Seven Mile Beach, Grand Cayman

Beach restoration and shoreline management

Mathematical modelling studies and analyses

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1 Introduction and background

Recently observed shoreline erosion along the west coast of Grand Cayman has reached alarming proportions and needs urgent action. An analysis of the causes of the observed erosion is needed to identify and evaluate adequate mitigation concepts.

During recent years intense erosion has been observed along Seven Mile Beach (hereafter SMB) on the west coast of Grand Cayman. The area is one of Cayman's principal tourist attractions and the erosion has now caused damage to buildings and loss of beach. Figure 1-1 shows examples of the damage observed recently and the local scale solutions that are implemented in an attempt to protect the properties. Figure 1-2 shows the shoreline at the Cayman Reef Resort. The highwater marks in the right figure indicate that the property is directly exposed to waves during periods with elevated water levels.

Figure 1-1 Observed damage to coastal infrastructure and emergency protection works in an attempt to mitigate the problem.

Figure 1-2 Severe beach erosion at Cayman reef resort, 2023. On the right photo the location of the water line during a recent high-water event can be noticed.

There is a need for urgent action, if no measures are taken to halt the ongoing erosion, then severe damage to the existing infrastructure cannot be avoided and there is a risk that beach will be lost permanently.

There are several possible reasons for the observed erosion such as increased storm intensity, long term changes in offshore wave conditions and sea level rise.

The main objective of the present work is to create profound knowledge of the coastal system that provides a basis for qualified assessments and important decisions regarding the development of a shoreline management plan for West coast of Grand Cayman. The aim is to provide a basis with wider perspectives of how the coastal system functions, how it is affected by changes in meteo-marine conditions, and how different concepts of mitigation will work out.

The analyses presented in this study, are used to identify adequate mitigation measures to halt the erosion. Our goal is to provide technical insight and valuable input to future shoreline management plans that are aimed at re-establishing and maintaining SMB in a sustainable manner. We believe that, by implementing adequate mitigation measures, a healthy, stable, and safe beach can be re-established that provides protection for the coastal infrastructure and is of excellent quality for tourism.

To achieve sustainable management of the coastal area it is of utmost importance to adopt an integrated approach that includes the coastal system as whole and avoids local scale, ad-hoc ”solutions” that could even have reverse effects on the stability of adjacent areas.

The basis for such integrated approach is first a good understanding of what mechanisms are causing the observed erosion. The key factor here is the action of waves. Waves are necessary to create and maintain a beach that is stable and suitable for recreation. On the other hand, waves are the single most important cause of coastal erosion. Waves can transport sand along the coast, which can result in beach accretion but also erosion. Furthermore, waves are responsible for the erosion of the upper part of the coastal profile during storms but also for the recovery of the beach during following calmer periods. The importance of storm events on the long term sediment balance along SMB is a key focus area of this study.

SMB is a relatively narrow beach protected by a reef with a wide shoal behind it. The reef and the shoal absorb most wave energy during storm events and as such provide a natural protection of the beach.

During events with elevated water levels (storm surge) waves can easier propagate across the reef and typically cause erosion of the upper part of the beach profile. This is commonly referred to as acute erosion. During a following period with calm conditions the sand can gradually be transported back to the shoreline. However, the process of beach restoration normally takes much longer than the erosion. The risk occurs that the next erosive event occurs before the beach has recovered from the previous one. What makes SMB especially sensitive to this type of erosion is its narrow beach. This, combined with the fact that coastal infrastructure is located very close to the shoreline creates a high risk for damage to buildings and roads and loss of beach. Obviously, a rise in the sea level can have devastating effects on the coast.

Coastal erosion can also be the consequence of a gradual shift in the magnitude and direction of the littoral sediment transport. For the case of SMB, this would typically lead to a sediment deficit in one part of the beach and a surplus along the other. This type of erosion is normally referred to as "chronic erosion".

The present study includes detailed mathematical modelling of waves, coastal hydrodynamics, and sediment transport. Previous modelling studies are used as basis for the present study. On the basis of modelling studies, the cause of the observed erosion is analysed. Mitigation measures are identified and evaluated.

2 Executive summary and conclusions

A comprehensive study was carried out to analyse the cause of the observed coastal erosion along Seven Mile Beach (SMB) and to define adequate mitigation measures to halt the erosion and restore the beach. The study included advanced mathematical modelling of waves, coastal hydrodynamics and sediment transport and was supported by high-resolution bathymetric data.

The modelling study included a long term (43 years) analysis of nearshore wave conditions, and the resulting sediment transport, under normal conditions and during nor'westers.

Special attention was also given to the generation and propagation of waves during hurricanes. A total of 23 tropical storms and hurricanes within the period 2000-2022 were simulated and their contribution to the coastal sediment balance along SMB was calculated.

An analysis was made of the beach erosion due to cross shore sediment transport during storms and hurricanes. During these events sediment is eroded from the upper part of the beach and deposited in deeper water further seaward. This type of erosion, often referred to as "acute" erosion can cause considerable damage to buildings and other coastal infrastructure located close to the shore.

The following main conclusions were drawn from the study:

1. The coastal sediment balance at SMB is highly event-based and is determined by two key factors: 1) – Extratropical cyclones (nor'westers) that cause wave-driven currents and sediment transport from north to south along SMB and, 2) Tropical storms and hurricanes that mainly drive sediment from south to north.

2. The analysis of historic wave data (1979-2022) suggests that the intensity of the nor'westers has decreased significantly since the late 1990s. This has led to a decrease in sediment transport from north to south along SMB. At the same time, no major hurricanes with direct impact on SMB were recorded in the period between 2008 (Paloma) and Laura (2020). As a result, both northward and southward directed transport rates were reduced. Consequently, no major changes in the sediment balance that could lead to chronic beach erosion occurred in that period.

3. Since 2020 a series of storms and hurricanes have affected Grand Cayman and caused excessive sediment transport from south to north along SMB. The net northward directed transport during the past years has caused a sediment deficit in the southern part of SMB. This has resulted in beach erosion. The sediment deficit, and the associated shoreline retreat, is migrating along SMB towards north.

4. During tropical storms and hurricanes, waves and strong winds cause complex sediment transport patterns across the entire shoal, a part of the sediment is transported across the shoal towards the edge of the reef, causing sediment loss to deep water. The loss of sediment to deep water occurs along the entire SMB but is concentrated in the northern part.

5. During storms and hurricanes, cross shore sediment transport can cause significant acute erosion where volumes of up to 30 m^3/m can be removed from the shoreline within a few days. This results in a retreat of the mean water line of around 20m and vertical displacements of the beach of up to 1m. Often this type of erosion is reversible as the displaced sediment can be transported back to the shore during a calm period after the storm. However, much damage can be done if properties are located too close to the shore.

6. If the present trend in meteomarine conditions continues, then the observed erosion along the southern part of SMB will get worse and gradually spread towards north. If no measures are taken, then chronic erosion along the entire SMB is likely to occur the coming years/decades.

7. The best way to mitigate the erosion along SMB is through artificial beach nourishment. It is recommended to feed the sand to the beach in two designated spots in the southern part of SMB. These so-called sand engines will gradually feed the neighboring beaches. A major advantage of the use of sand engines instead of integral beach nourishment is that the establishment of the nourishment does not require the use of heavy machinery on the beach. The sand engines can be created using floating pipelines where sand is pumped directly from the dredger to the beach.

8. An initial nourishment volume of 200,000 m^3 sand is recommended, equally distributed between the two sand engines. The sand must be distributed along a 500m long stretch. The initial increase in beach width at the sand engine is around 40m. After the initial charging, the sand will gradually be dispersed by waves and currents to neighboring areas.

9. The nourishment requires maintenance through periodic re-charging of the sand engines. The recommended frequency of re-charging the sand engines is once every 5 years but can be adjusted if desired. In any case, maintenance depends on the frequency and intensity of storms.

