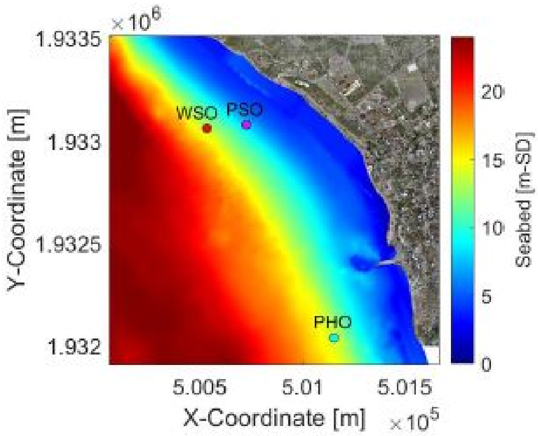
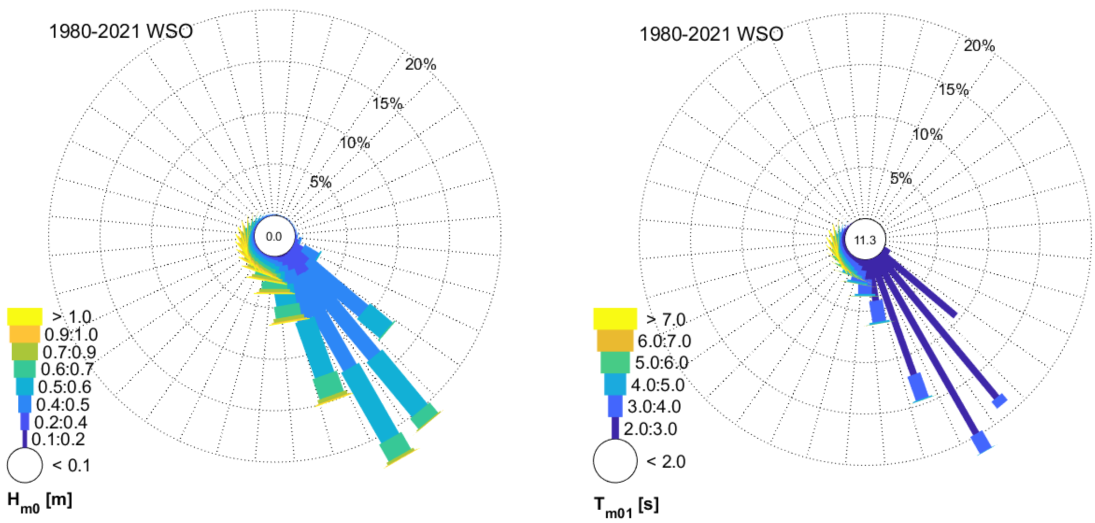



**Figure 2.5:** Location of the wave buoy Smoke Alley offshore 'WSO'. Seabed in Statia Datum (MSL-0.19 m)




**(a)** Significant wave height

**(b)** Mean wave period

**Figure 2.6:** Wave roses of the significant wave height and mean wave period during the 42 year hindcast at 'WSO' by Gautier and Doeleman (2022).

***Extreme conditions***

Next to the yearly wave patterns, extreme events occur at St. Eustatius since the island lies in the Atlantic hurricane belt. In Figure 2.7 an impression on the storms at Oranjestad Bay can be gained. Figure 2.7 shows the computed wave heights at the WSO wave buoy location during the 42 years. On average, once every 5 years, a tropical storm and Category 1-2 hurricane pass over St. Eustatius measured within 60 nautical miles (Carribean Hurricane Network, 2020). Higher category storms, category 3-5, occur (on average) every 10 years based on historical hurricane data from stormcarib.com. Depending on the category and travel path this causes storm conditions at the nearshore of Oranjestad Bay.

The recent hurricanes that affected the Island were hurricanes, Irma and Maria, in 2018.

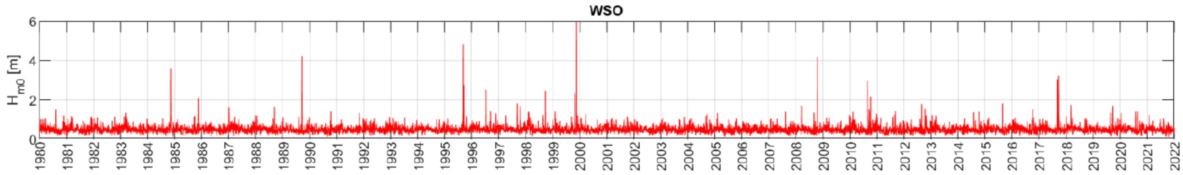



**Figure 2.7:** Computed timeseries of the significant wave height at the WSO wave buoy during the 42-years hindcast (Gautier & Doeleman, 2022)

**Sea-Level rise**
According to the latest Intergovernmental Panel on Climate Change report, the relative sea level rise for small islands in the Caribbean is on average 25 cm in the near-term predictions (2021-2040) and 50 to 70 cm in the long term (2081-2100). Although the predictions are rather general and subjected to uncertainty, it gives an indication of the expected relative sea level rise in the future for small islands in the Caribbean. Moreover, an intensification of tropical cyclones due to climate change may be expected which will affect the storm conditions at Oranjestad Bay.

In this research, the effects of climate change are not considered because the focus of the study is on understanding of the morphological system in the present situation. Also, due to time limitations, the effects of climate change are out of the thesis scope.

## Water levels and currents

First observations on water levels and currents in the vicinity of Oranjestad Bay were obtained in a measuring campaign in 2021-2022 by Gautier (2022). The study showed that the water level fluctuates roughly between approximately +/- 0.3 m relative to MSL. The tide is mainly daily. Moreover, an analysis on the mean water level illustrated that a seasonal variation exist. The mean water level during spring is approximately 0.15 m above Statia Datum ($\approx$ -0.04 m relative to MSL). During summer and autumn months (July-November) this is approximately 0.30 m above Statia Datum ($\approx$ 0.10 m relative to MSL). The observations by Gautier (2022) are in line with research by Kjerfve (1981) and Slijkerman et al. (2011), which also expect a low tidal range on St. Eustatius.

Current velocities were measured by Gautier (2022) on approximately 8 m depth. Based on a 10-weeks period, observation data showed values up to 0.3 m/s a few meters above the sea bed. The velocity component in north-south direction is much smaller than the eat-west component.

Overall, a low tidal range and a wave height below 1 m imply that the coastal character of Oranjestad Bay is wave-dominated (Bosboom & Stive, 2015). In addition, based on the seasonal wave climate a wave-induced longshore current is expected to be northward most of the year due to the waves approaching the coast from a southern direction. In the winter months a southward-directed current could occur due to the more western swell waves. The tide is expected to play a lower role than the waves due to the limited water level fluctuations and the expected low current velocities in the nearshore of Oranjestad Bay.

## 2.4. Morphology

### Sediment

The coastline of Oranjestad Bay consists of pocket beaches, volcanic rocks and ruins. North of the harbour to approximately the old gin house, the coastline contains mainly volcanic rock as illustrated in Figure 2.8a. North of the old gin house to Smoke Alley, small sandy stretches are found. Along the entire coastline ruins of old warehouses are positioned. Figure 2.8 shows the different elements on the coast. This means the characteristics of the coast at the water line are a mix of rocks, sand and ruins of old ware houses.

Oranjestad Bay has a sandy foreshore. The beaches are characterized by black sediment that is composed of titanium and iron weathered from the volcanic rocks (de Vroeg, 2022a). In 2021, Deltares conducted several bed sediment samples at Smoke Alley, Scubaqua dive centre and the Harbour area. The results show a bed formation with a median grain size (D50) between 0.2 to 0.3 mm. The grain size distribution is presented in Figure 2.9. In addition, above MSL -7 m no organic material is available in the bed samples.

Moreover, Deltares-Imares analysed the soil layers based on drilling logs at the harbour. The report concludes that the bed in the nearshore area consists of volcanic rock that is overlain by sand and gravel. The sand and gravel can also contain rock fragments eroded from the rocky shore. Due to the coral-rich environment, especially in the top layer, the mixture of sand, gravel and rock is cemented by calcium carbonates (Slijkerman et al., 2011). Therefore, the thickness of the sand layer in the foreshore is uncertain.

**(a)** Picture of the rocky shoreline north of the harbour, St. Eustatius (Site visit 28 July 2022)

**(b)** Picture of the beach at Scubaqua dive center, St. Eustatius (Site visit 28 July 2022)

**Figure 2.8:** Pictures of the coastline of Oranjestad Bay, St. Eustatius

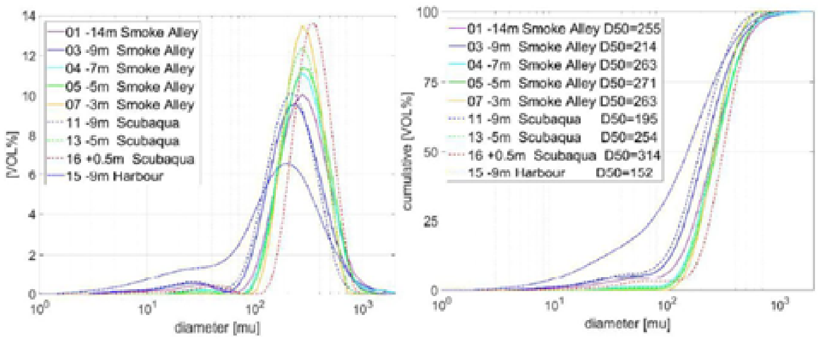



**Figure 2.9:** Grain size distribution of various bed samples by de Vroeg (2022a)

## Sediment transport

According to the inhabitants of St. Eustatius the widest beach at Oranjestad Bay is present during the Eastern weekend. At this time of the year several activities take place at the beach such as beach barbeques, parties and overnight stays. However, limited data is available on morphological changes at Oranjestad Bay so that it is unclear if the widest beach occurs every year at Eastern and if the size of the beach is constant.

Next, an indication of the sediment transport capacity in cross-shore and longshore direction are based on the hydrodynamic processes found in literature and the experiences of beach fluctuations during the site visit.

*Long shore sediment transport*

The findings of the UNIBEST-CL+ study by de Vroeg (2022b) showed that most of the sediment transport capacity is generated above MSL-3 m contour. In Figure 2.11 the results of the longshore transport capacity along the cross-shore profile of two locations at the coast are shown. It can be seen that the main peak of the net transport capacity is generated close to the waterline (approximately at MSL). This peak is in northward direction, caused by the waves which approach the coast from the south. In addition, for location 6 (see Figure 2.10) the gross southward directed transport capacity exceeds the gross northward directed transport capacity at larger water depths (approximately MSL-1.5 m). This may be explained by the swell waves from a more westerly direction that tend to break at larger water depths.

Furthermore, de Vroeg concluded that the net total longshore sediment transport capacity increases from zero at the harbour to a maximum of 15,000 $m^3$ in the northern part of the study area, assuming a fully sandy profile. The study gives insight in the longshore sediment transport capacity at Oranjestad Bay. However, it must be noted that the shoreline model considers fluctuations caused by alongshore sand redistribution and does not include fluctuations based on cross-shore sand re-distribution.

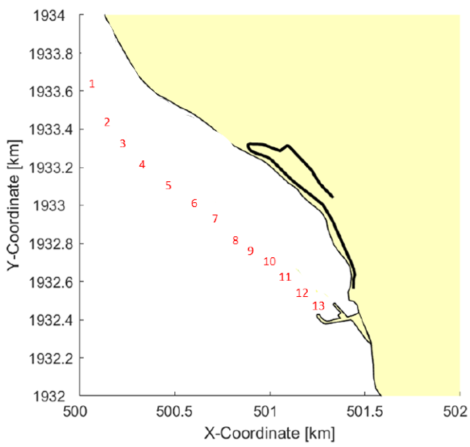



**Figure 2.10:** Output locations for UNIBEST modelling study by de Vroeg (2022b)

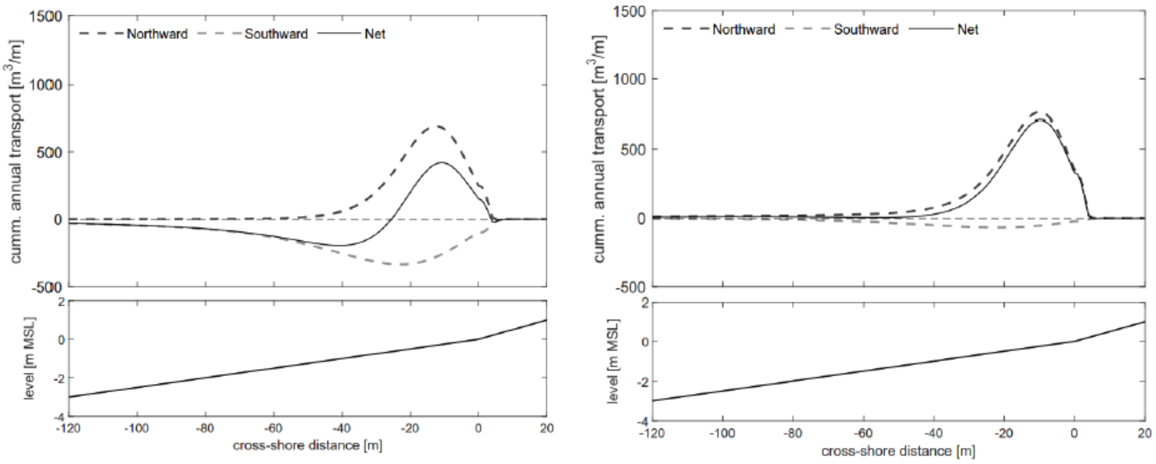



**Figure 2.11:** The cross-shore distribution of the longshore transport capacity for location 6 (left) and 9 (right) assuming a fully sandy profile, by de Vroeg (2022b)

*Cross-shore sediment transport*

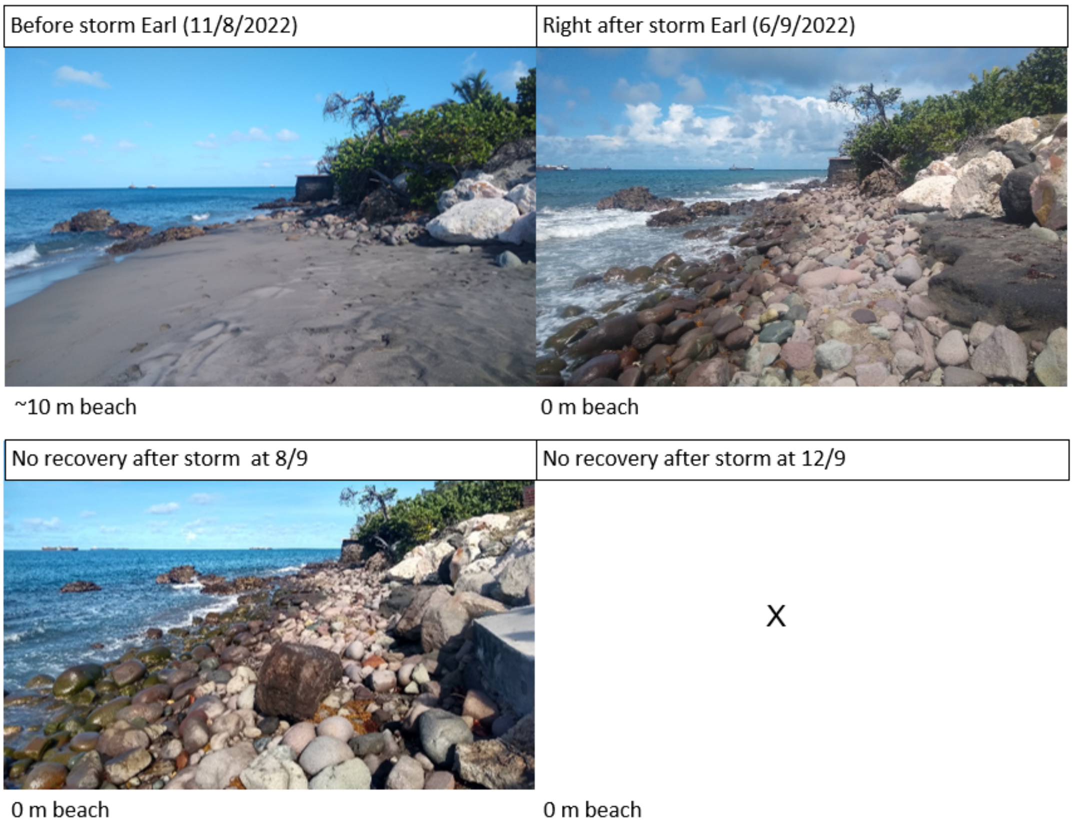
During the site visit from July 2022 till October the effect of storms on the beaches of Oranjestad Bay was captured by imagery. In Figure 2.13 the effect of tropical storm Earl on the beaches of Scubaqua and Smoke Alley are presented before, just after and one week after the storm. The pictures of Scubaqua beach (see Figure 2.12a) illustrate a fast beach recovery after the storm. This indicates that during the tropical storm Earl pre-dominantly cross-shore transport occurred. In addition, Figure 2.12b shows that different processes took place for the two locations because at Smoke Alley the beach did not recover. Another difference between the two locations is the number and sizes of the volcanic rocks present. The larger number of stones at Smoke Alley may influence the recovering process of the beach. Due to the waves reflect against the stones, it is more difficult for the sediment to settle on this location compared to Scubaqua beach.

In Figure 2.13a the measured wave data of the WSO wave buoy during Storm Earl is presented. The mean wave direction is estimated with the help of the wave buoy data of the Spotter wave buoy since the measurements of the WSO buoy were incorrect. The location of the Spotter buoy is illustrated in Figure 2.13b. The estimated mean wave direction has a South-West to Westerly direction on the shoreline. This indicates a slightly northward transport current during the storm and a southward directed transport current after the storm. The figure shows that the peak wave period before and after the storm is approximately 10 s, while during the storm it is, on average, 5 s. Furthermore, the maximum significant wave height is approximately 1.4 m.

Two weeks after Storm Earl, the second tropical storm (Fiona) passed by St. Eustatius. At this storm the same beach states occurred at Scubaqua beach. First the beach eroded and the sediment was transported to the foreshore. After one week the beach was mostly recovered. Pictures of storm Fiona are illustrated in Appendix B. Since Smoke Alley beach was not recovery yet, no beach was present at Smoke Alley before or after storm Fiona.

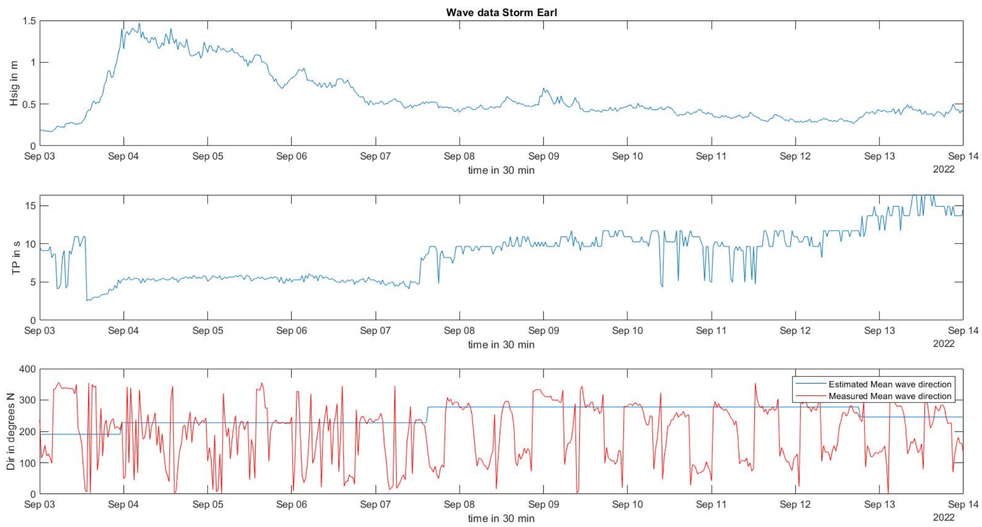
To conclude, cross-shore sediment re-distribution is present during storm conditions. However, the beaches at Smoke Alley and Scubaqua show a different recovering pattern.


**(a)** The beach states of Scubaqua beach before, just after and after storm Earl

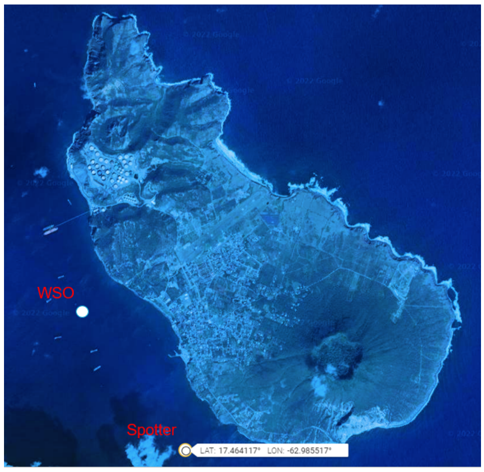



**(b)** The beach states of Smoke Alley beach before, just after and after storm Earl

**Figure 2.12:** Picture series of beaches during Storm Earl




**(a)** Timeserie of WSO wave buoy data during Storm Earl




**(b)** Location of the SPOTTER wave buoy

**Figure 2.13:** Wave data of WSO wave buoy and location of buoys in St. Eustatius

## 2.5. Environment

In St. Eustatius, the National Marine Park encloses the entire island from the high-water line to 30 m water depth. In the park, no anchoring is allowed except for twelve designated locations. In the north and south of the island, two marine reserves are located (Slijkerman et al., 2011). The marine reserves acts as a conservation area for biodiversity. In the reserves, anchoring and fishing are prohibited. The location of the marine park and northern and southern reserves are presented in Figure 2.14.

The main ecosystems found within the marine park are coral reefs and seagrass. In 2014, the study of Debrot et al. (2014) resulted in a habitat map which is based on a large-scale video survey. In Figure 2.15 the habitat map is illustrated. It can be seen that coral reefs are dominant on the eastern and southern sides of the island, while seagrass is found mostly in the north. The habitat at the project location is bare sand with occasionally algal fields, seagrass and gorgonian reefs. In deeper water algae fields become more dominant and multiple reef types are present. The habitat types at the project location are in line with the results of the bed sample survey and recent site visit were above MSL-7 m mostly bare sand was found.

The marine park is home to various species that use the Statia National Marine Park as home, migratory stop, or breeding site. In this study, only the animals that live around Oranjestad Bay or make use of the project domain are mentioned because an environmental assessment is out of the study scope. According to the webpage of STENAPA, a critically endangered animal is the Lesser Antillean Iguana. This is a rarely found specie in the world. In St. Eustatius, the Iguana can be found all around the island. One of the favourite habitats is open space with rocky outcrops. Secondly, all Caribbean turtles are present on the island, which are Hawksbills, Green turtles, Leatherbacks and Loggerhead. The most common species that are found in the marine park are the Green turtle and the Hawksbill turtle. The turtles use the island beaches for nesting grounds. At Oranjestad Bay, mostly the Hawksbill turtle utilises the beach at Scubaqua dive centre as a nesting site. It is expected that the Hawksbill turtle prefers this beach because of the high crest height and the accessibility from the water to land.

Next, the nurse shark is regularly seen in the reefs of St. Eustatius and close to Crooks Castle, south of the harbour. The shark lives close to sandy and rocky bottoms. Furthermore, various birds benefit from the island as a breeding site or stopover, among others Frigate Birds, Red Billed Tropicbirds, Brown Pelicans and Audubon's Shearwater. No specific information is found on the preferred location of the birds on the island. Also, the sea bottom is home to mobile and sessile animals such as brittle stars and sea cucumbers, octopods and sponges.