10. It is strongly recommended to initiate a shoreline monitoring program where the beach width is measured twice a year, at the beginning and the end of the hurricane season. Good quality information of the sediment distribution along the shore makes the maintenance activities easier to plan and more efficient.

11. It is recommended to consider the use of sediment traps to re-use sand that is transported during hurricanes and reduce sediment loss to deep water. A sediment trap is a strategically located, dredged pit. Currents generated during storm events will carry the sediment to the traps where it is deposited.

12. Sand areas near the reef, in water depths between 10m and 20m, can be sources for nourishment. The use of sand from these areas will not have a negative impact on shoreline stability.

3 Historic photos of SMB

The shoreline along SMB has always been dynamic and quickly responding to changing Meteomarine conditions. Figure 3-1 shows the beach in front of the Marriott hotel in 1998. The picture shows relatively high waves coming from a southerly direction. The beach is clearly eroding as can be derived from the exposed foundation of the stairs in the center left part of the picture.

Figure 3-1 Beach in front of the Marriot hotel, 1998

The continuous back-and-forth movement of the shoreline in response to changing waves and water levels is a normal feature observed on natural, exposed beaches. During a storm with elevated water levels (surge), waves climb up high on the shore and transport sand from the upper part of the beach and deposit it in deeper water further seaward. After the storm, the sediment is then gradually transported back to the shore, reestablishing the original beach width. The situation shown in the photograph indicates that the beach is too narrow to absorb the natural shoreline fluctuations. The property is directly exposed to incident waves.

Field observations suggest that the beach width along SMB has reduced over the past years, especially in the southern part. As a result, the beach is losing its capacity to absorb the shoreline fluctuations during storms. In several locations along SMB chronic beach erosion can be observed. An example is shown in Figure 3-2 that shows the beach at Plantation village in the southern part of SMB. The pictures show the situations in 1985, 2013 and 2019. Between 2013 and 2019 the beach appears to have been lost completely.

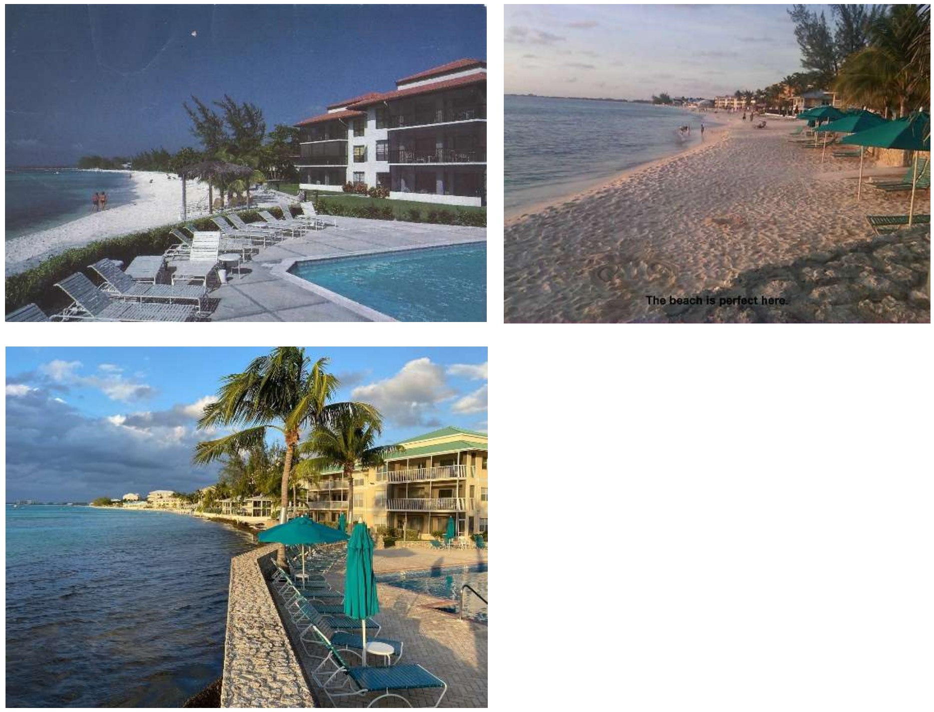

Figure 3-2 Plantation Village looking northwards. Upper Left 1985, upper right: 2013, lower picture: 2019

The beach in front of the Royal Palms hotel is shown in Figure 3-3, Figure 3-4, and Figure 3-5. The photos show a wide and healthy beach back in 1973. The present situation (Figure 3-5) shows a narrow beach with highwater marks very close to the wall protecting the property.

The wall shown in the picture is clearly not a marine structure designed to provide protection against persistent erosion. In this present configuration the wall and the beach have a negative impact on each other. The waves are likely to damage the wall within short time, either through direct impact or by gradually undermining its foundation. At the same time, the wall disturbs the natural passage of sand along the beach. Reflection of incident waves causes increased erosion in front of the wall.

The problem can be solved by increasing the volume of sand between the properties and the highwater mark. In principle, this could be done by withdrawing the property wall to a safe distance from the shore. In practice this may not turn out to be a viable long term solution. Simply withdrawing a wall does not guarantee that the beach would be reestablished or that the erosion would stop.

An alternative could be active maintenance of the beach through artificial nourishment, supported by a monitoring program that enables early intervention if, when and where needed. This, in combination with good regulations about the minimal distance between permanent infrastructure and the waterline, could result in a safe and attractive beach that provides protection to properties and is suitable for leisure.

Figure 3-3 Beach in front of Royal Palms, looking northwards, 1973.

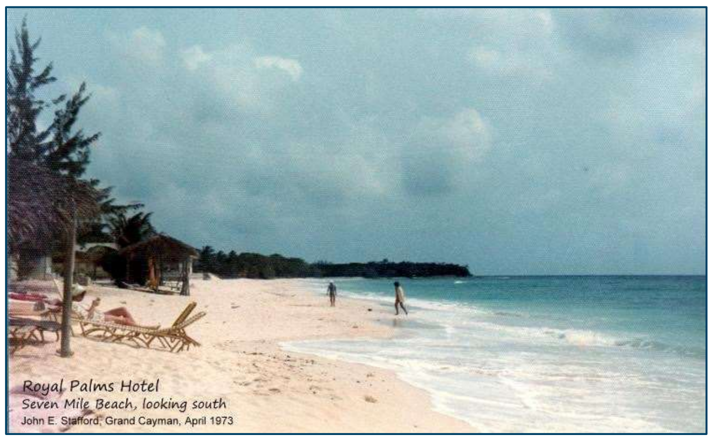

Figure 3-4 Beach in front of Royal Palms, looking southwards, 1973.

Figure 3-5 Beach in front of Royal Palms, looking southwards, 2023.

In some locations artificial beach nourishment has been applied to increase the width of the beach in front of a property, see Figure 3-6. These interventions are beneficial for the property that they aim to protect and do not have a negative impact on the adjacent beach. However, from a larger shoreline management perspective, such interventions are small and not very sustainable in the long run as the sand is likely to get dispersed rather quickly along the shore. The volume of sand necessary to restore - and maintain, the entire shoreline along SMB is orders of magnitude larger than the sand volumes supplied at one individual property. Therefore, a coordinated and integrated approach is needed to obtain the optimal result.

Figure 3-6 Sand replenishment in front of Royal palms, looking southwards, 2005.

4 Previous work

Previously, several studies have been conducted concerning geological, sedimentary, or ecological aspects of Seven Miles Beach. A number of these studies specifically focused on the possible removal of beach rock in various locations along SMB.

Modelling studies of waves and sediment transport were carried out by CGA, APEC & ATM (2016), DHI (2010, 2019), and Baird (2015). Reviews of previous numerical modelling and beach stability studies were presented in Douglass (2017), in Olsen (2017a) and DHI (2022). Furthermore, general studies about the history of Seven Miles Beach including discussion on sediment transport patterns and erodibility can be found in Clark (1988), Seymour (2000), and BRAC (2013). Studies on beach rock geology, ecology, and feasibility studies for the removal of parts or the totality of the beach rock were carried out by Roberts (1979), Cardno (2016a, b), Jones (2016, 2017), CGA, APEC & ATM (2016, 2017) and DHI (2019). A series of field monitoring and measurement studies were presented by Lee E. Harris (2003), Smith Warner (2015), Olsen/Kevin R. Bodge (2017a, b). Finally, coastal stability studies for Barker's and Starfish Point were carried out by DHI (2020). A scientific paper about the shoreline dynamics along SMB are presented in Johnston (2023)

A synopsis of the most important previous studies is provided below.

DHI (2010): Assessment of bed rock beach stability, numerical modelling – phase 2 & 3.

Analysis of impact of partial and complete removal of beach rock in specific locations along SMB. The analysis was supported by mathematical modelling studies of waves, littoral currents, sediment transport and shoreline dynamics.

Olsen Associates and South Coast Engineers (date unknown): Beach Rock - Synopsis of reviews by:

Review of report by Dr Bodge (Olsen & Associates – EAB 3rd party reviewer) and Dr Douglas (South Coast Engineers – Dart 3rd party reviewer) especially pointing at deficiencies on the modelling efforts that underpin the CGA-APEC report & conclusions.

CGA, APEC & ATM (2016): Rock Outcrop Removal Assessment Proposed Recreational Beach Improvements Seven Mile Beach, Grand Cayman.

Extensive review of previous studies by others, field investigations, data collection and numerical modelling, to identify possible challenges and resultant impacts that may occur with the removal of part of the beach rock formation to remove the hazard to swimmers and reattach the LSTR to the shoreline to enhance the beach to the south. The report also recommends steps that should be (or not be) taken to minimize any impacts to the beach in front of the adjacent properties and preserve the natural character and beauty of SMB.

CGA, APEC & ATM (2017): Beach rock Removal Assessment Proposed Beach Improvements Seven Mile Beach, Grand Cayman.

This report examines the feasibility of removing an existing shallow submerged rock outcrop that extends along 1600 feet of Grand Cayman's Seven Mile

Beach (SMB) shoreline. Numerical models are applied to assess the impact of removing the beach rock.

DHI (2022): Memorandum on redevelopment Royal Palms Hotel site

An evaluation is provided of documents related to the proposed works for the Palm Sunshine Hotel.

ATM & CGA (2017): Coastal engineering support for a proposed redevelopment on Seven Miles Beach, Grand Cayman.

Analytical and numerical modelling methods are applied to determine what anticipated shoreline adjustment could occur with the removal of a beach rock formation. A three-part initiative was employed. Initially, numerous studies and references were reviewed in detail to clearly understand the past observations and study results. The review of studies extending back more than 30 years were thoroughly examined to help determine existing and anticipated erosion and accretion trends in the area of the proposed project.

B. Jones (2017): Geology of onshore and offshore beach rock, Seven Mile Beach, Blocks 10 (part) and 11(part), Grand Cayman.

The report provides detailed geologic information off the onshore and offshore sands and also the beach rock found on Seven Mile Beach in Blocks 10 (part) and 11 (part) on the west coast of Grand Cayman.

S. L. Douglass (2017): Douglass 3rd Party Review - Beach rock Seven Mile Beach.

This note is a third-party review of a coastal engineering study report by ATM/CGA “Coastal Engineering Support for a Proposed Redevelopment on Seven Mile Beach Grand Cayman” dated January 2017, concerning the effects of partial removal of beach rock in front of some Seven Mile Beach properties.

Cardno (2016): Environment Assessment DRCL Seven Mile Beach Shoreline Trial Area.

The report is detailing an environmental assessment with review of the substrate characteristics within the proposed excavation area, and also included areas extending to the limits of proposed silt curtain installation. Assessment of the substrate characteristics included general mapping of the geologic substrate types and general characterization of the ecological communities found specifically within the excavation and silt curtain areas.

Cardno (2016): Seven Mile Beach Shoreline Resource Assessment

The report has been prepared to provide a summary of the ecological data collected within the proposed test area only and include general observations relating to the geologic nature of the substrate within the project boundary. It also provides a summary of marine species associated with these geologic features, an overall discussion of potential habitat present, and will provide the approximate location of larger coral colonies mapped as part of this survey.

Jones (2016): Modern beach rock, Seven Mile Beach, blocks 10 (part) and 11 (part), beach rock study.

The report provides detailed information on the beach sands and beach rock found on Seven Mile Beach in Blocks 10 (part) and 11 (part) on the west coast of Grand Cayman. The analyses have led to different conclusions regarding beach rock characteristics.

Olsen Associates (2017): Proposed Beach rock Removal – Review & Recommendations

The report review and recommendations regarding the proposed removal of beach rock along the shoreline of Seven Mile Beach between the Kimpton Sea fire Resort (near Tiki Beach) and the Sundowner condominiums. Four (4) sets of beach survey data were provided extending from the upland (+5.5) to about -5.5 ft depth, and between about 675 feet (206 m) north and south of the 25-ft wide trial cut. The survey dates were approximately (1) December 1, 2016 [pre-cut], (2) January 31, 2017, (3) February 22, 2017, and (4) March 31, 2017.

Olsen Associates (2017): Seven Miles Beach Rock Removal Memorandum

The memorandum includes graphics that depict the results of Survey #12 (performed on 8 November 2017) along the trial cut area of Seven Mile Beach, relative to the prior surveys. It additionally includes an overview of results from all 12 surveys collected over the last year, beginning with Surveys #1 (1 December 2016) and #2 (31 January 2017) together with a description and analysis of the results.

Smith Warner (2015): Field Data Collection Report for the Cayman Island Government Cruise Berthing Facility (Prepared for Baird & Associates).

The study presents a program of data collection and analysis that has been conducted offshore Seven Mile Beach and at George Town Harbour. The program included measuring of water temperature, salinity, turbidity profiles, sediment samples, bathymetry and topography, tides, nearshore and offshore waves, and currents.

R. Clark (1988): Investigation erosion conditions on the Seven Mile Beach Grand Cayman

This regional study provides an assessment of the beach conditions of the Seven Mile Beach shoreline and made some recommendations regarding regional management of this shoreline.

L. E. Harris (2003): Status report for the submerged reef ball / Artificial reef submerged breakwater / Beach stabilization project for the Grand Cayman Marriott Hotel.

This report presents an update on the submerged Reef Ball artificial reef breakwater that was installed during the summer and fall of 2002 in front of the Marriott hotel. The purpose of this system is to assist with beach and shoreline stabilization, and the project also provides the additional benefits of environmental enhancement and snorkelling reef attraction for resort guests.

Roberts (1979): A Feasibility Study Concerning Modification of a Beach Rock Coast

The study concerns a feasibility study about the beach restoration project on block 11B parcel 17. The report describes the geological setting and physical process environment to which the West Bay area is exposed. The report then discusses the nature of the outcrop and finally propose engineering alternatives and suggestions.

R. J. Seymour (2000): Seven Mile Beach: A Natural History

The study is a general description of the Seven Mile Beach history and general sand transport patterns in the West Bay area.

The beach review & Assessment Committee, Interim report (2003)

The report documents the background and key issues primarily influencing SMB and its management with respect to erosion.

DHI (2010): Cayman Island Cruise and Cargo Terminal Wave Conditions and Sedimentation Studies

The study was carried out by DHI in the frame of the construction of the new cargo ship terminal. Various numerical models were used to assess the nearshore wave climate, currents, and sediment transport. Infilling rates of otherwise dredged areas were calculated.

DHI (2019a): Sea grass removal at Barkers Beach. Shoreline impact of removal of turtle grass.

The report presents a mathematical modelling study of the impact of partial removal of turtle grass on the shoreline and adjacent beaches.

DHI (2019b): Starfish point shoreline protection.

The report presents an analysis and modelling study of shoreline stability and recommendations for mitigation.