The Marine Environment Ordinance delineates all relevant legislation, rules, and guidelines within the marine park (Statia Government, 2022). Other policies and legislation guidelines are listed at https://dcnanature.org/bes-policy-legislation/st-eustatius/.

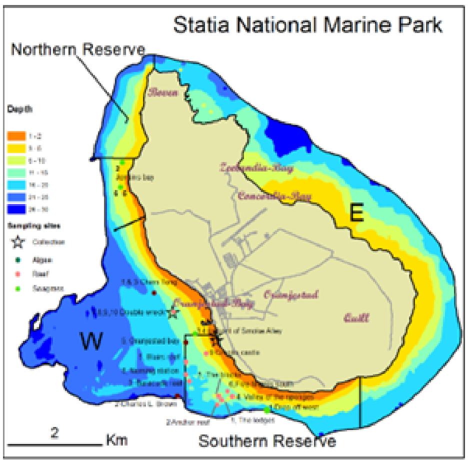



**Figure 2.14:** A map of St.Eustatius National park

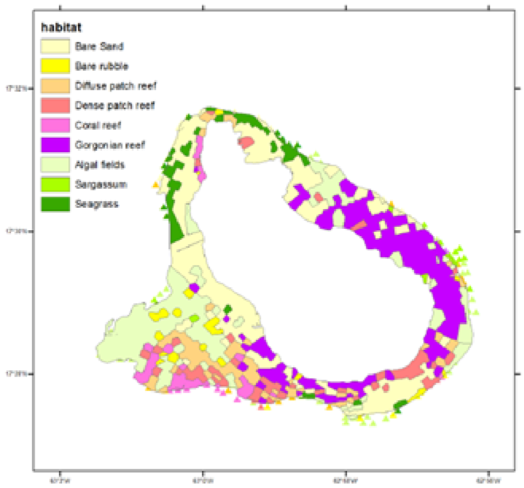



**Figure 2.15:** Habitat map by Debrot et al. (2014)

## 2.6. Stakeholders

To obtain a better understanding of the system in which a project is carried out, it is important to acquire knowledge on the social-economic system (Van Eekelen & Bouw, 2020). In this section, a brief stakeholder analysis is performed, where the main stakeholders and their interest are listed (in random order) and described. The findings are used in Chapter 5 to clarify the demands for a coastal solution in Oranjestad Bay. An extensive stakeholder analysis is out of the scope of the research. Therefore, this list provides only a first indication of the main stakeholder and their interest.

1. *Public Entity of Saint Eustatius*
   The government of St. Eustatius is a representative of the island. It is their task to adopt budgets, policies and regulations. The assignment to design a suitable solution for the coast of Oranjestad Bay is commissioned by the Public Entity of St. Eustatius. Additionally, they finance the project. As the client, the Public Entity of St. Eustatius has a high interest in the project. One of the main interests is the cost and benefits of the project.

2. *Environmental Organizations*
   The purpose of environmental organizations is often to conserve, restore and manage environmental related issues like the protection of endangered wildlife. On St. Eustatius, the local nature organization is called St. Eustatius National Park Foundation, also known as STENAPA. The organization is a non-governmental, not-for-profit foundation. STENAPA manages the protected areas such as St. Eustatius National Marine Park, The Quil and Boven National Park and Miriam C. Schmidt Botanical Garden. The project is of value for STENAPA since the project site is located inside the St. Eustatius Marine Park. Also, the project is of interest due to the nesting of turtles on St. Eustatius' beaches. The interest of STENAPA is the environmental impact and possible environmental benefit of the project.

3. *Hotel and restaurant owners*
   The project site is located on the bustling main road of St. Eustatius. Hotels and restaurants are stationed along this road such as Barrel house and The Old Gin House. A beach location is among others an attractive destination for tourists, which can use the restaurants and hotels for leisure activities. Therefore, the hotel and restaurant owners share an interest in the project as these parties will directly be affected by a beach at Oranjestad Bay.

4. *Scuba diving centre and Golden rock dive centre*
   Just like the hotel and restaurant owners, two dive centres are located at Oranjestad Bay. These centres offer people a dive experience on the island. A sandy beach is attractive for both dive centres as it simplifies the entrance to the water for diving. Also, the dive centres could benefit from the possible increase in the number of tourists due to the presence of a beach. The diving centres have an interest in the project because it may directly influence their business.

5. *Tourists*
   Each year around 1,000 tourists visit Sint Eustatius (Statia Government, 2022). They enjoy among others hiking, diving and the historical sights on the island. Nature is preserved and with that, the island promotes a form of eco-tourism. The tourists are a stakeholder in the project as they will be one of the users of the beach. The interest of the tourist will be the presence of a clean beach, that may be used for leisure activities.

6. *Research institutes*
   Caribbean Netherlands Science Institute (CNSI) is the research institute on St. Eustatius. It aids projects in all relevant expertise domains (marine and terrestrial; natural sciences, life sciences, social and economic sciences and humanities). CNSI may support the project with their local knowledge. On the other hand, the outcome of the executed research for the project may be of value to the institute. Therefore, a shared interest is present. However, since the institute is not directly affected, the interest is low.

7. *Inhabitants of St. Eustatius*
   The inhabitants of St. Eustatius use Oranjestad Bay for leisure activities like recreation or fishing. Due to the vital location of Oranjestad Bay, their interest is high. Additionally, based on the small scale of the island and the number of inhabitants, the people are likely involved. Therefore, inhabitants are an important stakeholder that needs to be considered.

8. *Harbour master*
   The harbour of the island is stationed at the southern boundary of the project site. The harbour is one of the economic lifelines for the island. Various types of ships such as cargo ships, tankers and pleasure crafts can moor in this area. The harbour master is responsible for a safe and available harbour. The harbour master's interest on the project is a minimal hindrance for harbour activities due to project.

9. *Fishery*
   Around twenty-five fishermen are active on the island. Since the assigning of the marine reserves the fishing in the northern and southern area of St. Eustatius is restricted by law. The main fish catch on the island is the spiny lobster (Panulirus argus). The fishermen are interested in the project as they are active in the project area. The fishermen's interest is the effect of the coastal solution on the fish and fishery.

10. *Archaeological organizations*
    Historical old warehouses can be found along the coastline of Oranjestad Bay. The ruins mark the important history of the island, which was once known as 'The golden rock'. A coastal solution for Oranjestad Bay may protect or affect the historical ruins. Therefore, archaeological organizations such as St. Eustatius Center for Archaeological Research (SECAR) have an interest in the project. SECAR's goal is to protect and develop knowledge of the historical resources. The interest of archaeological organizations is the effect of the coastal solution on the historical sites along the coastline.

# 3

# Modelling the existing situation

This chapter describes the setup of the numerical model and the model outcomes of this research. The modelling study is used to obtain a better understanding of the waves, currents and sediment patterns at Oranjestad Bay. First, the model setup is described in Section 3.1 and Section 3.2. In these sections, an elaboration is given on the model choice, model limitations and approach. In addition, the model input data is provided and the applied model settings are listed. In Section 3.3 the model outcomes are presented. In this section, the model is also validated and the outcomes are analysed. By the end of this chapter, a better understanding of the waves, currents and sediment patterns at Oranjestad Bay is acquired. Based on the findings in Chapter 3, Research Question 2 is answered, which states:

*To what extent can a numerical model simulate the coastal processes at Oranjestad Bay?*

## 3.1. Model methodology

### Model choice

A model choice is based on specifications, such as the purpose of the model, the time- and spatial scale and the model limitations. The model objective is to obtain a better understanding of the dominant processes that affect the morphology in Oranjestad Bay. Therefore, a 2-dimensional XBeach model and a Delft3D-4 model were considered in this study. Both models are capable of simulating the nearshore hydrodynamics and morphodynamic behaviour of a coastal zone so that a better understanding of the dominant nearshore processes is gathered.

Xbeach is initially developed as a storm-impact model. The time and spatial scale are minutes to hours and meters to kilometres. For a Delft3D-4 model, the timescales used are typically days to a decade and hundreds of meters to tens of km. The domain of the project location is approximately 1.5 km, which suits both model types. However, in this study, a period of one to multiple years was more suitable since the project location is characterized by a seasonal wave climate. To obtain more in-depth system knowledge, it is important to include these wave characteristics and the related sediment transport processes in the modelling study. Therefore, a Delft3D-4 model may be more optimal based on the time- and spatial-scale requirements.

Additionally, the model limitations are considered. A Delft3D-4 model is user-friendly and robust; however, it is not able to include infra-gravity waves in the simulation. An Xbeach model can consider infra-gravity waves. However, the Xbeach model has a large computational time as it requires a high spatial and temporal resolution. Due to time limitations, a high calculation time is undesirable. In addition, infra-gravity waves are of less value in this study area as the wave periods are mostly between 4 to 13 seconds.

Considering the purpose of the model, the time- and spatial scale and the model limitations, a 2-dimensional Delft3D-4 model was chosen for this modelling study. The more robust Delft3D-4 was selected in contrast to the newest version Delft3D Flexible Mesh. For the reason that some features of Delft3D FM are still under development, especially for morphology simulations.

## Model Limitations

Limited data and information were available for setting up and calibrating a numerical model for Oranjestad Bay. First of all because only short-term hydrodynamic data series were available. These data series were obtained by the measuring campaign from 2021 until 2022 and represent a relatively mild year. Secondly, there was no quantitative data on the morphological development in Oranjestad Bay. Also, the information on the availability of sand was lacking. This makes it difficult to validate a morphological simulation.

With the lack of detailed input data, the set-up of a highly detailed numerical model is less suitable for this modelling study. In this case, the complexity of the numerical model will lead to more uncertainties and inaccuracies. Consequently, a simplified modelling approach was chosen:

- A 2-dimensional Delft3D-4 model was set up. This means the flow and transport quantities were resolved in a depth-averaged way. This mode was considered appropriate because the study area is in the open sea and well-mixed.
- Tidal conditions were not considered. Having regard, to the tidal range of approximately +/- 0.3 m and tidal flow velocities < 0.30 m/s in the nearshore area (at approximately 8 m depth), this was acceptable.
- The influence of wind was not taken into account. Considering, the averaged wind velocities at the harbour < 6 m/s and the increasing complexity in the model by including wind characteristics.

Despite the simplified modelling approach, the model provided insight into the relevant nearshore coastal processes in Oranjestad Bay.

## Model approach

Delft3D-4 consist of several modules such as D-Flow, D-Wave and D-Water Quality, which can run independently or coupled. To provide insight into the coastal processes, a coupled Flow-Wave model was set up. This means the effect of flow on waves and waves on currents is considered in an online coupling of the D-Wave module with D-Flow module. The hydrodynamic numerical flow model solves the unsteady shallow water equations in 2D (depth-averaged) and 3D based on tidal and/or meteorological forcing at the boundary conditions (Deltares, 2022a). The numerical D-Wave model uses the Simulating WAves Nearshore model (SWAN) to compute the non-steady propagation of short-crested waves in coastal regions. The SWAN model is based on the spectral action balance equation (Deltares, 2022b). In this study, the following physics were included in the third-generation SWAN model: wave refraction, depth and current-induced shoaling, transmission and energy dissipation due to bottom friction, depth-induced wave breaking and white capping. Furthermore, no morphodynamic loop was carried out in this study. This implies the bathymetry is not updated as a result of the varying hydrodynamic conditions. The model structure is illustrated in Figure 3.1.

The coupled Flow-Wave model was built in the following steps:

- **Definition of the area of interest and the model domain:** The domain is based on the available data for the boundary conditions. Also, the computational time, resolution and accuracy are considered.
- **Model grid and bathymetry:** The grid is curvilinear and varies from coarse on the boundaries to refined near shore. Subsequently, the bathymetry is composed with the help of various resources and added to the grid.
- **Model boundary conditions:** Boundary conditions are defined by the offshore wave measurements from the WSO buoy. Therefore, time-varying wave boundary conditions drive the model.
- **Model validation and simulation:** The model is validated with the measured near-shore data obtained during the site visit from July to mid-October 2022. Then, the model is run for one morphological year, simulating the schematized waves every hour.
- **In-depth assessment of model results:** The model outcomes such as wave directions, depth-averaged velocities and sediment transport patterns are analysed based on expert judgement. The findings are used to acquire in-depth knowledge of the coastal system. In addition, the combined knowledge obtained from the literature study, site visit and model analysis serve as the basis for Research Question 3.

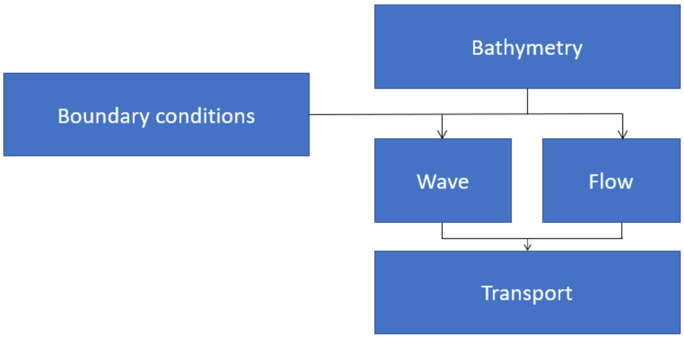



**Figure 3.1:** The modelling structure of the Delft3D-4 Flow-Wave model.

## Used data sources for the input file

*Bathymetric data*

For the bathymetry file, two data sources were used respectively, the bathymetry map of the Statia-SWAN wave study by Gautier (2021) and an estimated nearshore slope based on literature and the site visit in Chapter 2. By Gautier, bathymetry data extends to MSL -5 m. Additionally, a slope of 1:25 was estimated for the nearshore area. This estimation is based on the nearshore measurements by L. Harris showing an average slope of 1:20 to 1:30 between Smoke Alley and the vicinity of the harbour. Although in the area north of Smoke Alley no information is available on the nearshore area, the estimated slope was used along the entire shoreline. Furthermore, the dry beach, from the waterline landward, has an estimated slope of 1:8 based on expert judgement during the site visit in July 2022.

*Wave boundary conditions*

The Obscape wave buoy, ('WSO' Wave buoy Smoke Alley Offshore) located at 17.48 °N and 63.00 °W on approximately -13 m depth provided the wave data for the boundary conditions (See Figure 2.5). The buoy uses multiple motion sensors and an electronic compass to collect offshore wave data. The half-hourly observations are available online via the Obscape web page (https://obscape.com/portal/login) and include a set of bulk parameters such as the significant wave height, peak wave period and the mean wave direction. The wave parameters were calculated over a frequency range of 0.05 to 1.0 Hz. Figure 3.2 presents the wave buoy data applied in the input model.

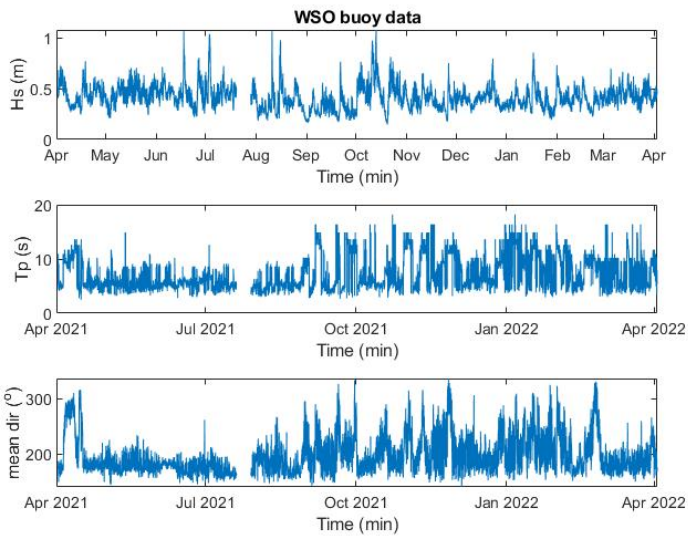



**Figure 3.2:** Wave data from WSO wave buoy downloaded from: https://obscape.com/portal/login (username:userstatia)

*Data for model validation*
An RBR pressure sensor with a 2 Hz sampling rate was installed during storm Fiona to provide validation data for the Flow-Wave model. The sensor was connected to an old pillar at Scubaqua beach in a water depth of approximately 1.6 m. The measurement period date from 15 September 2022 at 15:00 until 23 September 2022 at 00:00.

From the local pressure observations, a 1D energy spectrum is derived by a Fast Fourier Transformation. The wave parameters are determined from the spectrum such as the significant wave height and the peak wave period. It is not possible to derive the wave direction from the pressure sensor observations. In Figure 3.4 the observed wave parameters during storm Fiona are presented.

To validate the model outcomes, the nearshore wave data from the RBR pressure sensor is compared with the nearshore model outcome in the same area. Figure 3.3 demonstrates the locations of both points. The time series of the WSO wave buoy during storm Fiona is the input wave data for the model. Since the wave directions observed by the wave buoy are incorrect, an estimated wave direction is defined based on the neighbouring Spotter buoy. In Appendix C, an elaborated explanation is given for the defined wave direction. Figure 3.5 shows the wave data for storm Fiona, which serve as the input data for the Delft3D-4 model.

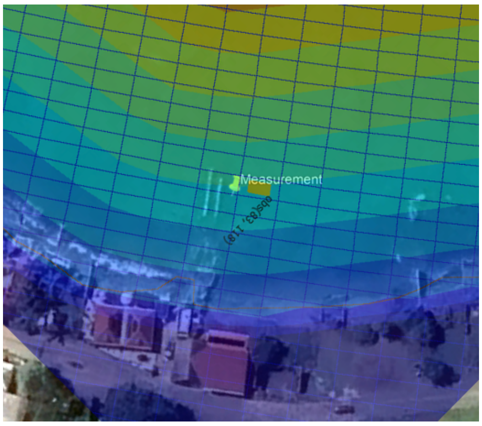
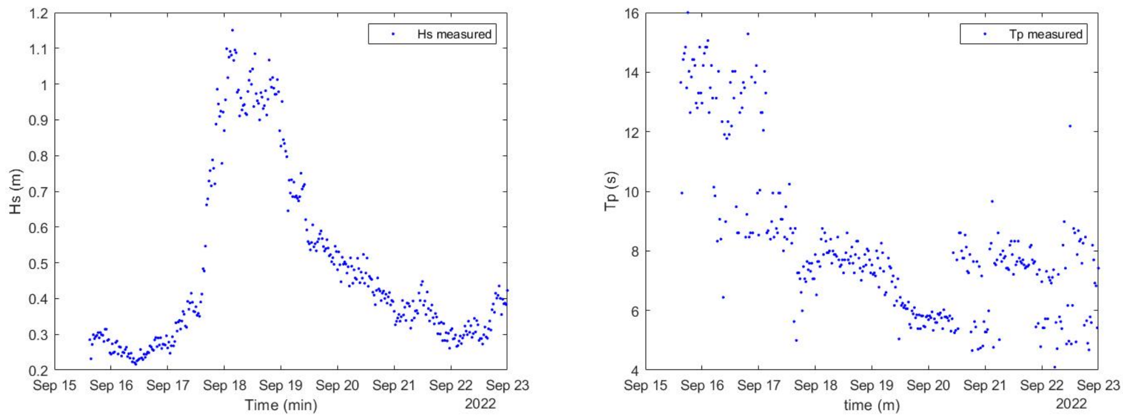



**Figure 3.3:** Location of the pressure sensor in Google Earth (yellow pin) covered by the Delft3D-4 model output in QUICKINN grid (orange square).




**(a)** Measured significant wave height

**(b)** Measured Peak wave period

**Figure 3.4:** Wave parameters of the location nearshore obtained by the RBR pressure sensor.

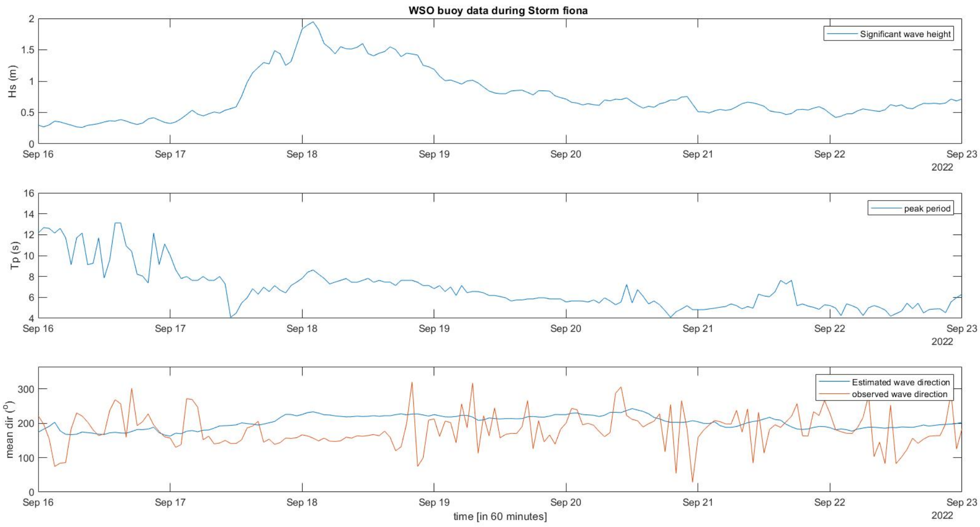



**Figure 3.5:** WSO wave input data during storm Fiona.

# 3.2. Setup of the input file

This section elaborates on the setup of the input file. The following elements are described: the computational grid, the bathymetry and the boundary conditions. Also, applied model settings are listed.

## Computational grid

Two curvilinear grids were considered in the Flow-Wave model, a wave grid and a flow grid respectively. Both models have the largest grid cells located near the edge of the model domain, which has a resolution of 20 m by 10 m (M, N direction). The smallest grid cells are located at the coastline and have a resolution of 5 m by 10 m. The flow grid is a smaller version of the wave grid. This means the number of nodes differs but the resolution is the same. The wave grid has 116 by 262 nodes, while the flow grid consists of 115 by 209 nodes. The morphological simulation is performed on the flow grid. Since the morphodynamics takes place at the nearshore of Oranjestad Bay and the computational time of the model is reduced with a smaller grid, the flow grid is chosen smaller than the wave grid. Figure 3.6 shows the computational grids, where the flow grid is highlighted in blue and the wave grid is projected in grey. The coastline of Oranjestad Bay is presented in red.

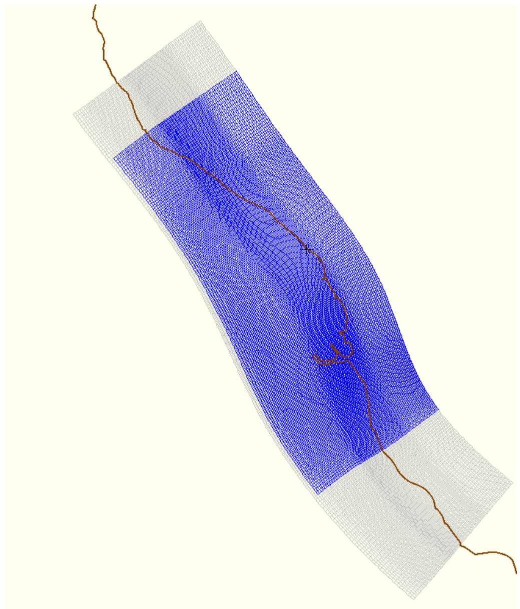


**Figure 3.6:** Wave (grey) and Flow (blue) grid computed with RGFGRID grid generator of Delft3D-4.

## Bathymetry

The bathymetry data is composed of the schematized bathymetry by Gautier and Doeleman (2022) and an assumed nearshore slope of 1:25 as described in Section 3.1. A grid cell averaging approach is imposed on the bathymetry data by Gautier, because this data was of high resolution. In contrary to the nearshore data where a triangular interpolation was used. Lastly, from the coastline inland, a slope of 1:8 is estimated and the harbour site is assumed at an equal height as the land. Figure 3.7 presents the bathymetry file on the flow grid.