W.G. Johnston, J.A.G. Cooper, J. Olynik (2023): Shoreline change on a tropical island beach, Seven Mile Beach, Grand Cayman: The influence of beach rock and shore protection structures. Scientific paper published in Marine Geology 457 (2023) 107006. https://doi.org/10.1016/j.margeo.2023.107006

This paper presents a case study of Seven Mile Beach of historical shoreline change. The local geomorphic setting is shown to be an important influence on shoreline behaviour. The authors identify five discrete, but interlinked sub cells delineated by low headlands of exposed beach rock. Long-term patterns of shoreline change are analysed. The effects of coastal structures and erosion abatement measures were assessed and recommendations for coastal management, including development setback lines are presented.

5 Site visit

In March 2023 DHI coastal engineers visited SMB. During this visit clear signs of erosion were observed, especially along the southern side of SMB. Figure 5-1 shows the area in front of the Marriot Beach Resort in the southern part of SMB. At the day the picture was taken, the beach had disappeared completely. The seawall that supports the hotels' outer terrace was directly exposed to incident waves. It is possible that the beach would gradually restore naturally following a prolonged period of calm conditions. However, the fact that the beach has retreated so far, even without an extreme event, is worrying. If a major storm would hit when the beach is in such a poor state, then major damage could occur to building and other infrastructure close to the shoreline.

Figure 5-1 Area in front of the Marriot Beach Resort I March 2023. The beach has eroded completely. Photo: DHI

In some locations along SMB vertical walls are constructed to protect properties, see Figure 5-2. When such a wall is directly exposed to waves then the beach erosion of front of the wall is enhanced by the effect of waves reflecting from the wall.

Further towards north the beaches gradually become wider and provide better conditions for leisure, see Figure 5-3.

Figure 5-2 Vertical wall at the beach directly exposed to waves do increase beach erosion due to the effect of wave reflection from the wall. Photo: DHI

Figure 5-3 The beach in the northern part of SMB is wider and provides better conditions for leisure. Photo: DHI

The beach along the northern end of SMB is not as heavily affected by erosion as indicated by the presence of trees and other vegetation close to the beach, see Figure 5-4. The northern limit of SMB rock exists entirely of rock with no sandy beaches, see Figure 5-5.

Figure 5-4 The beach in the northern end of SMB is less affected by erosion. Photo: DHI

Figure 5-5 The northern limit of SMB the coast exists entirely of rock. Photo: DHI

6 Bathymetry and present state of the shoreline

In this section the present state of the beach and nearshore bathymetry are analysed.

6.1 Bathymetry

The basis of any sound coastal engineering project is accurate data of the physical environment. Of key importance for the present study are bathymetric data and information about the sediment characteristics and bed mobility of the seabed in the area.

The bathymetry in the present area is characterized by shallow reef formations in front of a narrow beach of fine sand. Detailed bathymetric data was provided by DART. The data originates from a recent LIDAR survey by UKHO and provides excellent information about the nearshore bathymetry. Figure 6-1 shows a detail of the model bathymetry that was created on the basis of the provided survey data.

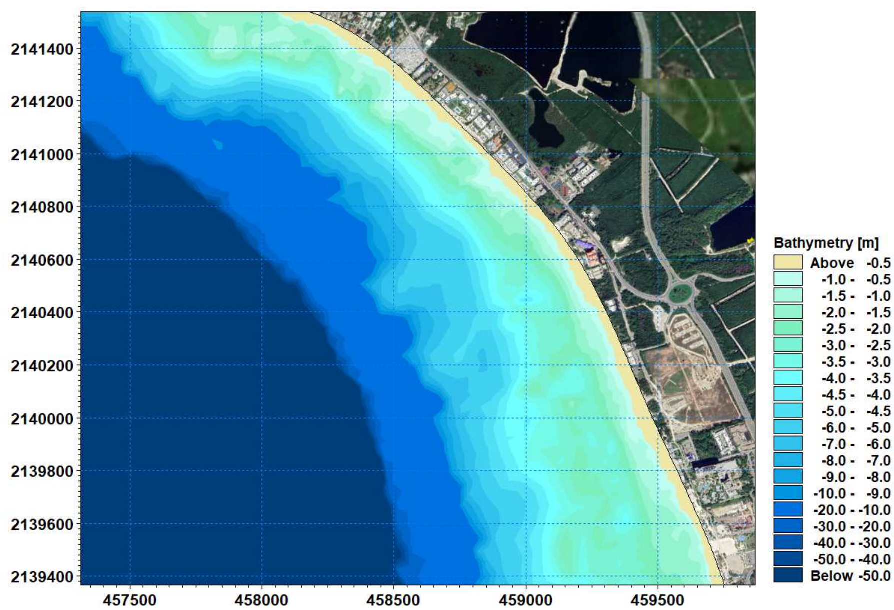

Figure 6-1 Detail of model bathymetry based on high resolution LIDAR data provided by DART.

6.2 Present seabed conditions along the shoreline

The state of the beach varies considerably along SMB. In Figure 6-2, Figure 6-3, and Figure 6-4 close ups of the shoreline along SMB are shown. In the southernmost part of SMB, the coast consists entirely of rock (Area 1). This location acts as a divergence point for the littoral current and longshore sediment transport. In the southern part of Area 1, the (potential) sediment transport current is directed towards south and in the northern part towards north. As a result, any sediment on the shoreline in this area will rapidly be washed away, either towards south or towards north. A little further towards north (Area 2) sandy beaches appear but they are quite narrow, and properties are located dangerously close to the waterline. This area is most vulnerable to damage caused by waves during storm events.

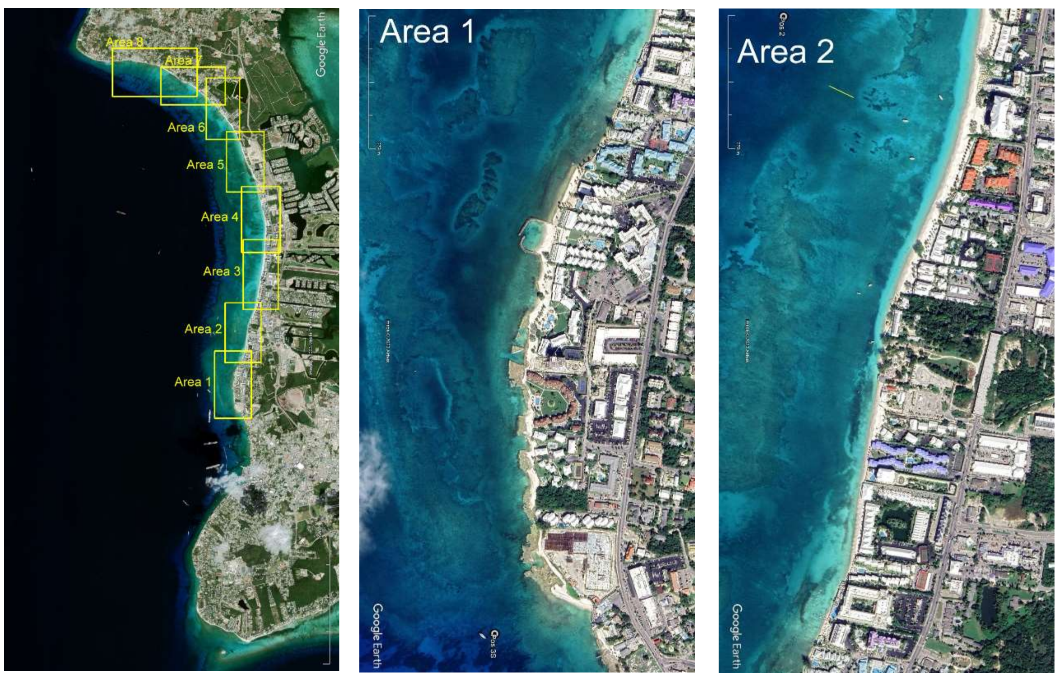

Figure 6-2 Overview of Sub areas and areas 1 and 2

In areas 3 ,4, and 5 the situation becomes gradually better. The beach is wider and permanent coastal infrastructure is located at a larger distance from the shoreline.