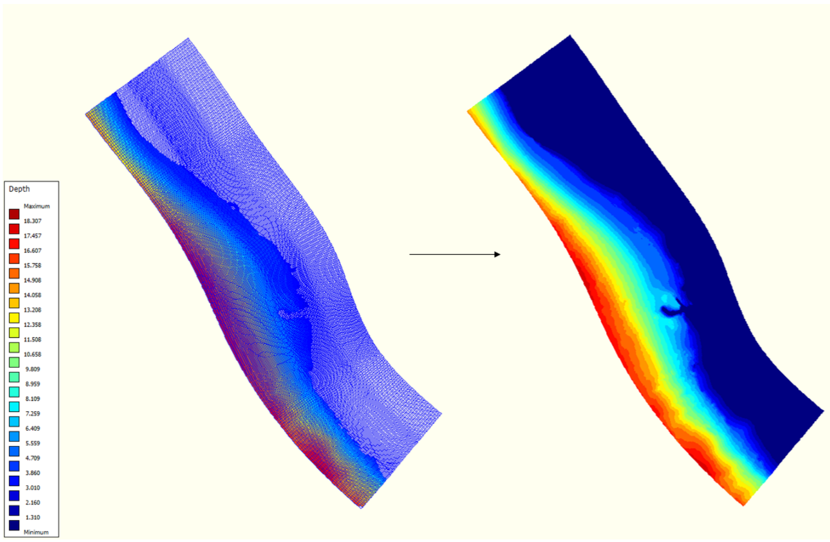



**Figure 3.7:** The composition of the bathymetry file on the flow grid using QUICKIN.

## Boundary conditions

### Wave climate

A schematized wave climate is imposed on the boundary conditions of the D-Wave model because simulating a full year of half-hourly wave data in the model would be too time-consuming. The schematized wave climate is based on a balance between the computational time and a complete representation of the occurring wave conditions. To account for the seasonal wave characteristics and the rapid beach fluctuations, a daily averaged wave climate is applied in this study. Consequently, the half-hourly wave data is schematized in 365 (daily mean) conditions. For the significant wave height, a weighted average is considered based on the CERC formula. In this way, the relation between the total longshore sediment transport and the wave height, respectively $S \propto H^{2.5}$, is included. For the peak period and the mean wave direction, the daily average was derived. Furthermore, it is noted that for the period from 19 July 2021 until 28 July 2021 no wave data was present (See figure 3.2). Therefore, a linear interpolation with a 30-minute time step is assumed to complete the schematized wave climate. In Figure 3.8 the result of the schematized wave climate is shown. The red dots are the daily averaged wave conditions. In the figure, also, the interpolation is visible.

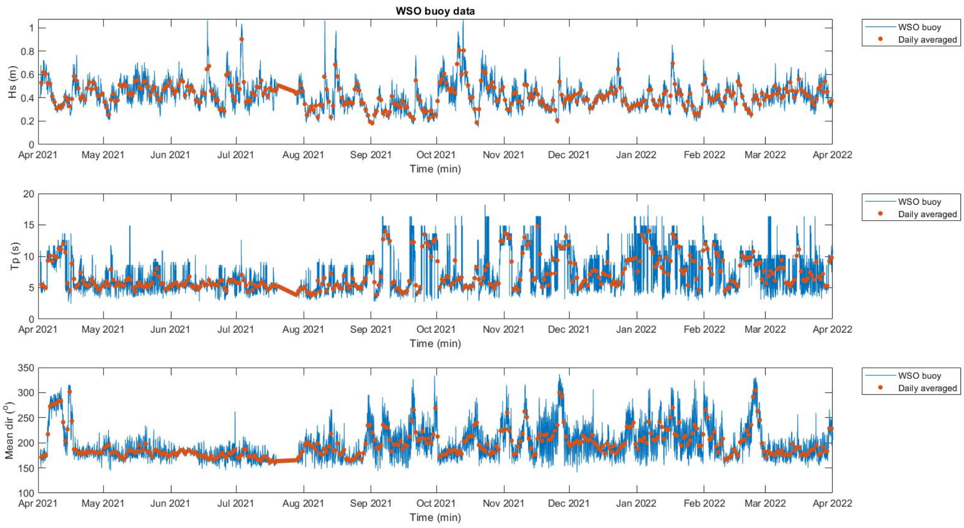



**Figure 3.8:** The half-hourly 'WSO' wave buoy data (in blue) and daily averaged wave climate (in red dots).

### Wind and Wave boundary conditions

The schematized wave conditions are imposed on the north, west and southern boundary of the Flow and Wave model domain. The input parameters are the significant wave height, the peak period and the mean wave direction. The wave directional spreading is uniformly set with a value of 24.9°. Furthermore, the standard JONSWAP spectral shape transforms these wave parameters into wave spectra.

For simplicity, no time-varying water levels or currents are input into the model. This is considered appropriate since Oranjestad Bay has a wave dominant character and the water level variations are limited as indicated in Chapter 2. In addition, limited data on the tide was available. Also, no wind input is provided, because on average, the wind speed at the harbour is relatively low (Uspeed < 6 m/s). Moreover, the inclusion of wind characteristics in the model would increase the model's complexity. For these reasons, wind is not included in the model. The influence of the wind and tide may be considered in a more extended version of this Flow Wave model.

### Sediment conditions

Next to the wave and flow characteristics, sediment transport is included in the Flow Wave model. A sand layer is assumed with a median grain size equal to 300 μm according to de Vroeg (2022a). The sediment thickness layer is estimated on 20 m. It is likely that this is an overestimation, however, information on the actual sediment thickness in the area was lacking. This means the model is simulating the sediment transport capacity rather than the actual sediment transport because no limitation on the sediment is considered. The specific density is 2650 kg/m$^3$ and the dry bed density is 1600 kg/m$^3$, which are default values for sand characteristics. Furthermore, an equilibrium sand concentration profile is applied on the north, west and southern boundary, the inflow boundaries.

The morphological acceleration factor is set to 24. Meaning, the model runs one morphological year, simulating the schematized waves every hour (See **Wind and Wave boundary conditions**). It is noted that for the validation, the morphological acceleration factor is equal to 1 and hourly wave data from Section 3.5 is imposed on the model boundaries.

For sediment transport, Van Rijn (2007) method is followed. This approach distinguishes sediment transport below the reference height as bed load transport, and above the reference height as suspended load.

## Applied model settings

The Flow Wave model contains mostly default settings, among others, because validation is limited. The applied model settings are listed here.

- The SWAN version is the third generation SWAN model version 41.20A.7.
- The time step in the Flow model is 0.1 minutes.
- The frequency domain is from 0.025 to 1.6 Hz to account for both wind and swell waves. Furthermore, the wave buoy has a domain of 0.05 to 1 Hz. In the model, the minimum and maximum frequencies are typically 0.6 times the value of the lowest peak and 2 to 3 times the value of the highest peak (Deltares, 2022b). Therefore, the frequency domain of the model is chosen larger than the wave buoy frequency domain. In the model, the domain is divided into 45 frequency bins.
- The Flow Wave model accounts for the full circle, meaning all 360 directions. The directions are split into 72 directional bins so that the directional resolution is 5°.
- The water density is set at 1025 kg/m$^3$.
- SWAN is run with physics, including bed friction according to JONSWAP, (bed coefficient is 0.067 m$^2$/s$^3$) and wave breaking (Battjes-Jansen, $\gamma$ = 0.73). Also, white capping is considered by Komen et all. (1984) using default settings (Deltares, 2022b). Wind growth as well as Quadruplet non-linear interactions are not included.
- The bottom roughness is computed according to Chézy, with a default uniform value equal to 65 m$^{1/2}$/s for both U and V directions.
- The horizontal eddy viscosity is set to 0.3 m$^2$/s and the eddy diffusivity to 0.1 m$^2$/s. The values are related to the flow and grid size used in the Flow Wave model. In addition, in D-Flow it is assumed that the horizontal eddy viscosity is typically larger than the eddy diffusivity (Deltares, 2022a).

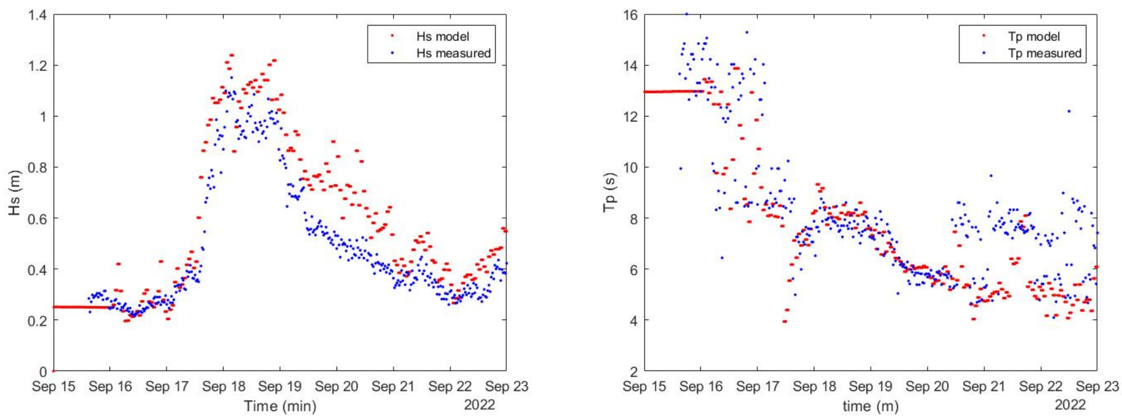
## 3.3. Model results

The model performance is evaluated based on general outcomes such as computational time and accuracy. Additionally, the outcomes are validated with the measured data during storm Fiona. After that, the results are presented and an analysis of the outcomes is provided.

### 3.3.1. Model validation

The computational time for one morphological year is approximately 10 hours and 30 minutes. This is an acceptable time for model simulations in this study. Additionally, in the SWAN wave model, enough accuracy is met in each time step to reach the solution (the convergence criteria).

Next, to validate the Delft3D-4 model, the model results are compared to the nearshore wave observations during storm Fiona. The location and the settings of the measurements are described in section 3.1. Although the validation is limited to one location nearshore during a short period, the comparison gives an indication of the model predictions. Figure 3.9 presents the model outcome and observed data in the vicinity of Scubaqua beach. The outcomes are obtained at approximately 1.6 m depth. In general, the wave model captures the significant wave height and the peak wave period quite well. Furthermore, it seems that at the peak of the storm the model outcome reaches the maximum breaking wave height. Based on the solitary wave theory, this wave height is still reasonable, with a wave breaking parameter, $\gamma$, set to 0.73 (Bosboom & Stive, 2015).




**(a)** Time series of the significant wave height.

**(b)** Time series of the peak wave period.

**Figure 3.9:** Time series during Storm Fiona 2022 at a location nearshore Scubaqua beach. The data obtained by the RBR pressure sensor is presented in blue and the model result in red.

### 3.3.2. Overview of the model results

The model outcomes are stored hourly, which leads to an abundance of results. Therefore, a selection of the most relevant model outcomes is shown in this section. Figure 3.12, 3.13 and 3.14 shows the simulated waves, currents and sediment transports for 3 representative conditions (sea waves, swell waves and storm waves). Based on the figures, the model results are analysed.

*Wave characteristics*

It is noted in Figure 3.8 that the wave climate of Oranjestad Bay may be characterized by mainly three types of wave conditions. These are respectively, a sea condition, a storm condition and a swell condition. The sea condition is most dominantly present. It is characterized by a significant wave height of approximately 0.4 m and a peak period of 5 s. The storm and swell conditions are related to a specific period in the year. The storm condition is associated with the Atlantic hurricane season from approximately June until November, while the swell condition appertains to the months from September until mid-April. The storm condition is expressed by a higher significant wave height (Hs > 0.8 m) and a short wave period. The swell condition is characterized by a higher peak wave period, generally between 10 to 16 s. Furthermore, it can be seen that the swell condition has a more South-West to Western direction. Additionally, the occurrence of the sea and storm condition is approximately 80% of the time, while the swell condition occurs only 20% of the time. This is shown in the Joint Occurrence Table in

Figure 3.10.

The schematized daily wave climate for the WSO wave buoy accompanied by the sea, storm and swell conditions is presented in Figure 3.11. The swell condition is highlighted in dark teal and the storm condition in orange. The remaining data points are characterised by the sea condition. Furthermore, for each wave condition, one moment in time is presented with a dashed line. The information of the dashed line is also given in Table 3.1. The model outcomes for each representable condition in Table 3.1 are shown in Figure 3.12, 3.13 and 3.14.

Joint Occurence Table, 2021-2022 WSO — $H_{m0}$ (m) ↑, Dir (°N) →

| $H_{m0}$ (m) | 360-90 | 90-120 | 120-150 | 150-180 | 180-210 | 210-240 | 240-270 | 270-300 | 300-330 | 330-360 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| >0.9 | | | | 0.14 | 0.27 | 0.02 | | | | | 0.43 |
| 0.8-0.9 | | | | 0.29 | 0.13 | 0.01 | | 0.01 | 0.01 | | 0.44 |
| 0.7-0.8 | | | | 0.46 | 0.36 | 0.13 | 0.02 | 0.07 | 0.02 | | 1.06 |
| 0.6-0.7 | | | 0.01 | 1.71 | 1.50 | 0.30 | 0.23 | 0.18 | 0.07 | 0.01 | 4.00 |
| 0.5-0.6 | | | 0.02 | 7.46 | 5.13 | 0.83 | 0.61 | 0.50 | 0.21 | 0.01 | 14.75 |
| 0.4-0.5 | | | 0.08 | 16.17 | 11.09 | 2.98 | 0.88 | 0.63 | 0.28 | | 32.10 |
| 0.3-0.4 | | | 0.05 | 10.80 | 11.81 | 6.36 | 2.46 | 1.36 | 0.41 | 0.01 | 33.27 |
| 0.2-0.3 | | | 0.01 | 1.60 | 4.08 | 3.67 | 2.39 | 0.78 | 0.22 | 0.01 | 12.75 |
| 0.1-0.2 | | | | 0.01 | 0.34 | 0.35 | 0.38 | 0.09 | 0.05 | | 1.21 |
| 0.0-0.1 | | | | | | | | | | | |
| Total | | | 0.17 | 38.64 | 34.70 | 14.64 | 6.96 | 3.60 | 1.25 | 0.03 | 100.00 |

Joint Occurence Table, 2021-2022 WSO — Tp (s) ↑, Dir (°N) →

| Tp (s) | 360-90 | 90-120 | 120-150 | 150-180 | 180-210 | 210-240 | 240-270 | 270-300 | 300-330 | 330-360 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| >16.0 | | | | 0.15 | 0.26 | 0.11 | 0.07 | 0.01 | | | 0.60 |
| 14.0-16.0 | | | | 0.31 | 0.50 | 0.47 | 0.40 | 0.16 | 0.06 | | 1.90 |
| 12.0-14.0 | | | | 0.59 | 1.66 | 2.45 | 1.30 | 0.46 | 0.24 | | 6.70 |
| 10.0-12.0 | | | | 1.01 | 2.83 | 2.42 | 1.97 | 1.69 | 0.44 | 0.02 | 10.38 |
| 8.0-10.0 | | | 0.01 | 2.89 | 4.39 | 3.00 | 1.96 | 1.05 | 0.19 | | 13.48 |
| 6.0-8.0 | | | 0.01 | 5.77 | 5.01 | 1.55 | 0.47 | 0.09 | 0.10 | 0.01 | 13.01 |
| 4.0-6.0 | | | 0.07 | 24.94 | 17.52 | 4.19 | 0.72 | 0.13 | 0.11 | | 47.69 |
| 2.0-4.0 | | | 0.09 | 2.99 | 2.54 | 0.45 | 0.07 | 0.01 | 0.10 | 0.01 | 6.25 |
| 0.0-2.0 | | | | | | | | | | | |
| Total | | | 0.17 | 38.64 | 34.70 | 14.64 | 6.96 | 3.60 | 1.25 | 0.03 | 100.00 |

**Figure 3.10:** The Joint Occurency Table [%] for location WSO, based on the half-hourly wave buoy data from April 2021-2022.

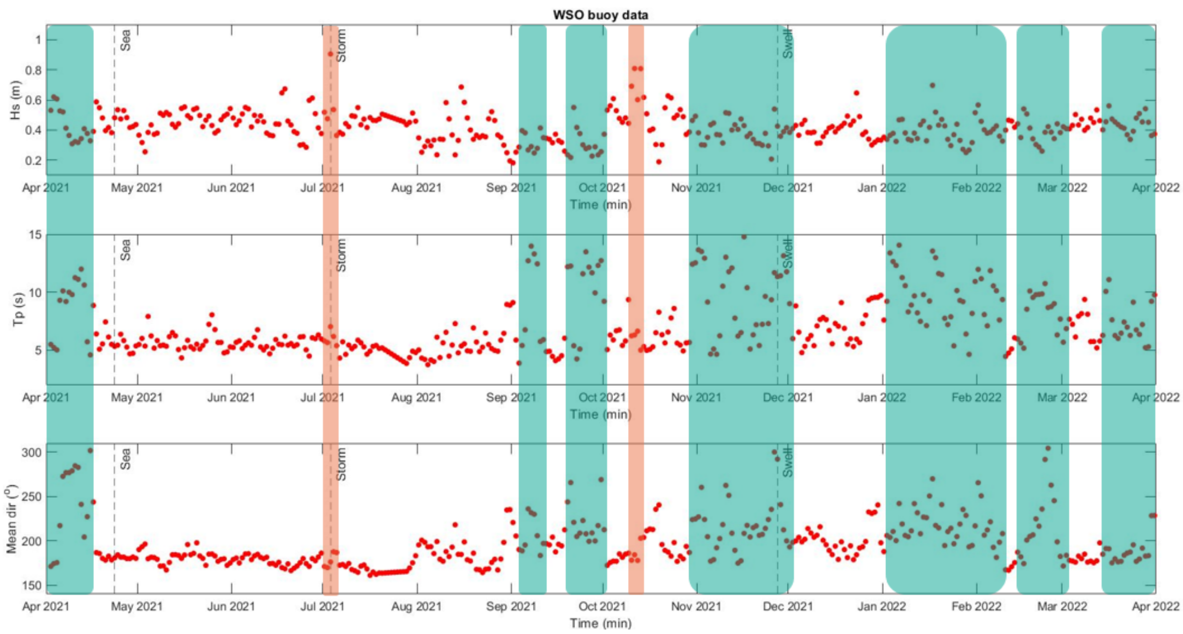



**Figure 3.11:** The daily wave climate as input for the Delft3D-4 model year simulation is presented in red dots. The swell wave condition is highlighted in dark teal and the storm condition is in orange. The remaining data points are characterised by the sea condition.

| Condition | Date | Significant wave height [in m] | Peak wave period [in s] | Mean wave direction [in °N] |
|---|---|---|---|---|
| Sea | 23/4/2021 | 0.48 | 5.3 | 181 |
| Storm | 03/7/2021 | 0.90 | 7.0 | 176 |
| Swell | 27/11/2021 | 0.43 | 11.4 | 292 |

**Table 3.1:** Data for each wave condition based on the dashed line in Figure 3.11.

*Model outcomes for each representable condition*
For each representable condition, the hydrodynamic and morphodynamic characteristics are described based on the model outcomes presented in the figures below.

**Nearshore waves characteristics**
Figure 3.12 presents the significant wave height and the mean wave direction for the sea, storm and swell conditions. It can be seen from Figure 3.12a and 3.12b that there is a difference in significant wave height around the harbour. This is caused by the sheltered zone of the harbour for waves approaching the coast from a southern direction. The variation in wave height leads to set-up differences at the coastline. This also influences the current and sediment transport close to the harbour. In addition, Figure 3.12c illustrates that the wave direction for the swell condition is from Southwest to West, which is in contrast with the sea and storm mean wave direction. An impression of the seasonal wave climate at Oranjestad Bay can be noticed having regard to the different mean wave directions for the sea, storm and swell states.

**Currents characteristics**
The depth average velocity for the sea, storm and swell conditions are presented in Figure 3.13. In the figure, the velocity magnitude is highlighted from 0.2 m/s till 0.7 m/s. The velocity direction is illustrated in light gray.

Figure 3.13 shows that the velocities occur close to the shoreline. This relates to the waves that are breaking close to the shore. It is apparent from Figure 3.13a that the current velocity is minimal during most times of the year. The velocity at Oranjestad Bay increases slightly during the storm condition, but it is maximum for the swell state. Furthermore, the velocity at the boundaries is the highest for all three conditions. An explanation for the extremes at the boundaries could be that the characteristics at these locations are less well represented in the model. For example, a rocky coastline is present north of Smoke Alley, while south of the harbour coral colonies are situated. The lack of these characteristics in the model indicates that the higher velocities at the boundaries are likely overestimated. Another aspect could be that model inaccuracy is more sensitive at boundary locations. In Chapter 6, an elaboration on the model inaccuracies is given.

The current vectors illustrate a northward-directed flow for the sea and storm conditions. In the swell condition, the vectors are pointed in a southward direction. This can be explained by the breaking waves arriving at an angle. These (breaking) waves drive a northward-directed current in the sea and storm conditions. For the swell wave conditions, this leads to a southward-directed current.

**Sediment transport patterns**
Figure 3.14 provides the instantaneous sediment transport in $m^3/day$ for each condition. The transects perpendicular to the coast are located every 150 m and the transect parallel to the coast lies on a 5 m depth contour. In the figure, the red arrow indicates the direction of the sediment transport. The number relates to the capacity in $m^3/day$. It must be noted, that the arrows are not on scale. For the cross-shore transports, the values are negligible (plus or minus a nihil number). This means the direction is not related to the physics.

Figure 3.14a and 3.14b show that the sea and storm conditions cause sediment transport in a northward direction assuming enough sediment available. This is opposite to the swell condition, which drives southward-directed sediment transport. These transports are a logical response considering the wave and current patterns of each condition. Due to the occurrence of the sea, storm and swell states, a net northward sediment transport capacity is present at Oranjestad Bay. This can also be seen in Figure 3.16a, where the mean total transport in $m^3/yr$ is shown.

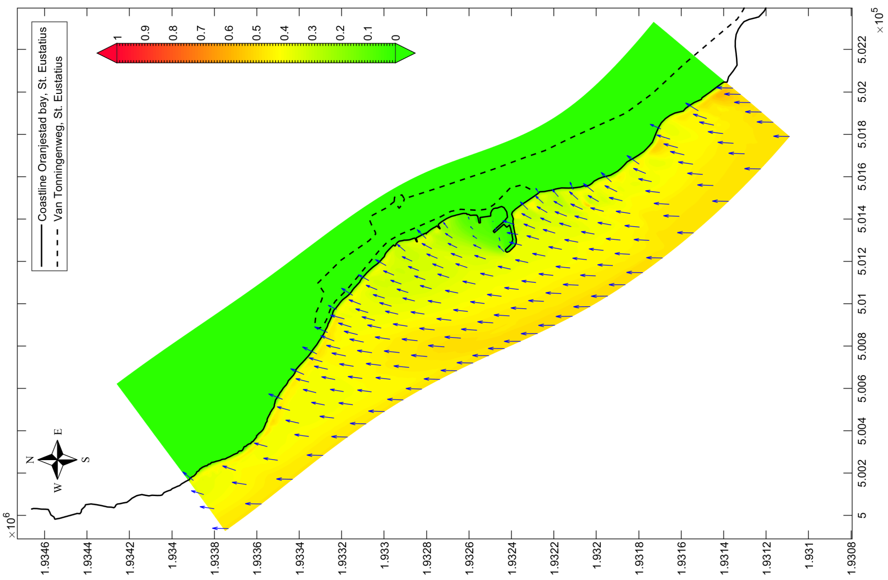
In addition, Figure 3.14 shows that sediment transport is increasing in a northward direction along the coast. The transport is minimum around the harbour and maximum north of Smoke Alley. This can be explained by the shadow zone of the harbour and the orientation of the coastline with the incoming wave angle. The shadow zone of the harbour leads to a decrease in significant wave height, which is causing a lower current velocity in this area and a lower mean sediment transport nearby the harbour.

The orientation of the coastline in relation to the incoming wave angle is also influencing the sediment transport rates (Bosboom & Stive, 2015). According to the so-called (S,$\varphi$)-curve (where the total longshore sediment transport is given as a function of the wave angle), a maximum of S occurs approximately at $\varphi$ = 45°. Since Oranjestad Bay is concave shaped with a shoreline orientation of 270 °N at the harbour and 210 °N at Smoke Alley, the sediment transport is minimum at the harbour and increasing northwards considering the mean incoming wave directions for each representable condition. The combination of the harbour obstacle and the orientation of the coastline may explain the increase in sediment transport in a northward direction.

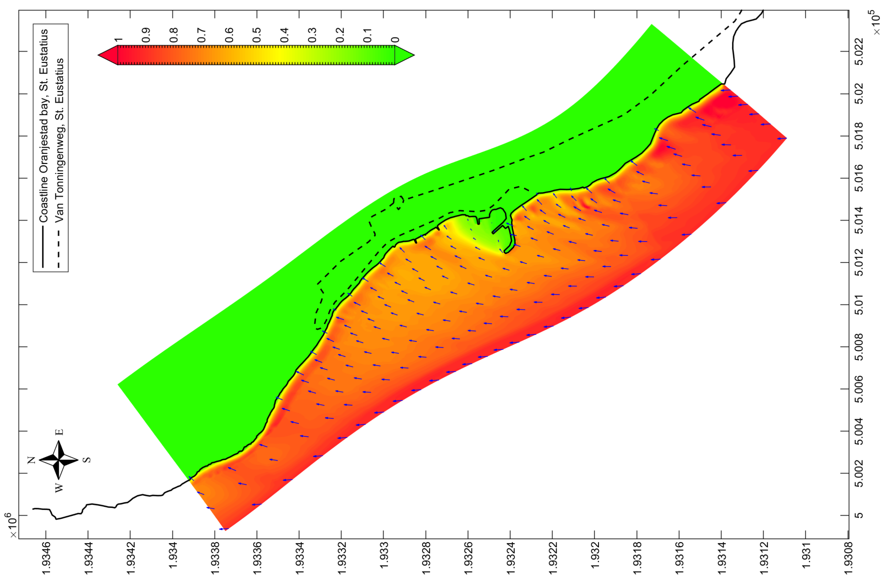
These model outcomes (the net northward transport capacity at Oranjestad Bay and the increasing transport in the northward direction) are in line with the UNIBEST-CL+ study by de Vroeg (2022b).

What is interesting about Figure 3.14b is that the sediment transport for the storm condition in longshore direction is fairly similar with the sea condition. A possible explanation for this might be the incoming wave direction, the low wave period and the limited current velocity of the storm. In general, the cross-shore component plays an important role during storms. However, Figure 3.14b shows for each condition, a negligible cross-shore transport. This might be due to fact that the coastal processes mainly take place close to the coastline, and the cross-shore transect is located at -5 m depth contour.

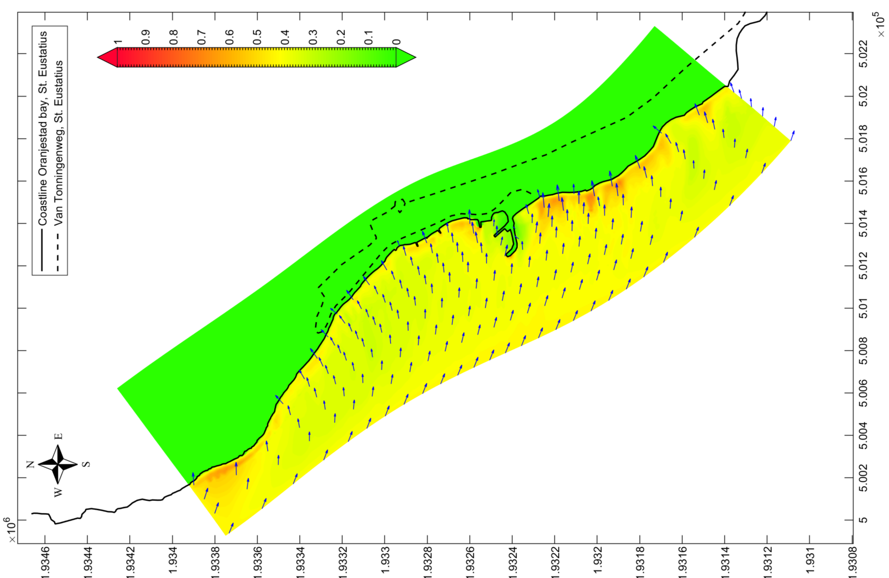
At last, due to the harbour obstacle, also diffraction takes place. However, this process is not considered in the Delft3D-4 model.




**(a)** Sea condition

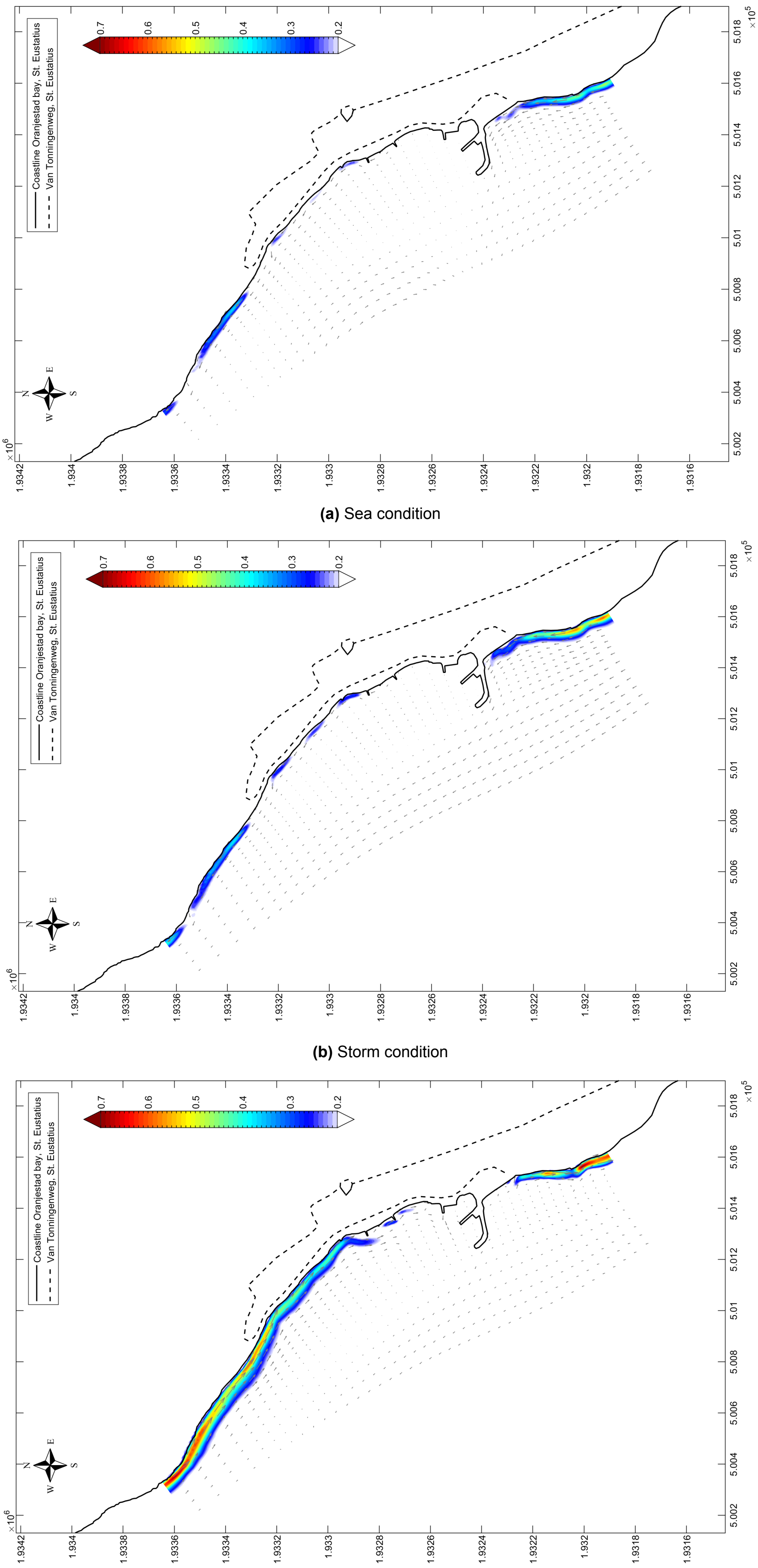



**(b)** Storm condition




**(c)** Swell condition

**Figure 3.12:** Significant wave height [m] and mean wave direction [$^\circ N$]

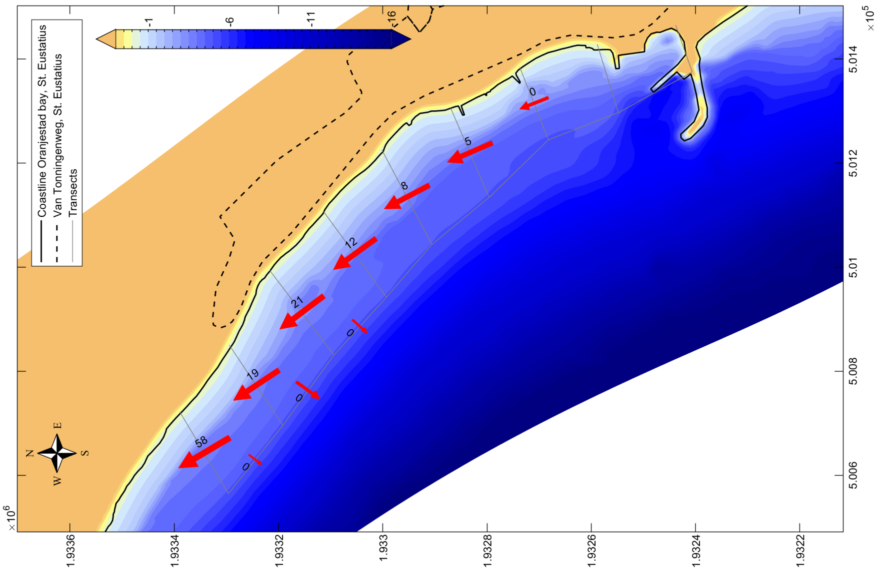



(a) Sea condition

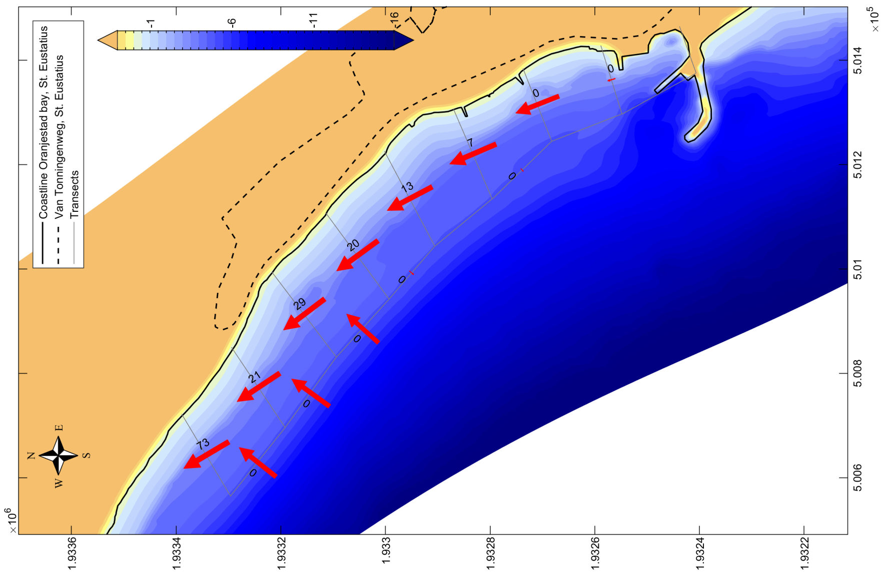
(b) Storm condition

(c) Swell condition

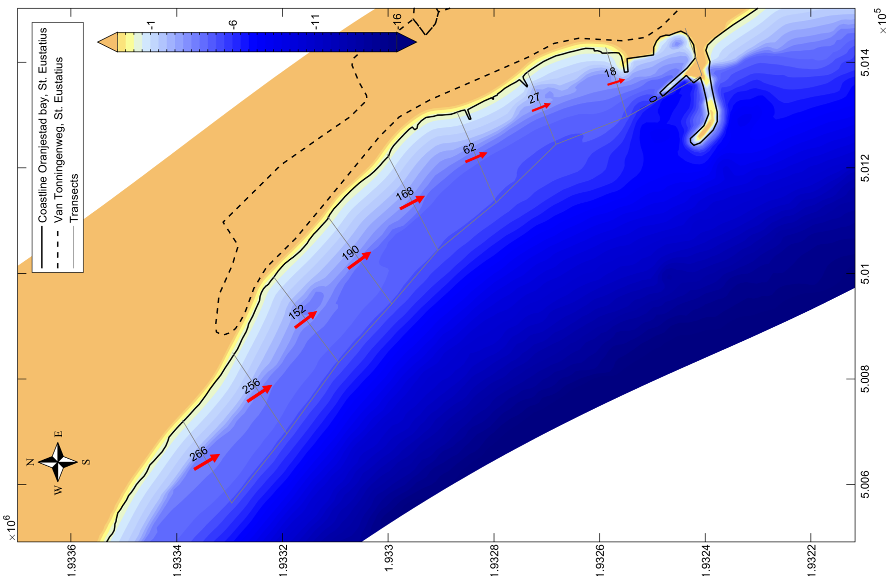
**Figure 3.13:** Depth average velocity [m/s]




**(a)** Sea condition




**(b)** Storm condition




**(c)** Swell condition

**Figure 3.14:** Instantaneous sediment transport [$m^3$/day]

**Sediment budgets for one morphological year**

Besides the instantaneous transport for each condition, the sediment budgets for one morphological year are presented in the following figures. Figure 3.15 illustrates the yearly total alongshore transport in northward and southward direction. Figure 3.16a shows the net total transport capacity in Oranjestad Bay. Additionally, the net total transport per season is presented in Figure 3.16b and 3.16c.

*Yearly sediment transport in northward and southward direction*

Figure 3.15 shows the total alongshore transport for the transects along Oranjestad Bay. Transect 1 relates to the harbour and transect 9 to the last transect north of Smoke Alley. Equal to the transects for sea, storm and swell condition in Figure 3.14. However, in Figure 3.15, the cross-shore transports are excluded since these are small in relation to longshore transport capacities. As transect 1 is located at the harbour, Figure 3.15 shows no transport on this location.

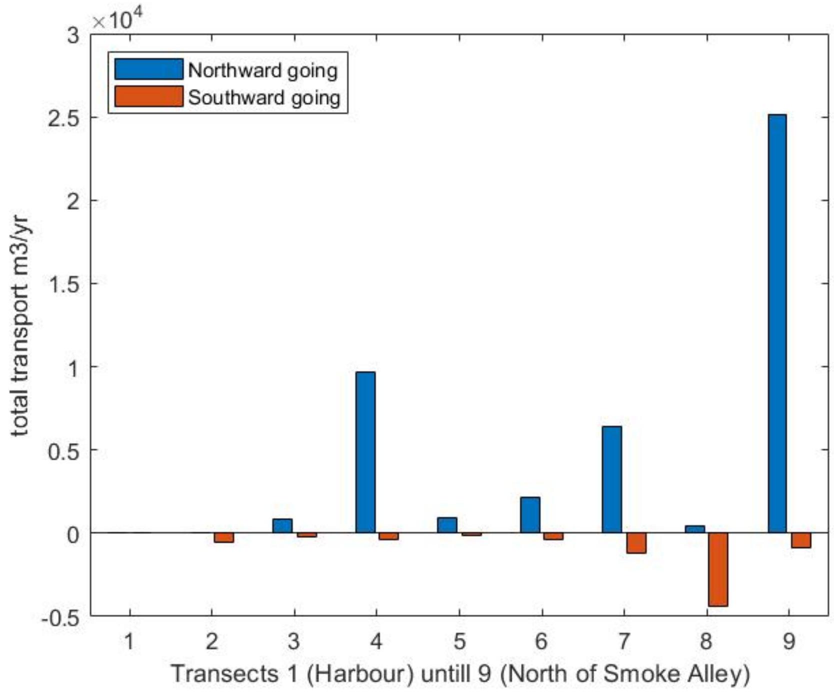



**Figure 3.15:** Alongshore yearly sediment transport in northward and southward direction (in m$^3$/year)

Figure 3.15 shows that mostly the northward going sediment transport is larger than the southward going transport. Two exceptions can be noticed. On transect 2, no northward transport is present. This can be explained by its location in the shelter zone of the harbour. Due to the lower wave heights in this area, the (wave-induced) current is directed in south-ward direction. This generates a southward going transport. Additionally, waves that are causing a northward transport are blocked by the harbour.

On transect 8, the northward going transport capacity is substantially lower than its neighbouring transects. This is contrary to expectations. It could be that model inaccuracies play a role here. Two model uncertainties can be considered. Firstly, the sensibility in the model for the location of the transect and its angle with the shoreline. Due to the transition in shoreline orientation around this transect, the sediment transports might be effected. Secondly, the characteristics north of Smoke Alley such as the slope and rocky coast are less well represented in the model. For this reason, more uncertainty in the model outcomes is expected at the boundaries. Therefore, the result on transect 8 must be interpreted with caution.

An overall increase in sediment transport from the harbour to Smoke Alley is also observed. This is inline with the instantaneous transports for the sea, storm and swell condition. Apart from transect 4, were a substantially larger northward sediment transport is found in comparison to each neighbouring transects. This can be caused by the lack of southward-directed transport during the swell season, which can be seen in Figure 3.16c. Due to the difference in coastline orientation at the location of transect 4, the influence of the swell waves are minimal. However, there is also a potential for model bias since the transects are not completely aligned with the shore-normal orientation. A more suitable result on transect 4 could be a sediment transport rate around 2500 $m^3$/yr based on the difference in seasonal variation between the various transects.

Lastly, the northward going transports at transect 9 is dis-proportionally larger than the other locations. It is important to bear in mind the possible bias of the sediment transport capacity at transect 9. As stated before, the characteristics of the area above Smoke Alley are not well represented in the model. Therefore, an overestimation of the sediment transport at this location is likely.

To conclude, an indication of the northward and southward going transport per year in Oranjestad Bay is provided in Figure 3.15. Overall, it is likely that the northward going transport is larger than the southward going transport. Some odd values are found for transects 4, 8 and 9. These are related to the varying orientation of the coastline and the sensitivity of the transect angles with the shore normal. Additionally, the northern part of the study area is less well represented in the model.

*Net total transport*
In Figure 3.16a the mean total transport capacity in $m^3$/year on transects along the coast is presented in longshore and cross-shore directions. Additionally, the mean total transport per season is displayed in Figure 3.16b and 3.16c.

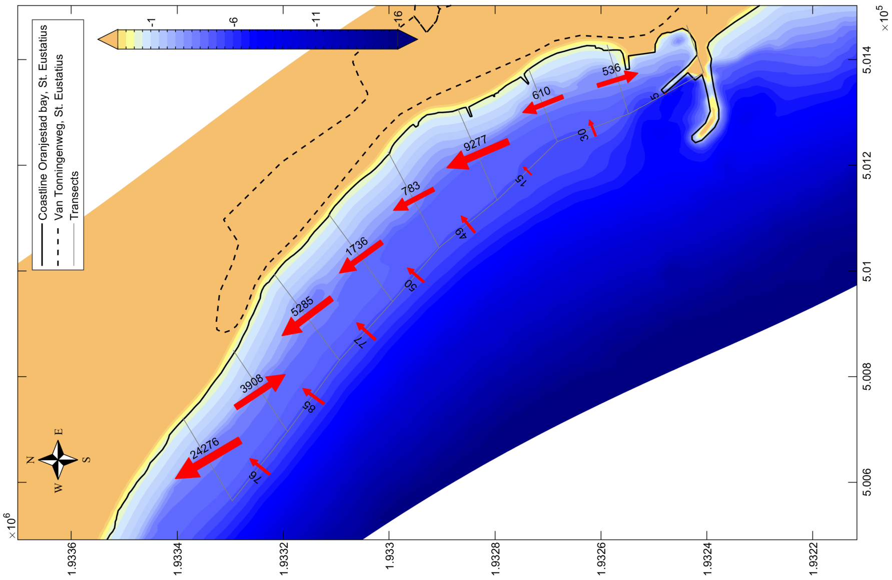
In general, Figure 3.16a shows an increase in longshore sediment transport capacity in a northward direction. Therefore, gradients in alongshore sediment transport are notable. An explanation for the increasing transport capacity is given in the description of the sediment transport patterns for sea, storm and swell conditions. Furthermore, what stands out in Figure 3.16a is the significant difference between the longshore and the cross-shore mean total transport capacity. This is generally the case as stated in Bosboom and Stive (2015).

On transects 4, 8 and 9 the results of the sediment transport rates are somewhat counterintuitive. This relates to the yearly sediment transport in northward and southward direction. An explanation for each transect is given here.

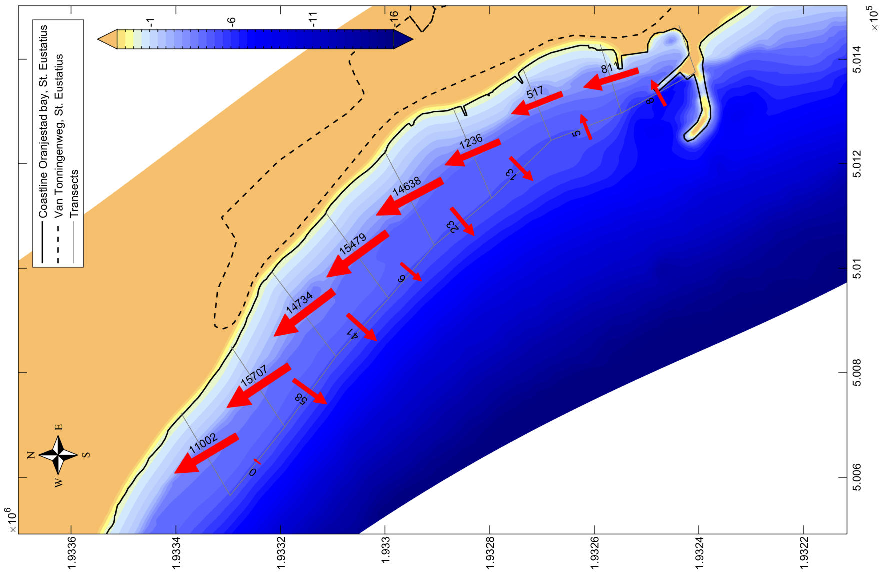
Moreover, the seasonal difference in total net sediment transport is clearly visible in Figures 3.16b and 3.16c. Figure 3.16b illustrates a dominant northward sediment transport from April to September. For September till April a southward directed sediment transport is shown in Figure 3.16c.