In the upper part of SMB, the beach gets narrower and in the northernmost stretch the coast consists of rock. In this part of SMB the orientation of the shoreline gets increasingly oblique compared to the prevailing wave direction. Therefore, no stable sandy beaches are found in this area. Any sand present on the shore would rapidly be transported towards south.

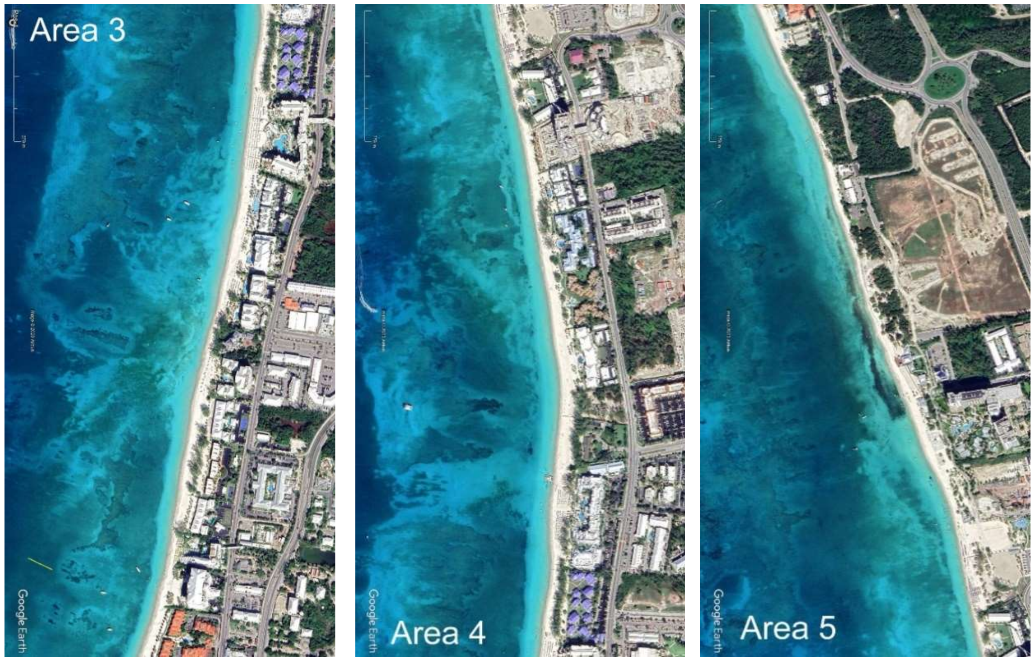

Figure 6-3 Sub areas 3,4 and 5

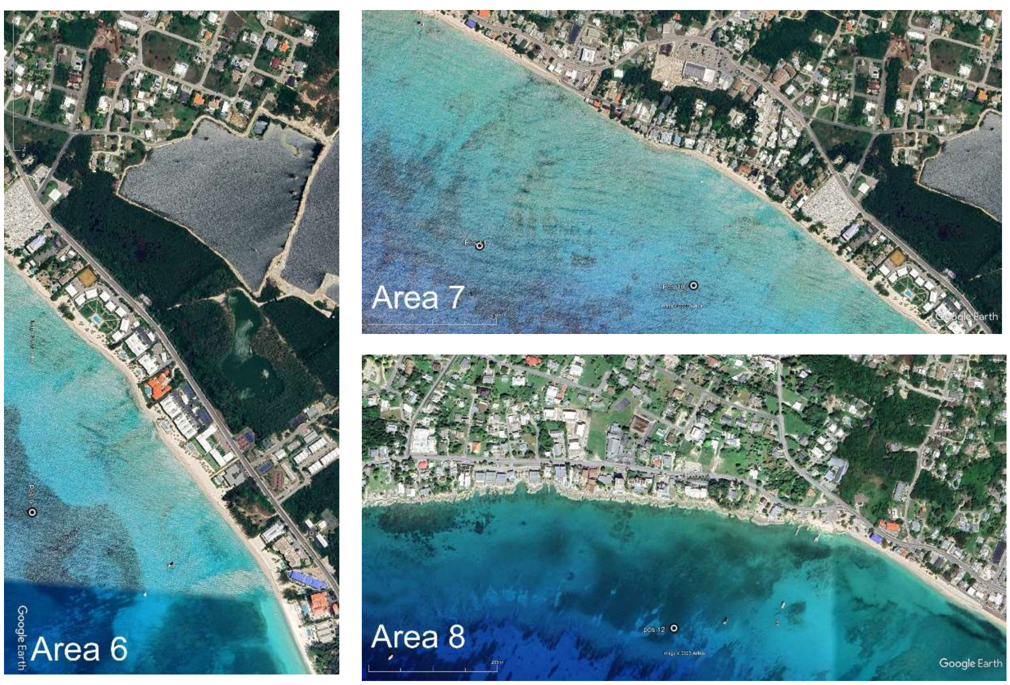

Figure 6-4 Sub areas 6,7 and 8

7 Meteomarine conditions at the project site

In this section an overview is presented of the Meteomarine conditions that are relevant for the shoreline dynamics at SMB

7.1 Offshore waves

In previous studies DHI has used offshore wave data from the GROW-FINE Caribbean-2 (GFC-2) Hindcast provided by Oceanweather. More details about these data are found in DHI (2020). These data provide an excellent source of offshore wave data. However, they do not resolve the generation and propagation of tropical storms and hurricanes in great detail. The reason for this is that the size of the storms, at least in their initial phase, is small compared to the spatial resolution applied in the model. Therefore, additional model simulations were carried out, specifically focussed on hurricanes as will be described in more detail in section 9. Figure 7-1 shows the offshore wave roses north- and south of Grand Cayman. In the offshore region, waves are typically between 1m and 2m high. Waves higher than 4.0 m occur rarely. The prevailing wave direction is ENE along the northern coast of Grand Cayman and ESE along the southern coast. As a result of its geographical settings, SMB is well protected from waves from easterly directions.

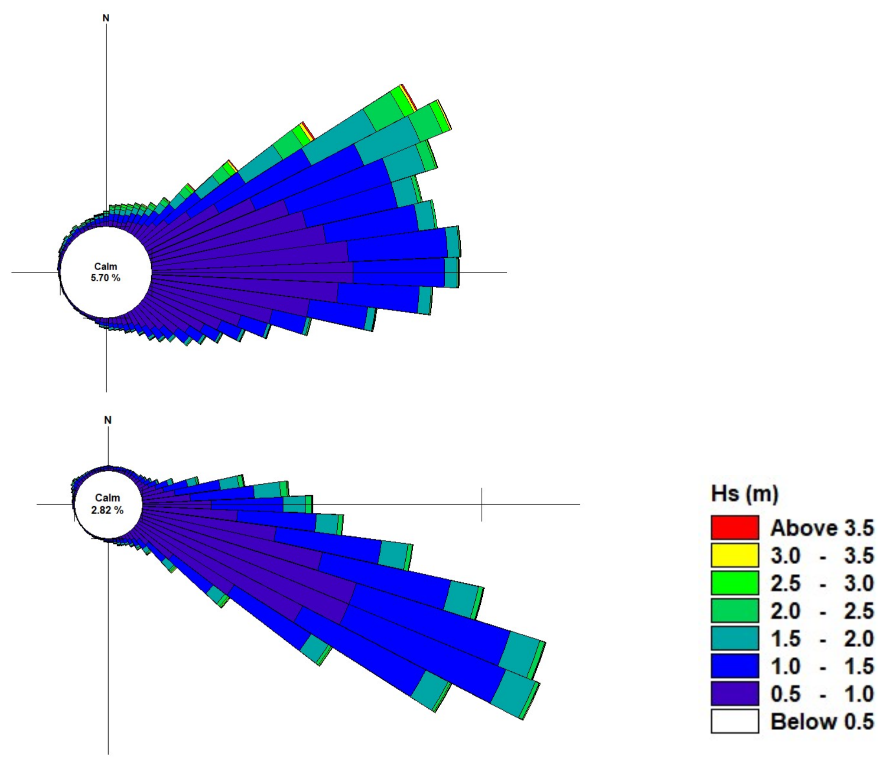

Figure 7-1 Offshore wave roses derived from GFC-2 data. Upper panel: North of Grand Cayman, lower panel; South of Grand Cayman. Source: DHI (2020)

7.2 Water levels

Water level variation due to astronomical tide is small with a maximal amplitude of around 0.25. During storms higher water levels are observed as a result of pressure differences and wind set-up (surge). Figure 7-2 shows a measured time series of water levels in three positions in front of SMB.