In the end, a net northward sediment transport capacity of approximately 24.000 $m^3/yr$ is present in Oranjestad Bay. This also accords with an earlier study by de Vroeg (2022b), which showed that a net northward transport capacity of 15.000 $m^3/yr$ is present assuming a sandy coastline. The difference between de Vroeg (2022b) and this study may be due to the difference in sediment transport formula. Bijker was used by de Vroeg (2022b) in comparison with Van Rijn 2007 used in this study. Also, the effect of sand redistribution in cross-shore direction is not taken into account by de Vroeg (2022b). Lastly, in this study an overestimation of the sediment transport capacity at transect 9 is likely. By taking every aspect into account, the total transport capacities may differ between de study by de Vroeg (2022b) and this research. Despite that, the underlying concept, which shows an net yearly northward transport is the same.

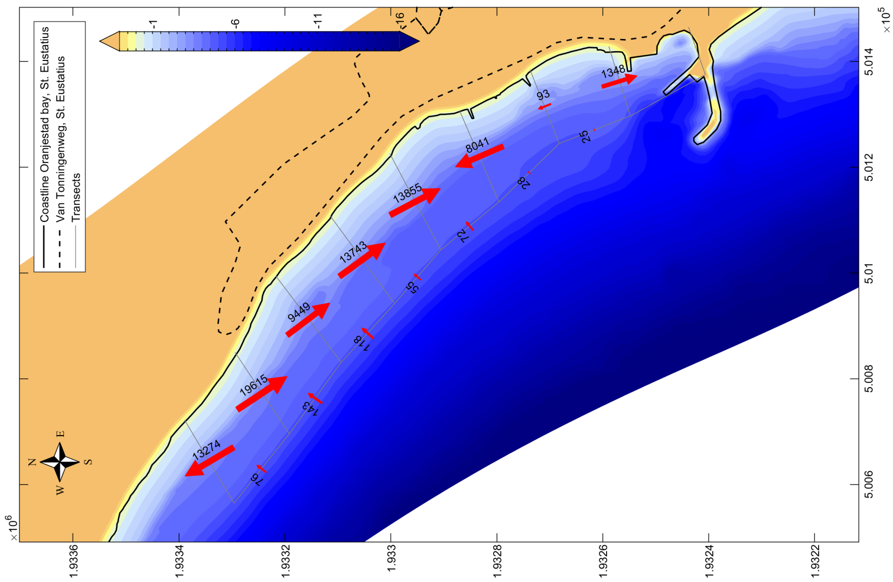
**Summarizing the model outcomes**
Together these results provide important insights into the nearshore coastal processes at Oranjestad Bay. The different wave characteristics highlight the seasonal wave climate at Oranjestad Bay. Moreover, the results in this chapter indicate that a net northward transport capacity is present as shown in Figure 3.16a. Both findings are in line with the expectations found in the literature study in Chapter 2. The next chapter, therefore, moves on to discuss the overall understanding of the coastal system at Oranjestad Bay based on the findings in Chapter 2 and 3.




**(a)** Mean total transport capacity for year simulation




**(b)** Mean total transport capacity from 15 April till September (sea season)




**(c)** Mean total transport capacity for September till April (swell season)

**Figure 3.16:** Mean total transport capacity in $m^3/year$.

# 4

# Presenting the conceptual model of the existing situation

In this chapter, a conceptual model describes the overall understanding of the coastal system based on the findings of Chapter 2 and 3. With the conceptual model, Step 1 of the BwN design cycle is completed. A distinction is made between the beach fluctuations during one morphological year and during a storm since the coastal morphodynamics differs between them. In the end, the findings of Chapter 4 answer Research Question 3:

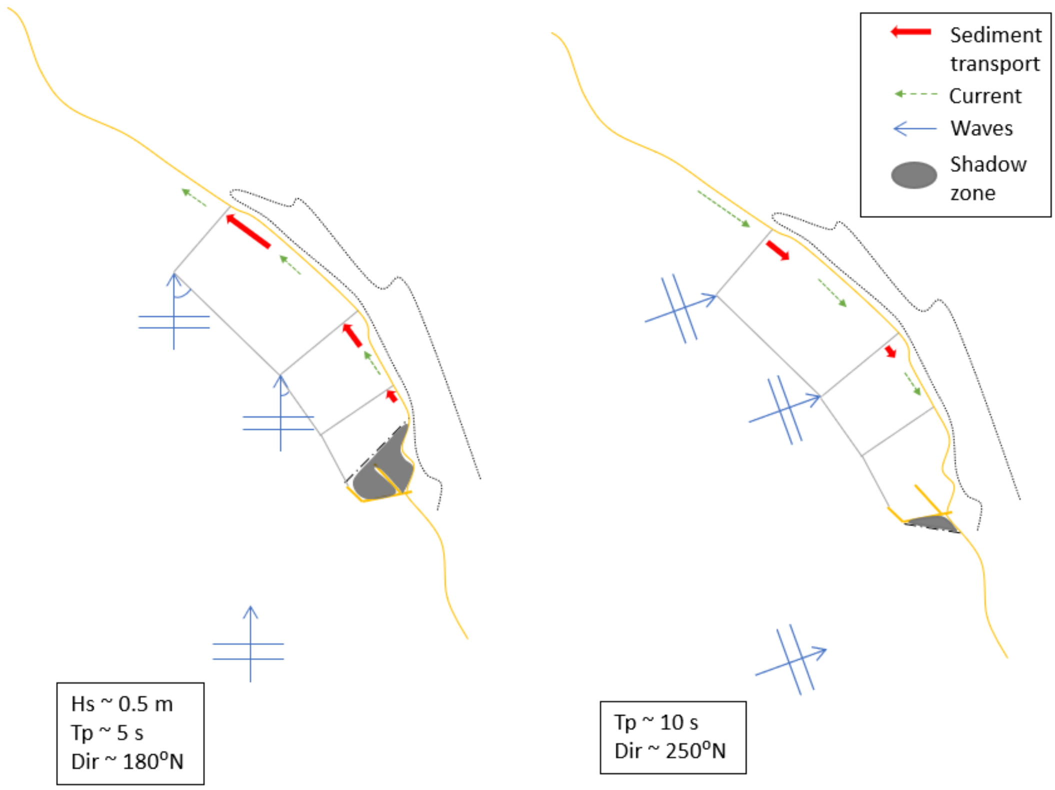
*Based on the system knowledge, what is causing the variation in beach fluctuations along the coastline of Oranjestad Bay?*

## 4.1. The coastal morphodynamics at Oranjestad Bay

From Chapter 2, it is seen that a fluctuating beach is present at Oranjestad Bay. Furthermore, the inhabitants mention that the widest beach is most often present in April. According to Bosboom and Stive (2015), coastal variations are caused by gradients in sediment transport rates along a coast. These changes occur among others due to variations in the angle of wave incident or the nearshore wave height. In Chapter 3, the model outcomes showed an increase in longshore sediment transport capacity in a northward direction. This confirms that the coast of Oranjestad Bay experiences (seasonal) gradients in alongshore sediment transport leading to coastal changes. It is noted that the coastline of Oranjestad Bay is relatively stable, as stated by Ruijter (2019) in Chapter 2. Hence, no structural coastal retreat is expected. The coastal changes refer to in this section are related to the sand layer which is located on top of the rocky shoreline. Furthermore, it is assumed that sediment is available in the coastal system. This means the sediment transport capacity is considered when describing the sediment transport patterns at Oranjestad Bay. In Section 4.1.1 attention is paid to the possible limitation of sediment availability in the coastal system.

The behaviour of the coastal changes at Oranjestad Bay are explained by a conceptual model shown in Figure 4.1. From April until September the dominant wave direction is from South-Southeast and most of the time a mild wave climate is present (Hs $\approx$ 0.5 m, Tp $\approx$ 5 s). In Figure 4.1a this is indicated with blue wave arrows. The low waves break close to the shore and cause a longshore current in a northward direction (green current arrows in Figure 4.1a). Neglecting the influence of wind and tide, the (wave-induced) longshore current drives a sediment transport capacity in the same direction. Considering the (S,$\varphi$)-curve, the transport capacity increases going north as shown by the filled red arrows in Figure 4.1a. No sediment is entering the coastal system, since the harbour is blocking any sediment transport from the south and no other sediment source is known. Additionally, cross-shore redistribution of sand can take place mostly due to storms from June to November. These processes together may cause a negative sediment balance in this period and the beaches at Oranjestad Bay are likely to erode.

Figure 4.1b shows the period from September to March, when waves periodically approach the coast from a Southwest to a Western direction. These waves tend to have a longer wave period, approximately between 10 and 15 s. The (swell) waves drive a longshore current in the southward direction, which is larger and in opposite direction than the first season. Furthermore, the (wave-induced) longshore current is responsible for a southward sediment transport capacity. Also during the swell season, the largest transport capacities are taking place in the northern part of the study area. Considering the sediment balance between the harbour and Smoke alley, the southward sediment transport serves as input into the coastal system. Therefore, it is likely that during the period from September until March, a temporary build-up of a beach is taking place.




**(a)** Season April to September

**(b)** Season September to March

**Figure 4.1:** Conceptual model of the seasonal variability at Oranjestad Bay

In addition to the seasonal sediment budgets, the yearly sediment budget is shown in Figure 4.2. For both sediment budgets, the sediment balance is assumed between Smoke Alley and the harbour. In Chapter 3 it was seen that the occurrence of sea and storm waves are dominant over swell waves. Therefore, it is expected that the northward transport capacity is larger than the southward transport capacity in the given area. Hence, on a yearly basis, a net northward transport capacity is present at Oranjestad Bay. This is corroborated by the model outcomes in Figure 3.16a, which present a net northward transport capacity of approximately 24.000 $m^3/yr$. In Figure 4.2 the net northward yearly transport is visible based on the seasonal sediment budgets.

Concluding, the coast of Oranjestad Bay may experience seasonal gradients in alongshore sediment transport leading to beach fluctuations. The seasonal reversal of the sediment transport capacity caused by the local wave climate provides an explanation for these beach fluctuations at Oranjestad Bay. It is observed that the beach is the widest in April. With the Atlantic hurricane season taking place from June to November and the temporary build-up of the beach during the period September to March, it is reasonable that the widest beach is often present in April. Lastly, considering the yearly sediment balance, it is expected that a net northward transport capacity is occurring at Oranjestad Bay.

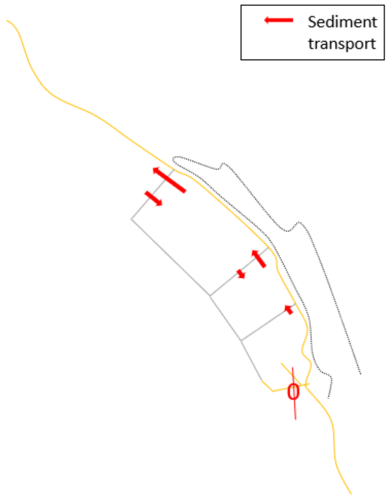



**Figure 4.2:** Illustration of the sediment budget for a morphological year at Oranjestad Bay.

### 4.1.1. Sediment availability at Oranjestad Bay

In Section 4.1 sediment availability is assumed to be guaranteed. However, the coastline of Oranjestad Bay consists of volcanic rock, ruins and pocket beaches as stated in Chapter 2. At locations where rocks and ruins are present, sediment availability will be limited. Therefore, the actual sediment transport is expected to be lower than the sediment transport capacity explained in Section 4.1. The smaller waves which break close to the shoreline may be most affected by the lack of sediment since these waves drive a sediment transport capacity close to the waterline (See Figure 2.11 in Chapter 2). Furthermore, the beach at Scubaqua may encounter beneficial effects compared to other locations along the coast. This is due to its position between hard elements (the old pier and a harbour dock ruin) and the bay shape of the coastline. For this reason, the beach is more enclosed than other locations along the coast. Figure 4.3 gives an impression of the possible beneficial location of Scubaqua beach.


**Figure 4.3:** Picture: part of the coastline of Oranjestad Bay indicating the hard elements at Scubaqua beach, (Google Earth 3-1-2022)

### 4.1.2. Summarizing the understanding of the coastal system

In this section, a summary of the overall understanding of the coastal system is described in bullet points.

- Most of the time waves approach the coast from a South-Southeast direction, however during the period September to March also waves approach the coast from a Southwest to a Western direction.
- A wave-induced longshore current is driven by waves which approach the coast at an angle.
- Neglecting tide and wind, the (wave-induced) longshore current is responsible for a longshore sediment transport capacity.
- Due to the seasonal wave climate, the sediment transport is pre-dominantly in northward direction in the first half of the season and southward-directed in the swell season.
- Net sediment transport increases alongshore (from minimum at the harbour to a maximum north of Smoke Alley), which is causing gradients in sediment transport rates along the coast.
- Due to storms, cross-shore redistribution of sand can take place at Oranjestad Bay, leading to rapid beach erosion.
- The seasonal reversal of the sediment transport capacity is an explanation for the beach fluctuations at Oranjestad Bay.
- Since sediment availability may be limited at certain locations along the coast, the actual transport is likely to be smaller than the sediment transport capacity.

## 4.2. The coastal morphodynamics during Storm Earl

In this section, an explanation for the different beach states before, during and after storm Earl is provided. The beach states of Scubaqua beach and Smoke Alley beach recovered differently as was illustrated with a photo series in Figure 2.13. Based on the obtained knowledge of the coastal system in Chapter 2 and Chapter 3, the behaviour of the beaches can be analysed. This analysis is carried out with a conceptual model.

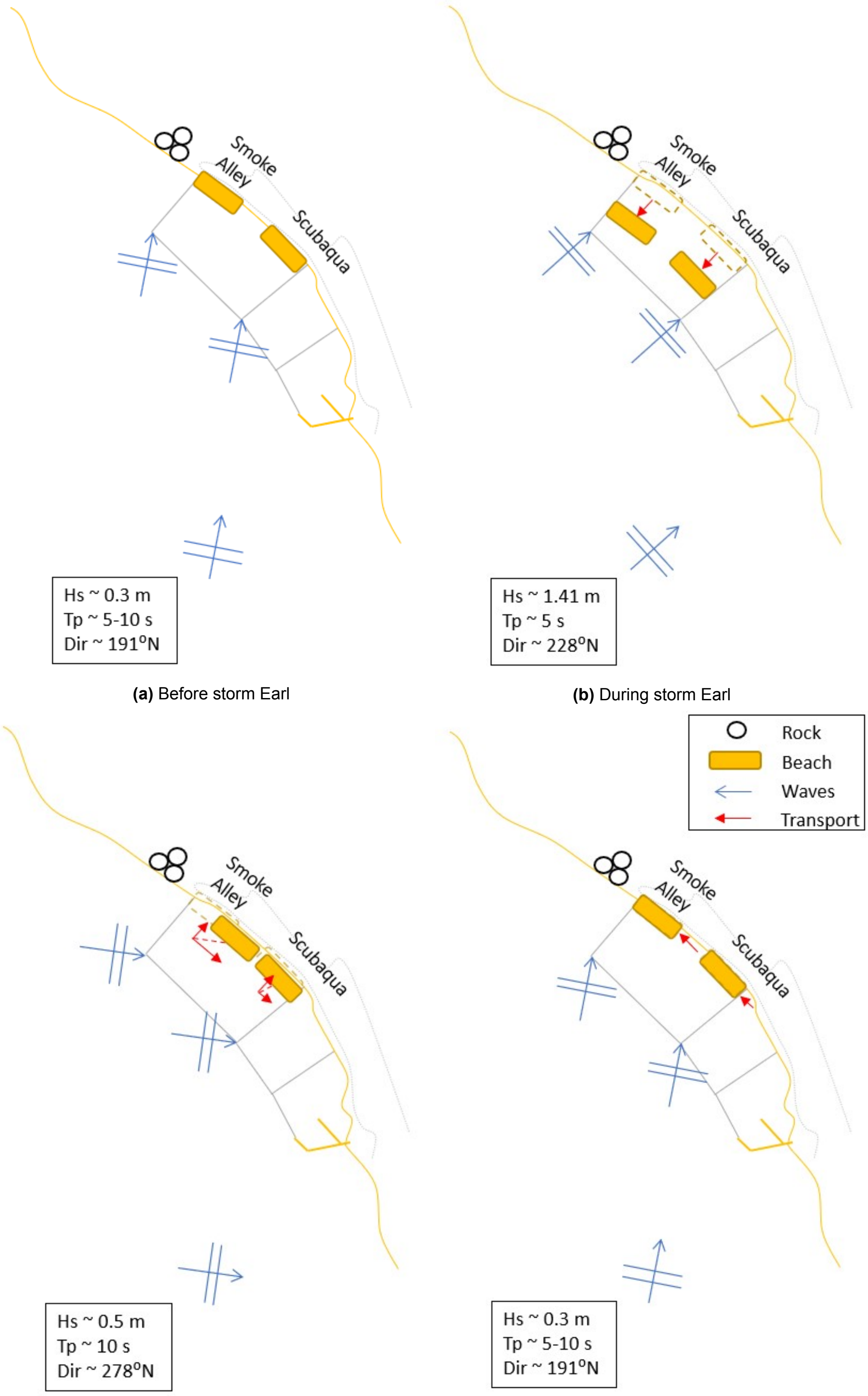
In Figure 4.4 a conceptual model for the beaches at Smoke Alley and Scubaqua is given in the period of storm Earl. Before the storm, both locations contain a beach of approximately 10 m in width. The WSO wave buoy measured a significant wave height of 0.3 m and a peak period between 10 and 5 s. Waves approach the coast from a slightly Southwest direction (Mean direction is 191 °N). This situation is illustrated in Figure 4.4a.

During the storm, the wave height increased to a maximum significant wave height of 1.41 m (at the WSO wave buoy) and a peak period of 5 s. The waves approach the coast from a more shore-normal angle (Mean wave direction is 228 °N). When waves approach the coast perpendicularly, no longshore transport occurs. Therefore, it can be expected that during the storm pre-dominantly cross-shore redistribution of sediment took place. Both beaches eroded and the sediment is expected to have moved to the foreshore. This is illustrated in Figure 4.4b.

After the storm, the significant wave height decreases steadily to an average wave height of 0.5 m. The peak period is approximately 10 s and the waves approach the coast from a more western direction (Mean wave direction is 278 °N). As seen in Chapter 3, these longer waves cause a southward-directed longshore current. The (longshore) current is responsible for longshore sediment transport in a southward direction. In the northern part, the sediment transport capacity is the largest. Hence, considering both locations on the shoreline, the beach at Smoke Alley is experiencing a larger southward-directed sediment transport capacity than the beach at Scubaqua. In Figure 4.4c this effect is visualised with a larger alongshore component at Smoke Alley compared to Scubaqua. It is expected that this difference affected the recovery of both beaches.

Next to the transport capacity, sediment availability is also playing a role. North of Smoke Alley, there is a rocky shoreline while between Smoke Alley and Scubaqua beach sandy stretches can be found. For this reason, there is limited sediment input at Smoke Alley. It is likely that the recovery phase of Smoke Alley beach will take longer than Scubaqua beach. This situation is illustrated in Figure 4.4c.

In the longer term, the beach of Smoke Alley is also expected to recover due to the waves approaching again from a southern direction. This causes a northward transport, which may feed Smoke Alley beach. Figure 4.4d visualizes the expected recovery some time after the storm.




**(a)** Before storm Earl

**(b)** During storm Earl

**(c)** After storm Earl

**(d)** Longer term after storm

**Figure 4.4:** A conceptual model of the beach states before, during and after Storm Earl.

To clarify the difference between both beaches during the recovery phase, a sediment balance is provided in Figure 4.5. This balance is based on the sediment transport capacity and sediment availability after the storm related to Figure 4.4c. As shown in Figure 4.5, the sediment input at Smoke Alley is smaller than the sediment output. This is caused both by the lack of sediment north of Smoke Alley and the larger outgoing alongshore sediment transport capacity at this location. The sediment budget at Smoke Alley is contrary to the sediment balance at Scubaqua beach. At Scubaqua, the sediment budget is positive due to the larger incoming sediment transport capacity. Also, sediment is available at that location. The different sediment balances at both locations provide an explanation for why Smoke Alley recovered differently than Scubaqua beach.

Another aspect that could affect the difference between the recovery of the two beaches is the cobbles which are present at the beaches. From the photo series, it is visible that directly after the storm Smoke Alley beach contains more and larger cobbles than Scubaqua beach. The cobbles are causing more turbulence at the shoreline, which hinders the sediment from settling. Accordingly, this aspect could also negatively affect the recovery of Smoke Alley beach.

To conclude, the beach at Smoke Alley recovers slower than the beach at Scubaqua. This can be explained by the lack of sediment availability north of Smoke Alley, the amount of larger cobbles present at the shoreline of Smoke Alley and the variation of the sediment transport capacity in alongshore direction. In Figure 4.4 the various processes that play a role are illustrated in a conceptual model. Moreover, in Figure 4.5 the sediment balance after the storm illustrates the different recovery states between both locations.


**Figure 4.5:** Sediment budget after storm Earl for Smoke Alley beach and Scuabaqua beach related to Figure 4.4c

# 5

# Proposing a potential solution

Based on the system knowledge obtained in this research and the stakeholders' demands and regulations, three alternatives are proposed to create a beach at Oranjestad Bay. Additionally, this chapter carries out a qualitative analysis to verify and evaluate the alternatives. Hereby, Chapter 5 provides a first indication of a possible solution for Oranjestad Bay.

In Section 5.1 a program of requirements is set-up and in Section 5.2 various concepts are created. Subsequently, in Section 5.3 and 5.4 a verification process is carried out and alternatives are evaluated in a qualitative manner. At the end of this chapter, an answer can be given to Research Question 4:

*What alternatives are suitable to create a beach at Oranjestad Bay based on system knowledge and the stakeholders' requirements and regulations?*

## 5.1. Program of Requirements

The main goal of the coastal solution is to create a beach at Oranjestad Bay that is present all year round. For the design of a coastal solution, a program of requirements is set up based on stakeholders' needs and legislation. In Chapter 2, a brief stakeholder and environmental analysis is performed, which helped to clarify these demands. Additionally, input for the program of requirements was collected through personal communication with stakeholders during the site visit from July to mid-October 2022. This resulted in a program of requirements, which consists of five main topics: Specification, Ecology, Archaeology, Recreation and Spatial quality. The program of requirements is listed below. It is important to note that in this study the stakeholder and environmental analysis were limited and no explicit requirements were found. For this reason, the program of requirements is bounded to an indication and should be reviewed in a more detailed design phase.

*Specifications*

1. **The beach should have a minimum width of 10 m during normal conditions.**
   A fluctuating beach is present at Oranjestad Bay, which fluctuates between circa 0 m – 30 m based on historical pictures and local stories. The minimum width occurs after heavy storms and the maximum beach width occurs primarily during Easter weekend. Desirably, the beach should have a minimum of 10 m for the inhabitants and tourists to enjoy the beach.

2. **The lifetime of the beach should at least be five years under normal conditions.**
   The occurrence of a storm is expected in the lifetime of a coastal solution at Oranjestad Bay. Once every five years, a tropical storm and or a category 1-2 hurricane pass over St. Eustatius. It is acceptable, that a beach erodes under these extreme conditions. Moreover, in order to be economically feasible the lifetime of nourishment is aimed to be 5 to 10 years (Bosboom & Stive, 2015). Therefore, the lifetime of the beach should be at least five years under normal conditions.

3. **The grain size of the nourishment should be in the same order of magnitude as that of the existing sandy beaches.**
   It is important to use sediment material for nourishment that is similar to the native material present on the beach. This is for reasons such as avoiding large initial losses during the construction phase, as well as for ecological reasons.

4. **The location of the beach should be freely accessible to inhabitants and tourists.**
   The coastline at Oranjestad Bay is partly public and partly privately owned. The beach should be in a freely accessible location so that the local community can benefit from it.

5. **The coastal solution should not negatively affect the harbour.**
   Meaning, no sedimentation should occur in the harbour area that could cause hindrance for vessels mooring.

6. **The coastal solution should not negatively affect currently present beaches.**
   Currently, three beaches are available at Oranjestad Bay; Smoke Alley beach, Scubaqua beach and Baby beach (at the harbour). The coastal solution should not cause erosion on these beaches.

*Ecology*

7. **The ecological habitat in the project area should not be negatively impacted.**
   Various species use the Statia National Marine Park as a home, migratory stop or breeding site. In Chapter 2 it was seen that at the project location, hardly any organic material is found above MSL - 7m. Furthermore, at the beaches of Oranjestad Bay, primarily the Caribbean sea turtles can be found, which use these locations for nesting. Since turtles return mostly to their spawning site, the beaches should stay accessible for the turtles to nest. In addition, numerous fishes can be found around Oranjestad Bay, which are essential to the ecosystem. Fishes especially benefit from shelter places or passages through rock formations. Therefore, these fish habitats should be preserved in the area.

*Archaeology*

8. **The heritage sites along the coastline of Oranjestad bay may not be harmed by the coastal solution proposed.**
   Many historical sites are situated along the coastline of Oranjestad bay. Examples are old warehouses, shipwrecks, and Fort Amsterdam. Harm to heritage sites is not allowed. This study simplifies the impact on the heritage site to a descriptive analysis because an archaeology investigation is out of scope. In the analysis, any form of digging is considered harmful to the site, while adding sand such as nourishment is examined positively.

*Recreation*

9. **Access from the beach to the waterline should be safe.**
   For recreational activities on the beach, such as snorkelling, diving and swimming it is relevant to have easy access from the beach to the water. Therefore, the coastal solution should take this into account. In this study, safe access means an individual can walk from the beach to the waterline without facing physical objects.

10. **At Oranjestad Bay, swimming activities should remain safe.**
    One of the main activities at Oranjestad Bay is water sports. Additionally, all inhabitants make use of the area. Therefore, the coastal solution should ensure a safe swimming environment at Oranjestad Bay.

*Spatial quality*

11. **The coastal solution should preserve the characteristic elements of St. Eustatius.** Statia, as locals refer to the island, is a relatively unknown island in the Caribbean with a rich history. Unlike other Caribbean islands, the coastline is characterized by ruins, volcanic black sand, rocks, and pocket beaches. It is crucial that the local elements that characterize St. Eustatius are preserved in the coastal solution.

## 5.2. Inventory of alternatives

Various alternatives are identified with the main goal of creating a beach that is preserved all year round. This can mainly be achieved by three measures; by keeping sediment in the coastal system [1], by adding sediment to the coastal system and by reducing the transport capacity. For this reason, the considered alternatives consist of a nourishment in combination with a structure. An elaboration on the type of nourishment and structure is provided in Section 5.2.1, after which three alternatives are proposed.

### 5.2.1. Basic design components

This subsection explains the type of nourishment and structure chosen for the alternatives. In general, there are four types of nourishments, respectively dune nourishment, beach nourishment, shoreface nourishment and mega-nourishment (Bosboom & Stive, 2015). The different types are related to the supply location or the size (such as a mega-nourishment). For Oranjestad Bay, beach nourishment is the most reasonable option. With this type of solution, a beach is immediately realised on the location. The other kinds of nourishment are less favourable. A dune nourishment is not fulfilling the purpose of the coastal solution (to create a beach). In addition, the uncertainty of shoreface nourishment is large due to the seasonal wave climate. Lastly, mega nourishment is not fitting into the characteristic elements of the island. Consequently, beach nourishment is selected as the type of nourishment in the alternatives considered.

Furthermore, for the alternatives, the focus lies on a structure that is built perpendicular to the coastline. The reasons for this are 1) longshore sediment transport is in the order of 10-100 times larger than cross-shore transport (see Figure 3.16a). Therefore, longshore transport plays an important role in the lifetime of the beaches. A structure perpendicular to the coast may be an appropriate measure to extend this lifetime. 2) Shore-parallel structures are expected to be less suitable in Oranjestad Bay. Generally, a mild wave climate is present (Hs $\sim$ 0.5 m at -13 m depth). This means that the crest height of a shore-parallel structure would have to be considerably high to have any effect on these low waves. This type of structure is therefore not expected to be cost-efficient. Moreover, shore parallel structures may have a negative effect on the recovery processes after (hurricane) storms. Accordingly, this study focuses on perpendicular structures (i.e., groynes) with beach nourishment.

**Beach nourishment**

Beach nourishment is an efficient manner for beach widening. Sand is usually placed directly on the beach, after which it is diverted by land-based machinery such as shovels (Bosboom & Stive, 2015). For the design of beach nourishment, there are some key aspects to consider:

- *Availability of sand*: The method is feasible if enough sediment volume is available at a not-too-far distance from the project site (Van Rijn, 2013).
- *Grain size*: To minimize sediment loss during construction, the nourished material should be identical to or slightly coarser than the native sediment material. Equal sediment material is also important for ecological reasons.
- *Initial loss*: To avoid large-scale initial losses, it is beneficial to construct the seaward slope in a way it resembles the existing profile. Nevertheless, after construction, it is expected that the nourishment will be re-distributed over the shoreface to develop towards its equilibrium state (Brand et al., 2022).

[1] In this case, the coastal system is defined as the coastal zone from the harbour to Smoke Alley

For a nourishment at Oranjestad Bay, sand seems to be available in the nearby region. Considering, Oranjestad Bay has a sandy foreshore and the grain size distribution is well sorted (See Figure 2.9). Additionally, there are plans to deepen the harbour (Ruijter, personal communication, June 2022). The dredged sediment that comes free in this situation, can be used for nourishment assuming, the sediment is not contaminated and meets the grain size requirements.

The nourishment volume is determined based on the desired beach width, the active height and the coastline length. According to de Vroeg (2022b), the depth of closure is approximately at MSL -3 m. The height above MSL is assumed to be MSL +1 m (site visit, July 2022). As a consequence, the amount of sediment needed to nourish a beach width of 15 m is $\Delta$V = 15*4*L, as presented in Figure 5.1. The figure illustrates an average slope of the present beach profile and the new situation (in its equilibrium state) after the nourishment. The length (alongshore) is dependent on the location along the coastline and varies between the alternatives. Moreover, to account for additional losses during construction works, the nourished volume needs to be increased by 20% (Bosboom & Stive, 2015). Based on executed projects on St. Eustatius, the cost for beach nourishment is estimated on 40-60 US$$/\mathrm{m}^3$ (Ruijter, personal communication, February 2023). This value considers the approximate cost per m$^3$ sand. The mobilisation cost will strongly depend on the available equipment on the island and the possible combination with the harbour renovation. For this reason, only the dredging cost are considered in this study.

To construct beach nourishment, sediment is often pumped ashore with pipelines since the water depth is too limited for vessels. The nourishment volume is concentrated in the upper part of the beach profile by the contractor. After that, the sediment needs to be spread along the beach by bulldozers. Nature will then do its work to redistribute the nourishment over the shoreface in order to develop towards its equilibrium state. Figure 5.2 gives an indication of a nourishment construction placed in the upper part of the profile.

At Oranjestad Bay another option to transport the sediment ashore could be to collect offshore sediment with vessels and transport it to the harbour. The sediment is then reloaded on trucks and again spread by bulldozers on the beach. In a later stage of the project, an elaboration should be made on the most cost-efficient construction plan.

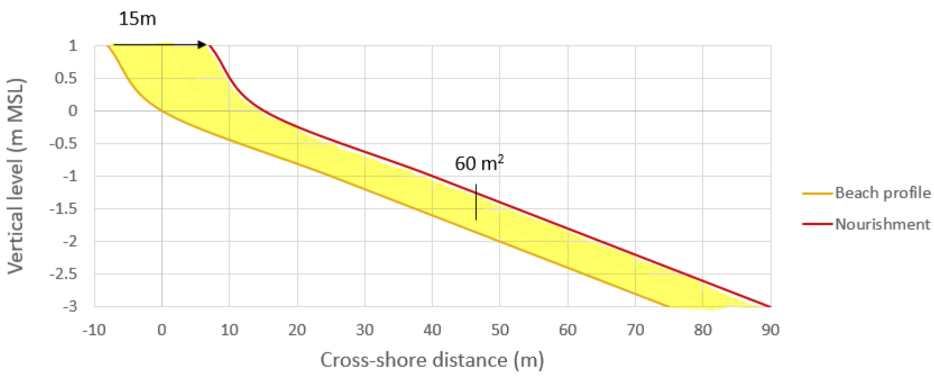



**Figure 5.1:** The average nearshore beach profile with an estimated slope of 1:25 (In yellow). The nourished profile (in red) for a beach width of 15 m, where the nourishment developed towards its equilibrium state. (in the ideal situation)

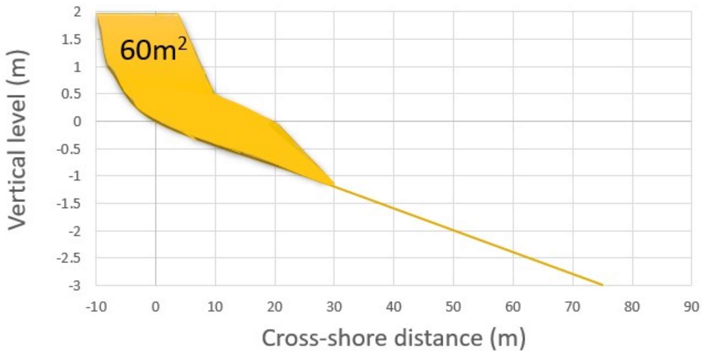



**Figure 5.2:** A sketch of the nourishment volume constructed in the upper part of the profile.

**Groynes**

To extend the lifetime of a beach, a groyne can be placed. At Oranjestad Bay, the main purpose of the groyne is to block northward-going sediment transport. This prevents sediment from moving out of the coastal system (in the study area) and will extend the lifetime of the beach nourishment.

For the design of a groyne, several characteristics are considered, such as the groyne's height, length and permeability. To fulfil the groyne purpose in Oranjestad Bay, an impermeable high-crested groyne is chosen (Schiereck & Verhagen, 2019). The groyne height is 0.5 to 1 m above the desired beach level. In this way, the northward sediment transport is blocked and the beach nourishment is kept in place. The groyne is constructed 1.5 m above MSL along the entire length. This means that the groyne is clearly visible to vessels and water activities in Oranjestad Bay.

The length of the groyne should be an optimization between the blockage of the northward-going sediment transport (going out of the system), the southward-going sediment transport (bringing sediment into the system) and the length of the beach nourishment in a cross-shore direction. In general, the northward-going transport is taking place close to the waterline and the southward-going transport is occurring in larger water depths (below approximately MSL - 1.5 m, at 40 m cross-distance) (de Vroeg, 2022b). This means sediment can be retained with a relatively short groyne length of 40 m. This still allows southward-going transport to enter the system. In addition, the beach nourishment extends to approximately 90 m seawards as can be seen in Figure 5.1 (assuming a 1:25 slope). For this reason, the groyne length is estimated to be between 40 - 100 m. In this study, the groyne length is assumed to be 70 m. In the next phase, optimisation of the groyne length can be considered with a modelling study.

In Figure 5.3 a cross-shore profile of the groyne and nourishment is sketched. The figure provides an illustration of the groyne height above MSL and groyne length of 70 m in combination with the nourishment.

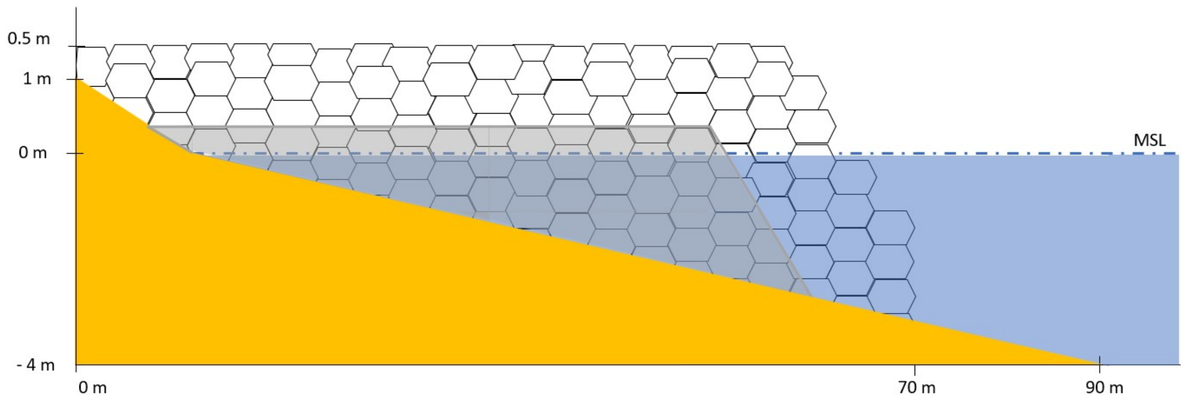



**Figure 5.3:** Sketch of groyne with nourishment in cross-shore direction. The groyne is illustrated in blocks (top layer) and a grey surface (core material). The nourishment is highlighted in yellow.

In Figure 5.4 a sketch of the groyne dimensions used in this study is provided. In general, a groyne consists of an impermeable core with on top an armour layer. For construction purposes, the core should be at least 3 m wide and above the high water level. Standard classes exist for rock material. As a first estimate for the armour layer, this study uses a rock sorting of 300-1000 kg. In this case, the armour layer has a thickness of 1.3 m (M. Onderwater, personal communication February 2023). A geotextile is applied between the core layer and the armour layer to prevent the loss of the smaller core material.

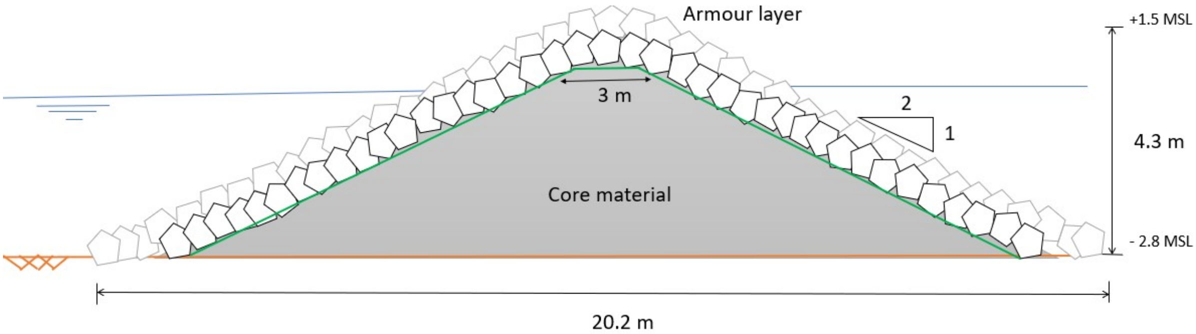



**Figure 5.4:** An indication of the groyne design used in this study.

The construction of a groyne is executed by land-based and or waterborne equipment. If local material is used, a land-based operation might be the first choice. With the help of trucks or cranes, the rocks are dumped or placed at the right location. However, for the type of equipment, hindrance due to construction also needs to be evaluated. Since the food supply needs to pass at the main road of Oranjestad Bay, hindrance on this location is unacceptable for a longer period. Therefore, waterborne equipment may be more efficient. In the end, the type of equipment is often decided by the availability of equipment and the source of material (Schiereck & Verhagen, 2019).

At Oranjestad Bay, rocks are available as well as old groyne structures. By using locally available material, the cost of a groyne can be reduced. Based on recently performed projects in St. Eustatius, the estimated cost for rocks is approximately 90 US$$/\text{m}^3$ (Ruijter, personal communication, February 2023). Besides that, the cost of the core material is usually somewhat lower. In this study, the cost for the core material is estimated at approximately 75 US$$/\text{m}^3$. Overall, the cost for the groyne is estimated at 286,000 US$.

A negative effect of groynes is erosion on the lee side of a groyne. This is illustrated in Figure 5.5. It is important to consider this effect when advising a groyne as a coastal solution.

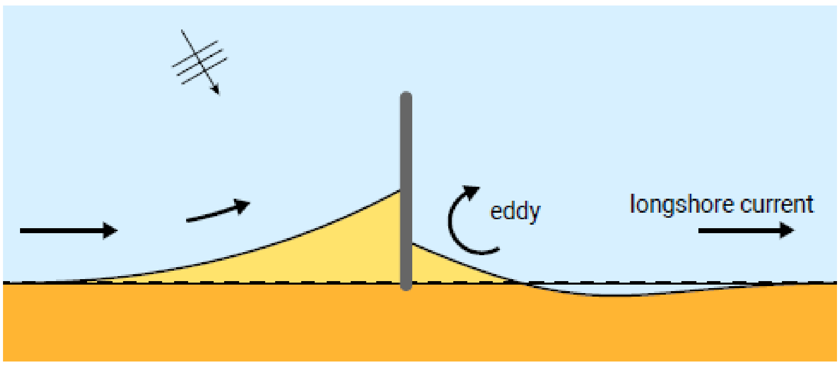



**Figure 5.5:** Erosion on the lee-side of a groyne due to the current pattern (Bosboom & Stive, 2015).

### 5.2.2. Alternative I: Re-use of structures

Alternative I is a nourishment in the vicinity of the harbour area. Figure 5.6 presents Alternative I. This solution makes use of the available structures which are present along Oranjestad Bay. Its location in the vicinity of the harbour area brings several advantages. First of all, due to the availability of structures, the nourishment is held in place. For this reason, the building cost of Alternative I is relatively low since the construction of a groyne is not necessary. Secondly, based on the coastal morphodynamics obtained, it is known that there is a relatively low current and transport capacity at this location due to the sheltered zone of the harbour. This is beneficial for a lifetime of a nourishment. Since the adjacent area of this alternative is currently a rocky shoreline, the effect of this coastal solution on the neighbouring coast is low. Fourthly, Alternative I has the potential to extend since multiple groynes are present in a northward direction along the coast. In Figure 5.6 the possible extension is illustrated with a dashed yellow line.

A disadvantage of this alternative is that during extreme events possible sedimentation can occur in the harbour area.

Based on the obtained knowledge of the coastal morphodynamics of Oranjestad Bay, the expected development of the nourishment over the years can be provided. In general, sediment will be transported in a northward direction. It is therefore likely that over time some sediment will cross the groyne structure. The lack of incoming sediment will cause a decrease in sediment volume in the location of Alternative I. On the other hand, the sediment that is transported in a northward direction is feeding the adjacent coastline. Overall, Alternative I can be a beneficial location for a beach nourishment. A low transport capacity is present which is an advantage for the lifetime of the beach. Furthermore, sediment that will be transported in a northward direction serves as a nourishment for the adjacent coastline.

The nourishment volume for Alternative I is circa 14 400 [2] $m^3$ (with a length of 200 m). If the nourishment is supplied by dredged sediment from the deepening of the harbour, the transport distance for Alternative I is small. The cost of the nourishment is approximate US$720,000 (assuming 50 US$/$m^3$). Additionally, an inspection of the present 'old groyne' should be carried out to evaluate its state. However, this is substantially cheaper than the building of a new groyne. In total the investment cost for Alternative I is estimated around US$721,000.

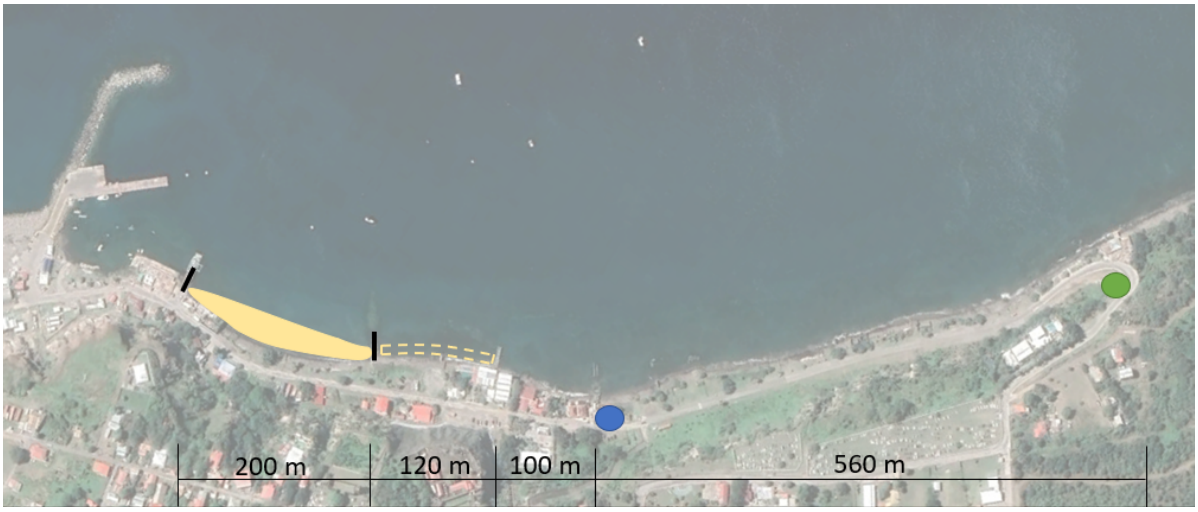



**Figure 5.6:** Illustrative sketch of Alternative I. The nourishment is coloured in yellow and the possible extension is noted with a dashed line. The location of Scubaqua is highlighted with a blue circle and the location of Smoke Alley with a green circle.

[2]The beach nourishment volume is calculated with $\triangle V$ = 15*4*200 + 20% for construction loss.

### 5.2.3. Alternative II: Hotels and beaches

Alternative II considers the bay shape of the coastline and the location for leisure activities. It is located around Scubaqua beach. Alternative II consists of a nourishment with a groyne. In Figure 5.7 Alternative II is shown. This alternative is a favourable location for a beach since sediment accumulates already naturally here. Furthermore, the presence of a beach could be beneficial for the turtles nesting at Scubaqua beach. If more beach is available over a larger length, the turtles have more place to nest. It is noted, that the construction of a coastal solution potentially also negatively affects the turtle habitat. Therefore, construction needs to be executed outside the hatching period and in close communication with ecologists. An extension of Alternative II is possible in southward direction.