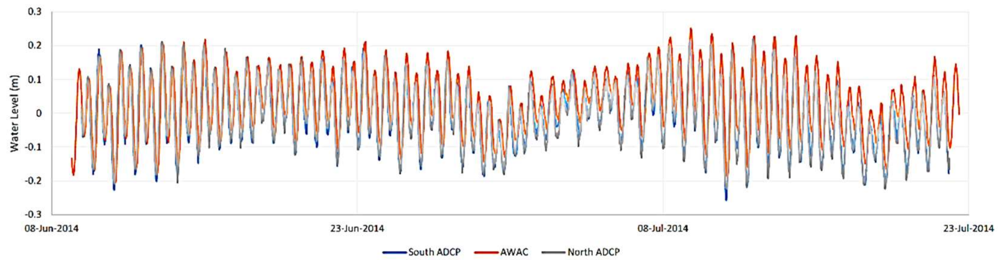

Figure 7-2 Measured water levels at SMB. Source: Baird (2015)

7.3 Currents

Ambient currents in front of SMB are generally weak and of no significance for the coastal sediment transport. Figure 7-3 shows a current rose based on measurements conducted in front of SMB at 15m depth. Details of the measurements can be found in Baird (2015).

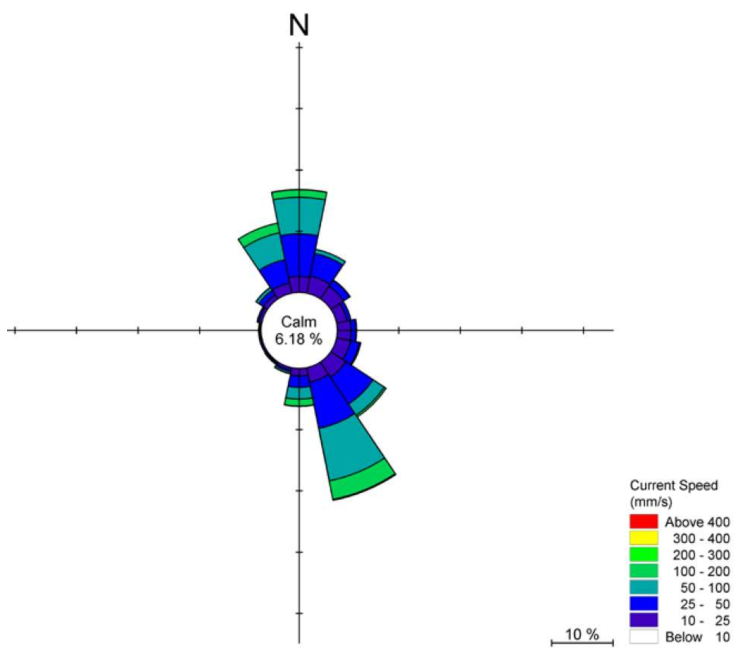

Figure 7-3 Current rose based on ADCP measurements at SMB in the period June 2014 – April 2015. Water depth: 15m, source: Baird (2015)

7.4 Wind

Wind data was derived from the Climate Forecast System Reanalysis (CFSR), NCEP, NOAA . The wind rose is shown in Figure 7-4. The average wind speed lies typically between 6 m/s and 8 m/s. The prevailing wind direction is ENE. It is noted that the wind data does not include hurricane data.

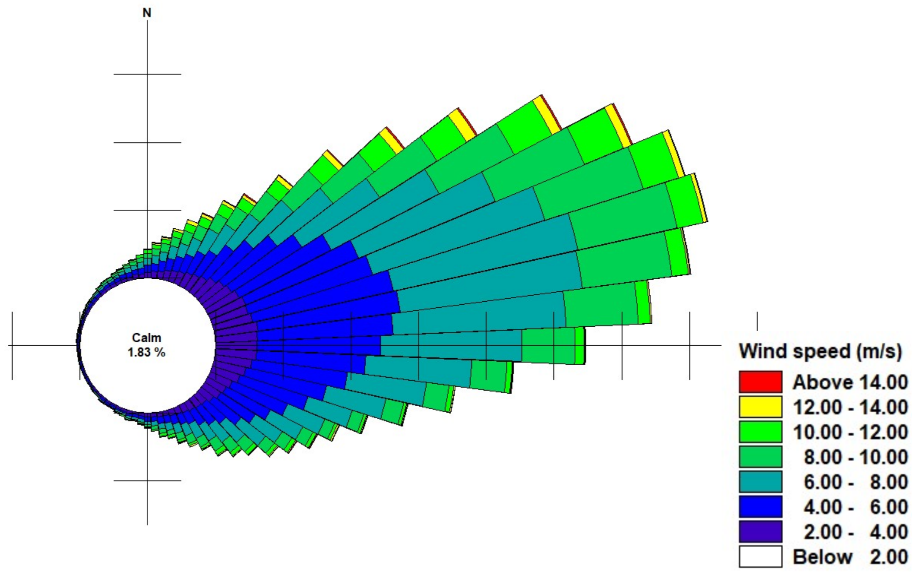

Figure 7-4 Offshore wind rose, source: CFSR (NOAA)

7.5 Sediment data

Sediments at SMB primarily consist of carbonate sand. Some variation in grain size was observed by. Grain size analyses indicate that the sediment corresponds to poorly graded sand, comprised mostly of medium sand and fine sand. The median grain diameter at the site is 0.36 mm (Figure 7-5)

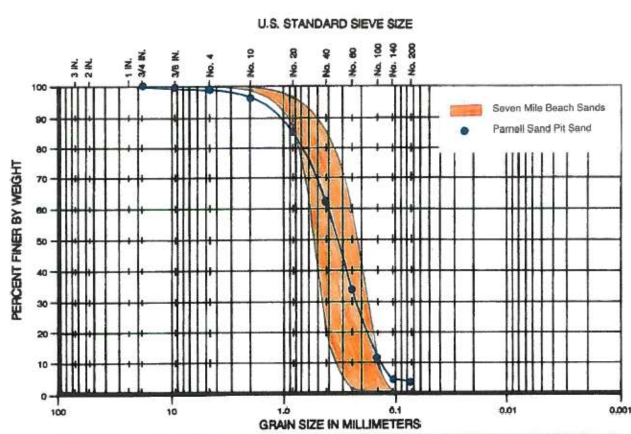

Figure 7-5 Sieve curve of the sediment at the study site. Source ATM (2017).

7.6 Hurricanes

Tropical storms and hurricanes are a known phenomenon in the region. However, SMB is rarely fully exposed to the waves generated by these events due its west ward orientation. In Table 7-1 the most important storms and hurricanes for the region for the period 2000 – 2022 are listed. Their trajectories are shown in Figure 7-6, Figure 7-7, Figure 7-8. The abbreviations used in the table refer to: T = Tropical storm, HU= Hurricane. MH = Major Hurricane.

Table 7-1 Overview of most important hurricanes for SMB in the period 2000-2022, source Hurdat2 (2021).