The disadvantage of Alternative II is that a groyne is needed to prevent northward transport. This can be difficult due to the density of archaeological sites along the bay. An option for the groyne could be to place a new pier, as the current pier at Scubaqua beach is in decay. Due to the construction cost of a groyne, Alternative II is more expensive than Alternative I. In the short term, the placement of a groyne is expected to have a negative impact on the adjacent beaches to the north. This is because the northward sediment transport that feeds these beaches will be blocked. However, no coastal retreat is expected. In addition, any southward-going transport may also be partially blocked. Therefore, the overall impact may be reasonable.

For the development of the nourishment over the years, it is expected that there will be fluctuations due to the seasonal wave climate. Sediment transport is increasing in a northward direction. For this reason, it can be expected that over the years more sediment passes the groyne and is transported to the adjacent coastline in Alternative II compared to Alternative I. Again, the sediment is still within the study area and is therefore not expected to cause much concern.

The nourishment volume for Alternative II is 14 400 m$^3$ (with a length of 200 m). The nourishment cost is approximately US$720,000 and the cost for a new groyne is estimated at around US$286,000. In total, the investment cost for Alternative II is around US$1,006,000.

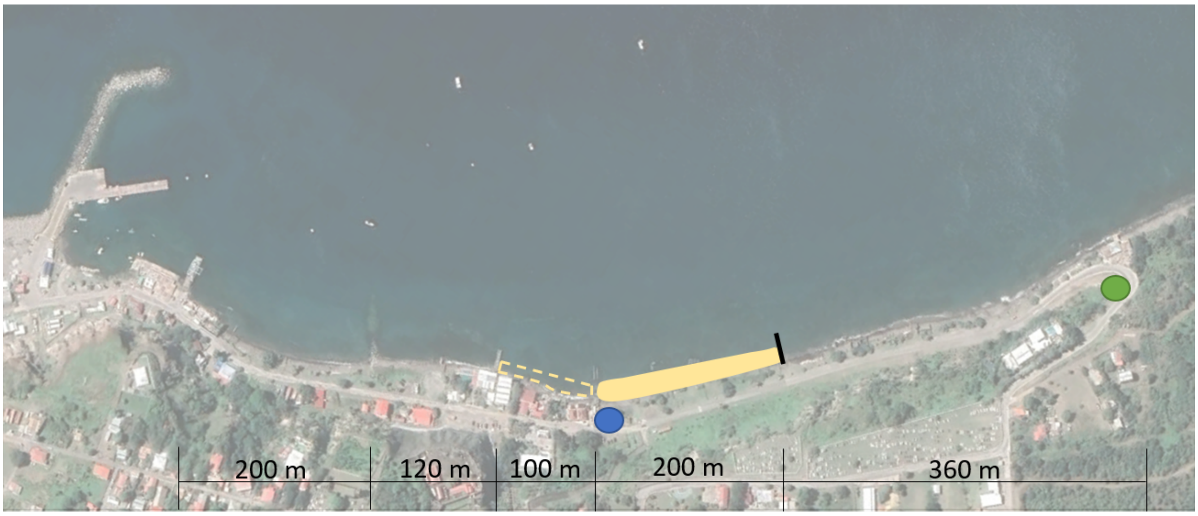



**Figure 5.7:** Illustrative sketch of Alternative II. The location of Scubaqua is highlighted with a blue circle and the location of Smoke Alley with a green circle.

### 5.2.4. Alternative III: Long-stretched beach

The starting point for Alternative III is the historical picture of a wide beach from the sixties. Alternative III consists of a large-scale nourishment with a groyne. In this alternative, the northward transport is blocked by a groyne just north of Smoke Alley. Figure 5.8 illustrates Alternative III. With its extended range, the solution is covering a large part of the cultural heritage, which is currently in decay. Also, both beaches (Scubaqua beach and Smoke Alley beach) are included and the solution is located mostly on publicly owned land.

On the downdrift side, significant fluctuations can be expected due to seasonal fluctuations and storm effects. Also, the largest amount of sediment is needed for Alternative III, which is visible in the cost.

For the development of the nourishment over the years, it is expected that there will be considerable fluctuations due to the seasonal wave climate and storm impacts. On a yearly basis, net northward sediment transport is expected. Therefore, the beach width is reduced and sediment will be transported in a northward direction.

The nourishment volume for Alternative III is 40,400 $m^3$ (with a length of 560 m). Consequently, the nourishment cost is US$2,016,000. Together with the cost for a new groyne around $286,000, the investment cost for Alternative III is estimated at around US$2,302,000.

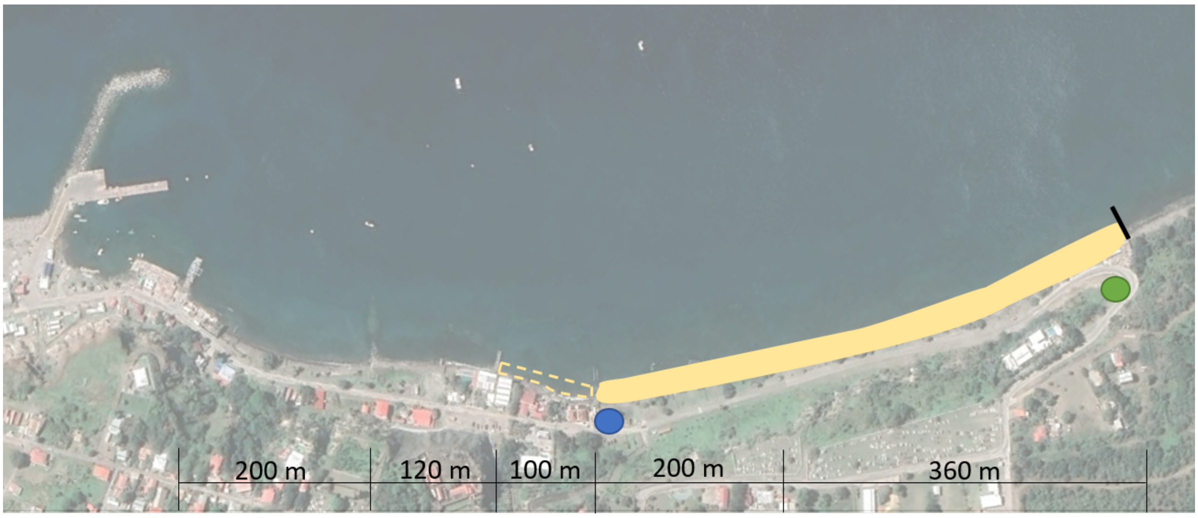



**Figure 5.8:** Illustrative sketch of Alternative III. The location of Scubaqua is highlighted with a blue circle and the location of Smoke Alley with a green circle.

## 5.3. Verification of alternatives

The verification process is carried out for each alternative. Each alternative should be in compliance with the program of requirements. If this is not the case, the alternative is not a viable solution. As a result, the alternative is rejected and will not be considered in further evaluation. The verification process is carried out in a qualitative manner appropriate to the level of detail of the alternatives. Note that as the design becomes more detailed, the verification process will need to be reviewed.

### Verification check per alternative

Table 5.1 presents an overview of the verification check for each of the alternatives. In the table, the alternatives are verified against the eleven requirements in Section 5.1. The columns are highlighted green and a '✓' is given if the verification is met. Table 5.1 shows that each alternative meets the eleven requirements. Therefore, any of the alternatives could be used to create a beach in Oranjestad Bay. This is an exceptional situation. An explanation for this could be the low level of detail in the elaboration of the alternatives, the verification process is limited. In addition, there is no out-of-the-box alternative, as the alternatives are relatively similar (nourishment with a groyne). Nevertheless, as all alternatives pass the verification, each proposed solution will be evaluated in the next section.

| Requirements | Alternatives | | |
|---|---|---|---|
| | I | II | III |
| 1 | ✓<br>Through a small-scale nourishment, the beach width is reached | ✓<br>Through a small-scale nourishment, the beach width is met | ✓<br>Through a large-scale nourishment, the beach width is reached |
| 2 | ✓<br>Through the limited sediment transport. The lifetime is expected to be met. | ✓<br>Through the placement of a structure, the sediment is blocked and the lifetime is expected to be met | ✓<br>Through the placement of a structure, the sediment is blocked and the lifetime is expected to be met. |
| 3 | ✓<br>With the beneficial use of sediment (harbour deepening) This requirement is complied. | ✓<br>With the beneficial use of sediment (harbour deepening). This requirement is complied. | ✓<br>With the use of local sediment (harbour deepening). This requirements is met. |
| 4 | ✓<br>Through the location on public area. This demand is met. | ✓<br>Through the location on partly public area. This demand is met. | ✓<br>Through the location on (mostly) public area. This demand is met. |
| 5 | ✓<br>Through the small-scale nourishment and the mild wave conditions. This demand is met. | ✓<br>Through the location of the solution. This demand is met. | ✓<br>Through the location of the solution. This demand is met. |
| 6 | ✓<br>Through the location of the solution. The alternative complies. | ✓<br>Through the nourishment. This alternative complies. | ✓<br>Through the nourishment. This alternative complies. |
| 7 | ✓<br>Through the location, this solution complies. | ✓<br>Through the increase of habitat, this solution complies. | ✓<br>Through the increase of habitat, this solution complies. |
| 8 | ✓<br>Through the nourishment, this demand is met. | ✓<br>Through the nourishment, this demand is met. | ✓<br>Through the nourishment, this demand is met. |
| 9 | ✓<br>Through the nourishment, this demand is met. | ✓<br>Through the nourishment, this demand is met. | ✓<br>Through the nourishment, this demand is met. |
| 10 | ✓<br>Through the type of solution, this demand is met. | ✓<br>Through the type of solution, this demand is met. | ✓<br>Through the type of solution, this demand is met. |
| 11 | ✓<br>Through the use of local material. Characteristics elements are preserved. | ✓<br>Through the use of local material. Characteristics elements are preserved. | ✓<br>Through the use of local material. Characteristics elements are preserved. |

**Table 5.1:** Overview of the verification process.

## 5.4. Evaluation of alternatives

In this section, the alternatives are evaluated with a Multi-Criteria Analysis. This is a decision-making tool to evaluate solutions from various perspectives. Criteria cannot always be quantified and criteria are sometimes conflicting. An MCA helps to organize criteria and scores, which allows the decision-making entity to make thought-out and defensible choices.

The alternatives are evaluated on the basis of the evaluation criteria and costs. As no explicit requirements were found and the stakeholder analysis was limited, it was not possible to distinguish between stakeholder wishes and demands. For this reason, the evaluation criteria are equal to the program of requirements in this study. In the verification process, it was found that each alternative is suitable for creating a beach in Oranjestad Bay. Next, the evaluation process assigns a score to each alternative for each criterion. In this way, the alternatives are compared. Finally, the most suitable coastal solution for Oranjestad Bay is determined based on the ratio between the MCA score and the cost.

### 5.4.1. Multi-Criteria Analysis

Table 5.2 presents the MCA. For each requirement, a score from 1 to 3 is qualitatively estimated based on the knowledge acquired in this study. The minimum score is coloured in red and the maximum score is in green. Also, the alternative with the highest score is highlighted in dark blue. An elaboration on the scores per requirement is provided below.

*Specifications*

1. *The beach should have a minimum width of 10 m during normal conditions.*
   Each alternative will be dominated by fluctuations due to the seasonal wave climate at Oranjestad Bay. However, it is expected that Alternative III will be most affected by these fluctuations and Alternative I the least. This is mostly due to the locations of both alternatives. Alternative I benefits from the sheltering of the harbour and the lower transport capacities in the southern part of the project area. While Alternative III is located where the largest transport capacities occur. Based on this reasoning, the scores for each alternative are given.

2. *The lifetime of the beach should at least be five years under normal conditions.*
   Overall, a net northward transport capacity is present at Oranjestad Bay. For that reason, the southern side of each alternative is most vulnerable to erosion. It is likely that a saw tooth shape is developing over time, due to the net northward transport capacity in Oranjestad Bay. In order to maintain a minimum beach width of 10m, it is expected that the southern side of a nourishment will require the most maintenance.

   Again, Alternative I has the advantage to be located in the shelter area of the harbour, where relatively low transport capacities are present. A limitation of this solution is that no sediment input is expected due to the harbour. Overall, it is feasible that the lifetime of the beach for Alternative I is preserved and low to medium maintenance is expected after 5 years.

   The preservation of a beach for Alternative II is also reasonable as in this location the largest beach is currently developing. The new groyne will hinder northward transport, which is beneficial for the lifetime of the beach. On the other side, the seasonal fluctuations will affect Alternative II more than Alternative I. Therefore, medium maintenance is expected. Lastly, for Alternative III a relative stable central part is formed and considerable fluctuations on the boundaries are expected (de Vroeg, 2022b). To maintain the minimum beach width of 10 m, maintenance is expected. For Alternative III the largest maintenance is assumed because this is located in the place with the largest transport capacities.

3. *The grain size of the nourishment should be in the same order of magnitude as that of the existing sandy beaches*
   For the nourishment material, it is assumed that dredged sediment is available from the deepening of the harbour. Additionally, sand is expected to be available in the nearby region, based on the sandy foreshore and the beach samples taken by Gautier (2022). Although each alternative can benefit from the available sediment, Alternative III has the most favourable position. Due to its location in the vicinity of the harbour and the small-scale nourishment, this alternative has the highest score. Alternative II is located a bit further north of the harbour. Lastly, Alternative III is located the furthest away. Due to the larger scale nourishment of Alternative III, additional sediment is potentially required. Alternative III therefore has the lowest score.

4. *The location of the beach should be freely accessible to inhabitants and tourists.*
   Alternative III is freely accessible to inhabitants and tourists. Except for the area in front of Scubaqua beach, the location of Alternative III is government owned. In addition, the beach at Scubaqua is currently used as a public beach even though it is private land. This is also true for Alternative II. The alternative is freely accessible but located on partly public and partly privately owned land. In addition, a possible extension is more logical to the south which will benefit

the hotel area. Accurate data for the land ownership at Alternative I is not accessible but it is assumed that the area is public owned. Alternative I is therefore also freely accessible. Again, a possible extension would first be beneficial to hotel owners.

5. *The coastal solution should not negatively affect the harbour.*
   For each alternative, sedimentation in the harbour area is not expected considering the yearly wave climate. However, during a heavy storm possible hindrances may occur. This is most likely for Alternative I. No hinderance is expected for Alternatives II, and III, as they are further away from the port.

6. *The coastal solution should not negatively affect currently present beaches.*
   The adjacent coastline of Alternative I and III are characterized by a rocky shoreline. For both solutions, the impact of a groyne construction is minimal. This is contrary to Alternative II, where the neighbouring coastline contains sandy stretches. In addition, Alternative II is blocking sediment input for Smoke Alley beach. This is partly compensated by the southward sediment transport. Besides, Alternative II nourishes Scubaqua beach, and Alternative III provides sand at Smoke Alley and Scubaqua beach. Therefore, these two options are also beneficial for the currently present beaches.

*Ecology*

7. *The ecological habitat in the project area may not be negatively impacted.*
   In Alternative I the ecological habitat is preserve. At this location, mostly fishes are active which use the old groyne as shelter place. Moreover, if the groyne needs to be renewed, the fish habitat can potentially be improved. Alternative II could be beneficial for ecological habitats too, because a larger area for turtle nesting is provided. In this case, it is assumed that the artificial sediment is not causing a negative impact on the turtles nesting. In Alternative III an even larger area for turtles is created. Although, it is important that the construction is executed outside the hatching period to not negatively impact the ecology. In a later stage, an Environmental Impact Assessment needs to be performed to provide more information on the ecological effects of the alternatives.

*Archaeology*

8. *The heritage sites along the coastline of Oranjestad bay may not be harmed by the coastal solution proposed.*
   The heritage site is most positively affected by Alternative III. In this solution, a large part of the cultural site is covered with sand. The new groyne is placed just north of Smoke alley, which is now characterized by a rocky shoreline. Second best is Alternative I, since the nourishment covers cultural sites and no new groyne is placed on a vulnerable location. The least beneficial solution is Alternative II, as this only partly covers cultural heritages site and a new groyne needs to be placed in a cultural rich area.

*Recreation*

9. *Access from the beach to the waterline should be safe.*
   Safe access from the beach to the waterline is guaranteed in all alternatives. Hence, an equal score is given to all of them.

10. *At Oranjestad Bay, swimming activities should remain safe.*
    In all three solutions, circulation and local rip currents are generated due to the impermeable groyne structure. This can affect the safety for water users. In Alternative I, the groyne is already present and forms no problems for people enjoying water sports. The groyne has a total length of 60 m, where the first 30 m is above MSL and the second 30 m is below MSL. Since the groyne head is submerged, the rip current is expected to be minimized. Caution is needed for Alternative II and III, as swimming activity takes place here. The placement of a new groyne can cause

safety concerns for swimming activities. Nonetheless, the currents are most of the time relatively low owing to the mild wave climate. During storms, it is very unlikely that people go swimming. Therefore, attention should be paid primarily during the swell season.

*Spatial quality*

11. *The coastal solution should account for the characteristic elements of St. Eustatius.*
All three alternatives focus on the use of local materials and preserving the characteristic elements of the island. Since Alternative III is based on a nostalgic historical image, it might be that this alternative has advantages over the other alternatives. However, for the score of this requirement, the opinion of local inhabitants and stakeholders should be considered.

### 5.4.2. Cost per alternative

The coastal solution should be economically feasible to construct and maintain. In terms of initial construction costs, Alternative I is the cheapest solution (approximately US$721,000) and Alternative III is the most expensive (approximately US$2,302,000), considering the cost per $m^3$ sand and groyne material. Maintenance cost are also expected to be the lowest for Alternative I compared to Alternative II and III, taking into account sediment losses. However, it should be noted that the main cost is the mobilisation cost, which is the same for each alternative. Ultimately, the total cost of the alternatives should be determined as well as the feasibility of constructing a nourishment on St. Eustatius. Therefore, in a later phase of the project, a cost-benefit analysis will provide more insight into to this topic.

### 5.4.3. Selection

Based on the MCA, Alternative I and III had the highest average end score (11.7) compared to Alternative II, which had an end score of 9. Alternative II particularly scores less well on the impact on currently present beaches, swimming safety and covering the heritages site. Alternative III scores less on the beach width and lifetime since considerable fluctuations are expected but scores highest on Ecology and Archeology. Alternative I scores particularly well on Specifications. Besides, a higher score may also be associated with higher costs. Therefore, a cost-value ratio is obtained. In Figure 5.9 the costs per alternative are plotted against its MCA end score. In the figure, it can be seen that Alternative I has the highest MCA score for the lowest estimated cost. Alternative III may have the same MCA score, but is expected to cost significantly more. Alternative II has a slightly lower MCA score and is expected to cost more than Alternative I due to the construction of a groyne. Based on this cost-value ratio, Alternative I is considered the most suitable solution for Oranjestad Bay.

In the MCA analysis, the various topics and requirements had equal weights on the end score. In a later phase, this analysis could be evaluated with the stakeholders. Although the scores are assigned in a subjective manner and the cost are only a first estimation, the outcome gives an overview that can be used in the decision making for a coastal solution at Oranjestad Bay.

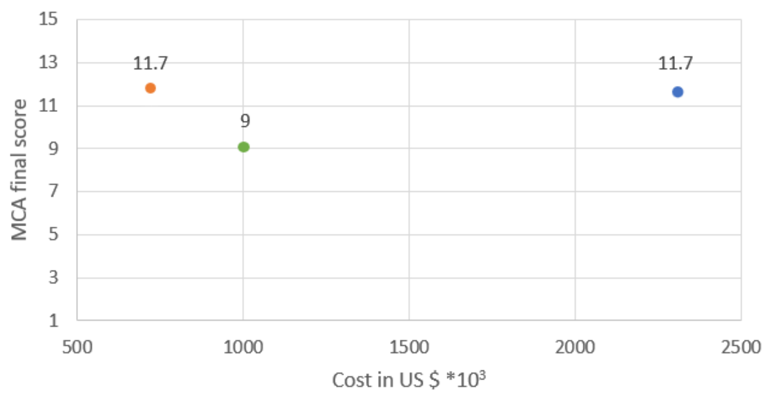



**Figure 5.9:** Cost-value graph for Alternatives I (orange) , II (green), III (blue).

| Topic | Requirement | Maximum score (=3) | Minimum score (=1) | I | II | III |
|---|---|---|---|---|---|---|
| Specifications | The beach should have a minimum width of 10 m during normal conditions. | More width is still present | Minimum width is reached | 3 | 2 | 1 |
| | The lifetime of the beach should be at least 5 years under normal conditions. | Low maintenance is needed | High maintenance is needed | 3 | 2 | 1 |
| | The grainsize should be similar as that of the existing sandy beaches. | Locally available sediment | Not locally available sediment | 3 | 2 | 1 |
| | The location of the beach should be freely accessible to inhabitants and tourists. | Free access to the beach | Mostly not accessible | 3 | 2 | 2 |
| | The coastal solution should not negatively affect the harbour. | No hinderance is expected | Possible hinderance is expected | 1 | 3 | 3 |
| | The coastal solution should not negatively affect currently present beaches. | Positive effect on beaches | Partly negative effect expected | 3 | 1 | 2 |
| | | | Average sum | 2.7 | 2 | 1.7 |
| Ecology | The ecological habitat in the project area may not be negatively impacted. | Ecology benefits from solution | Habitat preserved | 2 | 2 | 3 |
| | | | Average sum | 2 | 2 | 3 |
| Archaeology | The heritage sites along the coastline of Oranjestad Bay may not be harmed by the coastal solution proposed. | Positive effect for heritage site | No harm for heritage site | 2 | 1 | 3 |
| | | | Average sum | 2 | 1 | 3 |
| Recreation | Access from the beach to the waterline should be safe | Safe access | Caution signs needed | 3 | 3 | 3 |
| | At Oranjestad Bay, swimming activities should remain safe | No safety issues expected | Caution sign needed | 3 | 1 | 1 |
| | | | Average sum | 3 | 2 | 2 |
| Spatial quality | The coastal solution should account for the characteristic elements of St. Eustatius | Characteristic elements included | Partly characteristic elements | 2 | 2 | 2 |
| | | | Average sum | 2 | 2 | 2 |
| | | | Total sum | 11.7 | 9 | 11.7 |

**Table 5.2:** MCA for Alternative I,II,III.

# 6
# Discussion

This chapter provides a discussion on the used methods and obtained model results. In addition, the implications of the study are debated.

## 6.1. Considerations in the model methodology

In the model approach, various methods are used which led to the presented outcomes. Decisions that influenced the model results are discussed in this section. Firstly, for the year simulation, a schematized wave climate was imposed on the boundary conditions of the Delft3D-4 model. The wave data was schematized in daily mean conditions as illustrated in Figure 3.8. It is noted that on average the daily wave height is relatively low and during storms some peak heights are present. The daily wave conditions for the year simulation underestimate these peak heights during storms. In Figure 3.8 the difference between the peak wave height and the used daily condition can be noticed between June and July, and August and September. This approach results in a slightly underestimation of the storm characteristics in this research. On the other hand, the peak wave heights are related to only several hours. Therefore, the impact on the total year simulation may be moderate.