YEAR	Name	Period	Cat.
		mm/dd	
2000	Helene	09/15 - 09/25	T
2001	Iris	10/04 -10/09	MH
2001	Michelle	10/29 - 11/05	MH
2002	Isidore	09/14 - 09/27	MH
2002	Lili	09/21 - 10/04	MH
2003	Claudette	08/07 - 08/17	HU
2004	Bonnie	08/03 - 08/14	T
2004	Charley	08/09 - 08/15	HU
2004	Earl	08/13 - 08/15	T
2004	Ivan	09/02 - 09/24	MH
2005	Dennis	08/04 - 08/13	MH
2005	Emily	08/11 - 08/21	MH
2005	Wilma	10/15 - 10/26	HU
2007	Dean	08/13 - 08/23	MH
2007	Olga	12/11 - 12/12	T
2008	Gustav	08/25 - 09/04	MH
2008	Paloma	11/05 -11/09	MH
2020	Laura	08/20 - 08/29	MH
2020	Marco	08/21 - 08/25	HU
2020	Delta	10/04 - 10/10	MH
2020	Zeta	10/24 - 10/29	MH
2020	Eta	10/31 - 11/14	MH
2021	Ida	08/26 -09/01	MH
2021	Grace	08/13 - 08/21	MH
2022	Ian	09/23 - 09/30	H

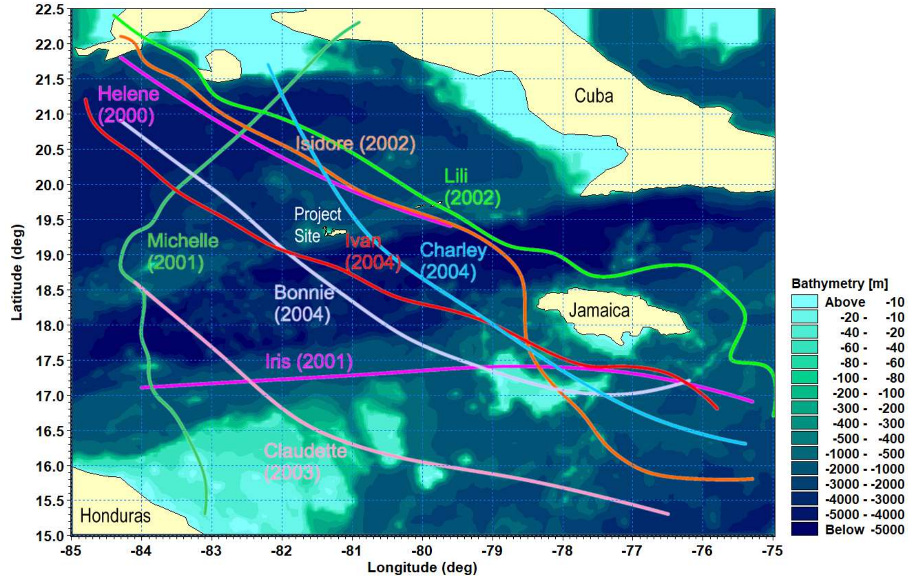

Figure 7-6 Trajectories of Tropical Cyclones near Grand Cayman for the period 2000-2004, Source: Hurdat2 (2021)

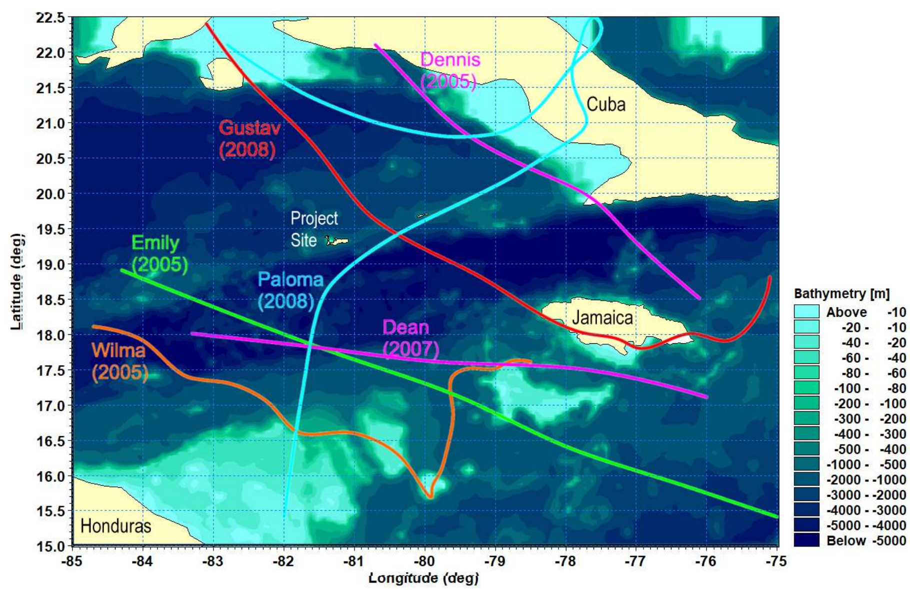

Figure 7-7 Trajectories of Tropical Cyclones near Grand Cayman for the period 2005-2009, Source: Hurdat2 (2021)

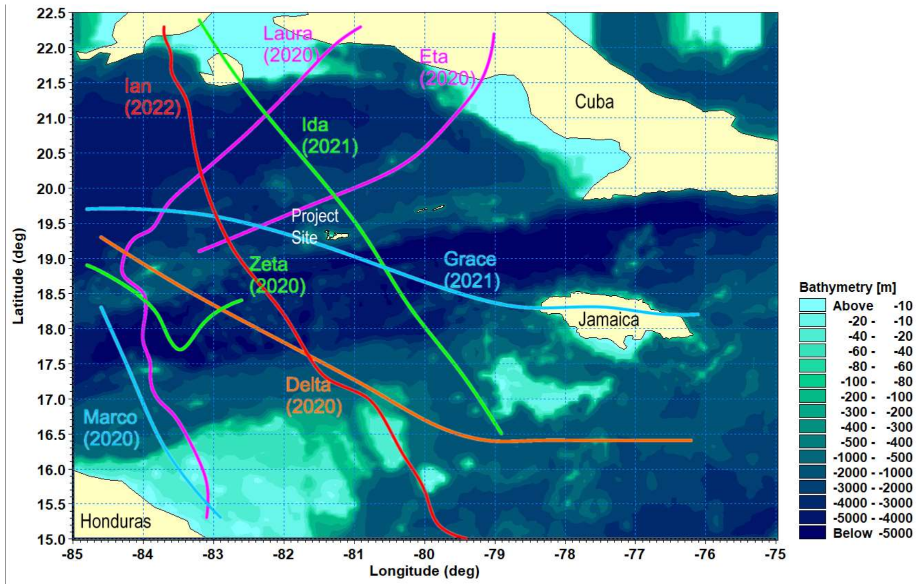

Figure 7-8 Trajectories of Tropical Cyclones near Grand Cayman for the period 2020-2022, Source: Hurdat2 (2021)

The most recent cyclone that approached the present shoreline was Ian (2022).

8 Waves and hydrodynamics under normal conditions

In this section a wave transformation study is presented to derive reliable nearshore wave and current conditions at the project site.

The propagation of waves from the offshore zone towards the coast was simulated using DHI's spectral wave model MIKE 21 SW. This is a state-of-the-art, internationally recognized, third generation spectral wind-wave model developed by DHI. The model simulates the growth, decay, and transformation of wind-generated waves in offshore and coastal areas. The model includes all physical phenomena that are of relevance for the present study such as 1)-wave growth by action of wind, 2)-Non-linear wave-wave interaction, 3)-Dissipation due to bottom friction, 4)- Dissipation due to depth-induced wave breaking, and 5)- Refraction and shoaling due to depth variations. Technical details of the model are provided in Appendix A. Model validation is described in DHI (2020).

8.1 Model domain and computational mesh

An unstructured triangular mesh covering the project area and the nearshore zone was prepared based on the available bathymetry data. The entire model domain is shown in Figure 7-1.