Secondly, in Chapter 4 the behaviour of Smoke Alley and Scubaqua beach during tropical storm Earl was analysed. Due to model instabilities, it was not possible to perform this analysis in the Delft3D-4 model. For this reason, the analysis was carried out with a conceptual model and a qualitative explanation was given. Rather than the Delft3D-4 model, a simplified 2D Xbeach model would have possibly provided fewer model instabilities. Because Xbeach is robuster for this type of waves. A modelling study could lead to a more in-depth understanding of the behaviour of the sediments during a storm in Oranjestad Bay compared to the qualitative analysis. If in the next study, the main focus lies on the behaviour of storms, the model instabilities in the Delft3D-4 model should be reconsidered. Also, a different model approach may be selected.

Furthermore, in the model, the influence of tide was not included. This may have consequences on the model outcomes. Due to the tide, the water level fluctuations can cause set-up differences that affect the flow velocities and therefore sediment transports in Oranjestad Bay. The latest report by Gautier (2022) showed that the water level can vary between approximately +/- 0.3 m relative to MSL. Since most of the time low waves are present, the influence of the tide may be more dominant than estimated in this study. On the other hand, a micro-tidal range is present and the beaches are characterized by a wave-dominant classification (Bosboom & Stive, 2015). Therefore, for this simplified model set-up it is reasonable to exclude the tide. However, in a more extended model version, it should be considered to include the tidal characteristics.

Also, the wind is not considered in the model. Based on the measuring campaign in 2021 (Gautier, 2022), the wind velocities are generally 3-5 m/s. Since the wind is mostly directed from the East, this could generate a longshore current. However, with the low wind speed, a minimal influence on the current and sediment transport at Oranjestad Bay is expected. During extreme conditions, the wind can be a relevant factor. However, no extreme events were measured in the available data set. For this study, the exclusion of wind is therefore considered plausible.

## 6.2. Discussion on the model results

Limited coastal data was available for the region of St. Eustatius. This had an impact on the modelling set-up and the model results. With respect to the bathymetry file, a nearshore slope of 1:25 was estimated along the entire shoreline. Due to the lack of nearshore data, a low-resolution bathymetry profile is used in the model set-up. At the same time, coastal processes are taking place in this zone and bathymetry plays an important role, for example in depth-induced breaking. It is therefore desirable to have more accurate data from this area. Currently, this low-resolution bathymetry adds some uncertainty to the model results.

Moreover, no literature was available for the nearshore bathymetry north of Smoke Alley and south of the harbour. In addition, south of the harbour, the foreshore is characterized by coral colonies instead of a sandy bottom. Therefore, these locations are less well represented in the model and the model outcomes on these locations should be used with caution. Since the sites are located outside the project domain, the model outcomes for the project site are not affected by this inaccuracy.

Another data limitation that influenced the model results is the lack of data on sediment availability. In the model setup, a sediment thickness layer of 20 m is assumed. However, the actual availability of sediment is unknown. Moreover, it is likely that the assumption is an overestimation of the real situation since the bed consists of rock overlain by sand (See Chapter 2). Accordingly, the calculated sediment transport values are related to the sediment transport capacity instead of the actual sediment transport. In this study, no morphological simulation is carried out, whereby the availability of sediment plays an important role in sedimentation and erosion patterns. Hence, the lack of this information is not directly hindering the research goals. However, data on the availability of sediment is necessary to gain insight into the actual sediment transport in Oranjestad Bay, which will ultimately be useful for the design of a coastal solution.

Finally, the wave input data used from the Obscape wave buoy data was limited to one year of observations. The data set was sufficient to build a model for one morphological year. However, it is desirable to have several years of data to obtain a more representative wave climate. In this case, the observed data is characterised by a relatively mild year since limited extreme storms are included. This means that the model results may also reflect mild morphodynamic characteristics.

Furthermore, the set-up Delft3D-4 model contained some limitations, which are described here. The model validation process is limited to a comparison of the nearshore wave height and wave period during storm Fiona. Although the Delft3D-4 model does a fairly good job of capturing the observed significant wave height and the observed peak wave period, the validation process is limited to the wave characteristics at one point and one moment in time. No validation on the nearshore currents or sediment patterns was performed. This leads to uncertainty in the model outcomes. Moreover, most of the time the calibration parameters have been taken as a default value. It is therefore important to bear in mind the possible bias in the model outcomes.

## 6.3. Discussion of the MCA

By means of an MCA and a cost-value ratio, the three proposed alternatives were evaluated in Chapter 5. Based on the outcomes, a suitable solution for Oranjestad Bay is provided. There are two points to consider in this final result. Firstly, it is important to note that the outcomes of an MCA serve as a tool for decision-makers to make decisive choices. This means that the highest score in the MCA is not fixed nor is it the only ‘right’ answer. The result of the MCA will support the Public Entity of St. Eustatius to clarify the different trade-offs between the selected alternatives. By discussing the results of the MCA with the relevant stakeholders, a defensible alternative can be chosen.

Secondly, this study provides a first inventory of alternatives. A refinement of the proposed solutions is necessary to make a decision on the coastal solution for Oranjestad Bay. Design aspects that still need attention are, for example, execution aspects, the impact on the ecology through an environmental impact assessment, a total cost and benefit analysis and the translation into technical design. The elaboration of alternatives in a preliminary design will help provide the necessary information to make a decision on a coastal solution for Oranjestad Bay.

# 7 Conclusions

The aim of this study is to advise the Public Entity of St. Eustatius on the decision for a coastal solution that will create a beach in Oranjestad Bay by analysing the morphological system. The main research question is: **What is a suitable coastal solution to create a sandy beach at Oranjestad Bay, St. Eustatius?** Four sub-questions were formulated to answer this main question. This chapter provides answers to each of these sub-questions. By answering these sub-questions, the answer to the main research question is formulated.

1. *What are the morphodynamic characteristics of the coastal zone in Oranjestad Bay?*
   A literature study was conducted to obtain the basic knowledge of the coastal system of Oranjestad Bay. The findings show that Oranjestad Bay has the characteristics of a wave-dominant coast (Bosboom & Stive, 2015). A micro-tidal range is present, and the island is mostly affected by the Northeast trade winds. Oranjestad Bay is dominated by a seasonal wave climate. Generally, waves approach the coast from a South-Southeast direction. During the period September until April, (swell) waves periodically approach the coast from a Southwest to Western direction. This seasonal wave climate has a large impact on the beach fluctuations that are occurring at Oranjestad Bay. St. Eustatius also lies in the Atlantic hurricane belt, which occasionally brings stormy conditions to Oranjestad Bay from June to November.

   Due to the seasonal wave climate, a northward wave-induced current is expected for most of the year. From September to April, this current is reversed in a southward direction due to the more westerly swells. These current directions are also reflected in the sediment transport pathways. Moreover, a study by de Vroeg (2022b) concluded that overall, a net northward longshore transport capacity is present of approximately 15,000 $m^3$. Sediment redistribution also occurs in the cross-shore direction. It was found that especially after storm conditions, the recovery process of beaches varies along Oranjestad Bay.

   The influence of tides and wind on sediment dynamics is expected to be minimal. Considering that water level variations are small (in the range of -0.1 m and +0.5 m to Statia Datum), current velocities are mostly assumed to be below < 0.3 m/s, and wind speed is generally 3-5 m/s.

2. *To what extent can a numerical model simulate the coastal processes at Oranjestad Bay?*
   A two-dimensional numerical model was developed to better understand the wave, current and sediment patterns in Oranjestad Bay. The model outcomes show that the wave climate can be described by three main wave conditions, namely a sea condition, a storm condition and a swell condition. The different hydrodynamic and morphodynamic characteristics of these conditions provide a reasonable simulation of the coastal processes in Oranjestad Bay. An impression of the seasonal wave climate is gained due to the different mean wave directions between the sea, storm, and swell conditions. Northward-directed flow velocities were found for the sea and storm

state, while the swell condition resulted in a southward-directed current. This seasonal variability is also seen in the sediment transport, where the sea and storm conditions drive a northward directed transport capacity. In contrast to the swell conditions, which drives a southward directed transport. In the model, also, a net northward sediment transport capacity is present. These findings agree with the expected coastal morphodynamics found in the literature study.

It was found that especially storm conditions are underestimated in the model, and model instabilities occur with the simulation of a heavy storm. In addition, due to the lack of detailed coastal data of Oranjestad Bay, the model outcomes on nearshore processes contain some uncertainty, and the actual sediment transport capacities are not calculated.

To conclude, the coastal processes of the Oranjestad Bay are well simulated by the two-dimensional numerical model (Delft3D-4). However, the model was found to be limited in characterising storms. Due to the lack of detailed coastal data, the model outcomes on nearshore processes also contain some uncertainties. A different model approach may be selected to study the behaviour of storms. For this type of study, a 2D Xbeach model could be considered as it is more robust to storm conditions.

3. *Based on the system knowledge, what is causing the variation in beach fluctuations along the coastline of Oranjestad Bay?*
   The coast of Oranjestad Bay may experience seasonal gradients in alongshore sediment transport leading to beach fluctuations. The seasonal reversal of the sediment transport capacity caused by the local wave climate provides an explanation for these beach fluctuations at Oranjestad Bay. The behaviour of the coastal changes is explained based on the different periods in the year.

   *April – September*
   Waves are generally originating from a South-Southeast direction with mild wave conditions (Hs 0.5 m, Tp 5s). The relatively low waves drive a net sediment transport in a northward direction. During this period, a negative sediment balance is expected due to the limited sediment entering the system, the periodic storm conditions, and the net northward sediment transport. For this reason, beaches are likely to erode.

   *June – November*
   This is the period of the Atlantic hurricane season. The beaches at Smoke Alley and Scubaqua erode rapidly due to periodic storm conditions. Long (swell) waves from a Southwest-West direction lead to the gradual restoration of the beaches. After storm Earl, it was noticed that Scubaqua beach restores much faster than the beach at Smoke Alley. The reason for that is the limitation of sediment north of Smoke Alley (rocky shoreline), the amount of larger cobbles present at the shoreline of Smoke Alley, and the variation of alongshore sediment transport capacity.

   *September- March*
   Beaches increase in size due to long (swell) waves from the Southwest to the western direction. The resulting longshore transport is in the southward direction, bringing sediment into the coastal system.

   *April*
   The beach is the widest due to the Atlantic hurricane season taking place from June to November and the build-up period of the beach during the period September to March.

4. *What alternatives are suitable to create a beach at Oranjestad Bay based on system knowledge and the stakeholders' requirements and regulations?*
   Three alternatives are proposed to create a beach at Oranjestad Bay based on the system knowledge and stakeholders' demands and regulations. The main objective of these solutions was to create a beach in Oranjestad Bay that is preserved all year round. The considered coastal solutions consist of a beach nourishment in combination with a groyne. Alternative I is a small-scale nourishment that is located in the harbour area and making use of the existing structures in the area. Alternative II is a small-scale nourishment in combination with a groyne and is placed around Scubaqua beach. Alternative III is a long-stretched nourishment combined with a groyne at Smoke Alley. The nourishment covers the area from Scubaqua beach to Smoke Alley. Each alternative is successfully verified in a qualitative manner. An MCA and cost-value ratio evaluated the proposed solutions. The results of the MCA provided an overview of scores and criteria that can be used as a tool in the decision-making process for a coastal solution in Oranjestad Bay. In this study, Alternative I has the highest MCA score in combination with the lowest cost.

**The main question: What is a suitable coastal solution to create a beach at Oranjestad Bay?**
In this study an understanding of the coastal system is obtained by an analysis of the hydrodynamic and morphodynamic behaviour at Oranjestad Bay. The results showed that there is a net northward sediment transport. Three solutions are proposed that could create a beach at Oranjestad Bay using this system knowledge and stakeholder requirements and regulations. The alternatives consist of a nourishment (to create a beach) in combination with a groyne (to preserve the beach). An MCA with a cost-value ratio is carried out to qualitatively assess the proposed solutions. The outcomes concludes that the most suitable solution for Oranjestad Bay is Alternative I. This is a small-scale nourishment in the vicinity of the harbour, which makes use of the existing structures. The results of the MCA provide an overview of scores and criteria that can be used as a tool in the decision-making process for a coastal solution in Oranjestad Bay.

# 8 Recommendations

This study has contributed to the understanding of the morphological system of Oranjestad Bay and proposed alternatives for the creation of a beach. Further research is needed to enhance the understanding of this system and to refine the suggested solutions to decide on a coastal solution for Oranjestad Bay. Based on the discussion and conclusions of this study, three recommendations for further research are made in this chapter.

1. *It is recommended to carry out further measurements of (extreme) waves, water levels, sediment characteristics and morphology in Oranjestad Bay.*

   In the study, limited coastal data was available for the model setup. In particular, information on the availability of sediment, on the nearshore bathymetry and measurements of extreme conditions were lacking. By obtaining more local data the missing data gaps will be filled and the local conditions can be better characterised. Further measurements can also contribute to the validation of modelling studies. This will help to improve the model results.

2. *It is advised to continue studying how extreme conditions affect the coastal morphology of Oranjestad Bay.*

   The impact of storms on the morphology of Oranjestad Bay has only been studied to a limited extent due to model instability and the lack of extreme weather observations. As the storms could have a major effect on the beaches of Oranjestad Bay, it is recommended that this impact be studied in more detail. This study could potentially be conducted with a two-dimensional Xbeach model.

3. *To make a decision for a coastal solution for Oranjestad Bay, it is advisable to elaborate on the selected solutions.*

   This study presents a suitable solution for Oranjestad Bay with the help of an MCA. The result of an MCA serves as a tool for decision-makers to make defensible choices. It is therefore advisable to discuss the results of this study with the relevant stakeholders. The first inventory of the alternatives is carried out in this study. For the decision-making of a coastal solution, it is recommended to refine the proposed alternatives. This refers to the follow-up steps in the BwN design cycle: 4) Refine the selected solution; 5) Prepare the solution for implementation. To develop a suitable design for Oranjestad Bay, it is needed to complete all the steps of the design cycle.

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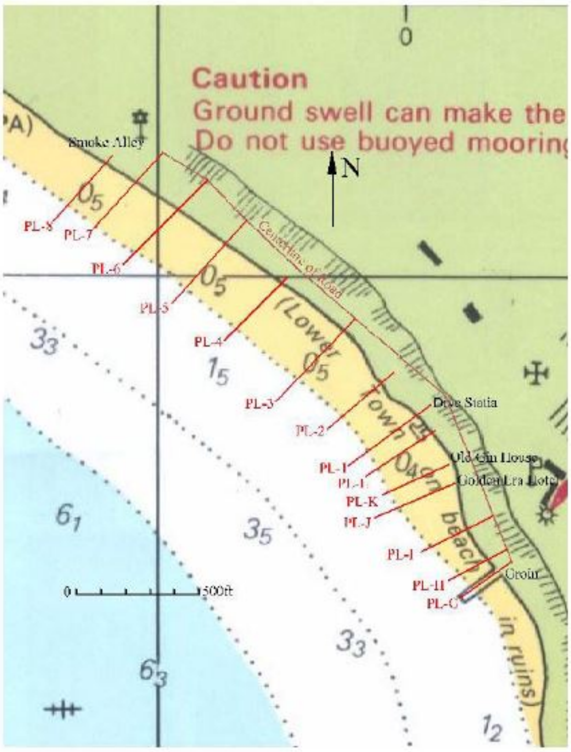
# A
# Bathymetry




(a) Location of beach profile lines by Harris


**(b)** Location of nearshore measurements by Deltares

**Figure A.1:** Locations of nearshore measurements by Harris (left) and Deltares (right)

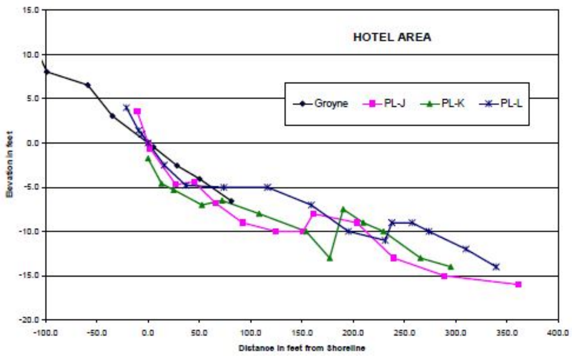
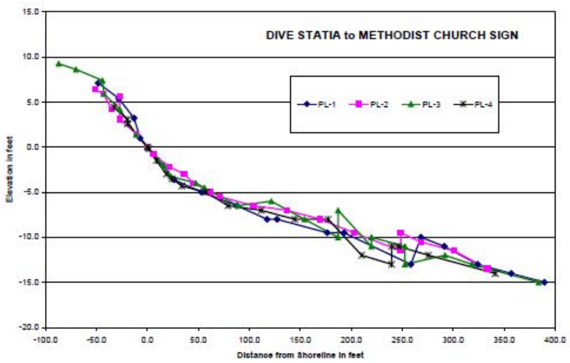
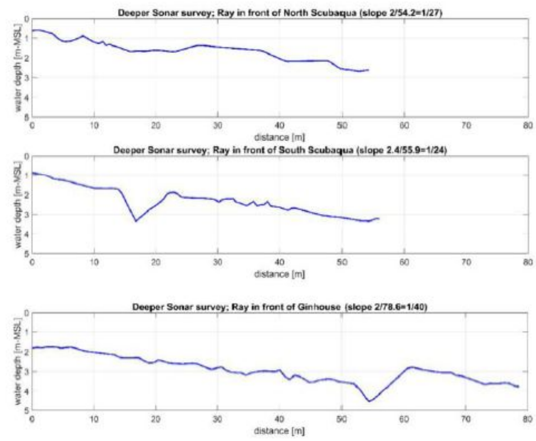



Figure 10. Beach Profile Lines in Hotel Area




**(a)** Nearshore measurements (in feet) from approximately MSL to -4m by Harris




**(b)** Nearshore measurements from approximately MSL-1m to MSL-3m by Deltares

**Figure A.2:** Nearshore measurements by Harris (left) and Deltares (right)

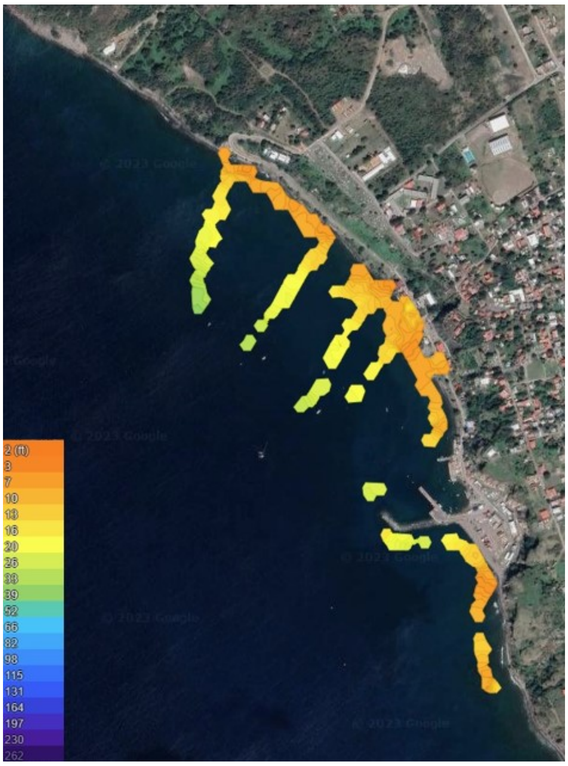



**Figure A.3:** Nearshore measurements carried out with the Fishdeeper instrument during the site visit from July to mid-October 2021

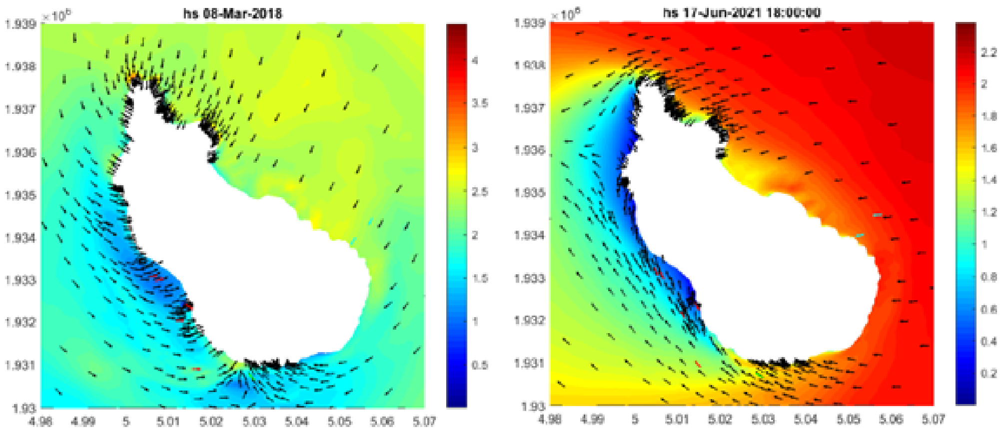



**Figure A.4:** Computed significant waveheight Hm0s (left) for a swell event at March 8th, and for a moderate condition on June 17th 2021 (right) by (Gautier & Doeleman, 2022)

# B

# Picture series of beaches during Storm Fiona


**Figure B.1:** The beach states of Scubaqua beach before, just after, and after storm Fiona


**Figure B.2:** The beach states of Smoke Alley beach before and after storm Fiona


**Figure B.3:** Beach state after storm Earl of location in between Smoke Alley and Scubaqua

# C

# Wave direction Storm Fiona

The WSO wave buoy varies in directions from the spotter wave buoy, as can be seen in Figure C.1.

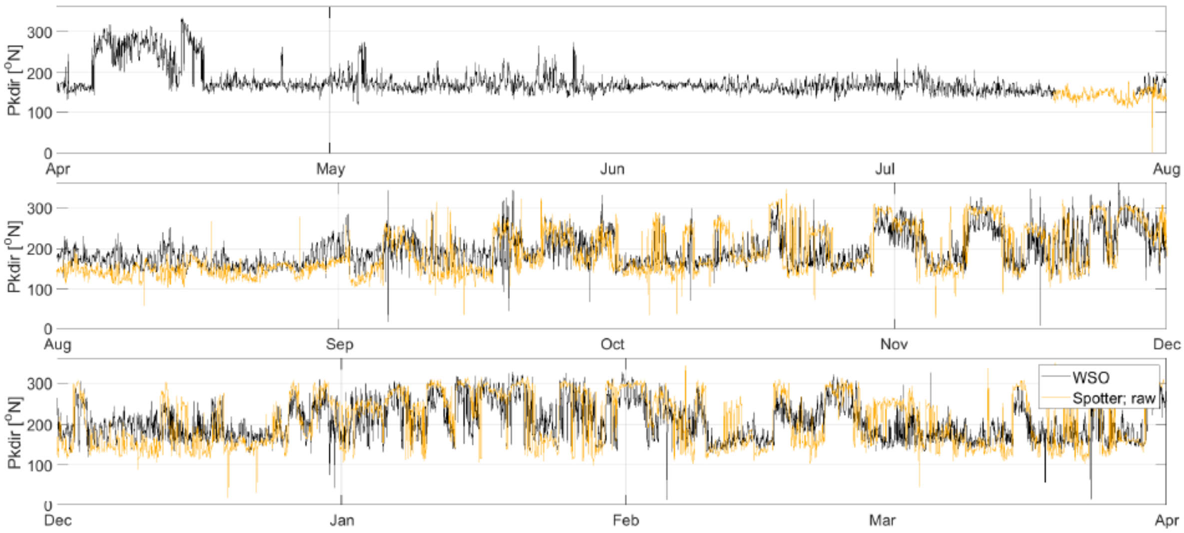



**Figure C.1:** Timeseries of WSO and Spotter observations of Peak wave direction from April 2021 to April 2022 by Gautier (2022)