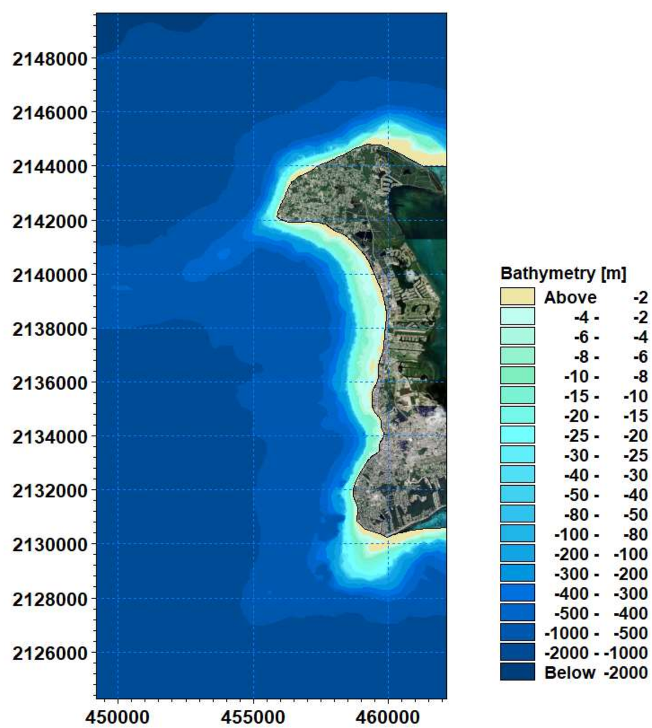

Figure 8-1 Model bathymetry applied in the simulations.

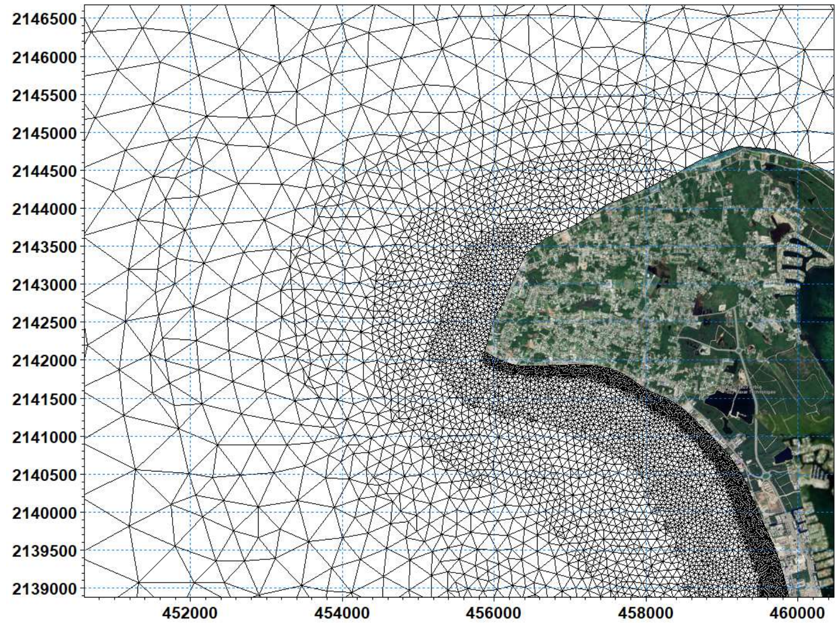

Figure 8-2 Detail of the computational grid used in the model simulations – area around the northern limit of SMB.

The resolution was graduated using finer resolutions in the areas between close to SMB. A detail of the computational mesh is shown in Figure 8-2.

8.2 Model set-up

The wind in the region mainly comes from eastern directions (see Figure 7-4). The north coast of Grand Cayman shelters for waves from southern directions. Therefore, waves mainly come from E to NE sector. Similarly, waves along the southern coast mainly come from SE to E. At SMB waves from both sectors are observed. Figure 8-3 shows an example of the wave conditions at SMB for waves from ESE. The model simulation shows the refraction of waves around the corners north and south of SMB. This example simulation was performed using an advanced non-linear wave model (MIKE 21 BW) that includes all wave transformation mechanism that are important for the propagation of irregular, directional waves from deep water to the shore. The results of the BW model were used to verify and confirm the adequacy of the spectral wave model (MIKE 21 SW) for the present purpose.

The model simulation illustrates that due to the effect of wave refraction, the wave height along SMB is strongly reduced compared to the offshore waves.

As a result of the sheltered location of SMB, wave conditions are normally very calm. Some seasonality can be observed in the wave conditions. During the summer months (May to October) waves are mainly coming from E-SE and during the winter from E-NE. Wave heights are generally somewhat higher during the winter months.

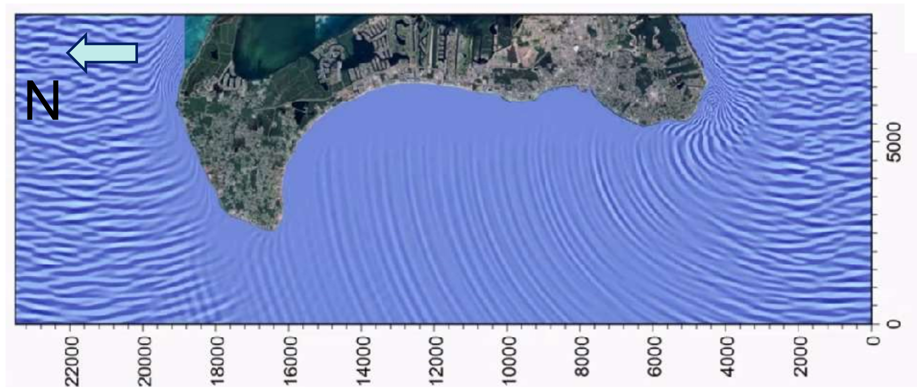

Figure 8-3 **Simulated wave field under normal conditions. Hs:1.5m, Tp=8s, MWD= ESE**

The spectral wave model was used to transform wave conditions from deep water to the coast. At the model boundaries offshore wave data, used in previous DHI studies, DHI (2020), were specified. A quasi-stationary formulation was applied in the wave model. A directional discretization of 10° (36 bins) was used. The bottom friction was described by the Nikuradse bed roughness with a domain constant value of 0.005m

8.3 Model results

Model results were extracted in a number of positions along the 5m depth contour. The analysis covered the period 2010-2022. The calculated nearshore wave statistics for three positions in the southern, central- and northern part of SMB are shown graphically in Figure 8-4.

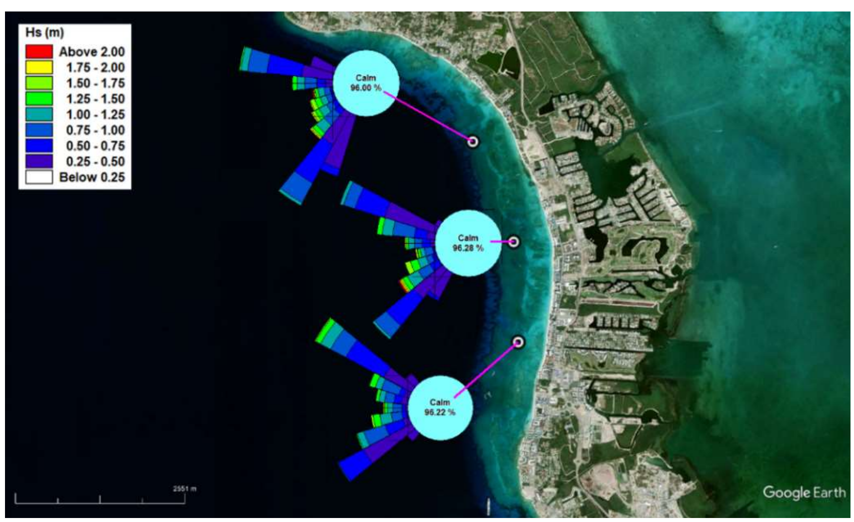

Figure 8-4 **Simulated wave roses along the 5m depth contour, period : (2010-2022).**

The data shows that most of the time waves are smaller than 0.25m. On a few occasions the wave height exceeds 1.0 m but only rarely exceeds 2.0 m.

It is important to note that SMB is highly sheltered for ocean waves as most waves at open sea come from eastern directions, as was shown in Figure 7-1. Only waves from northerly or southerly directions can refract around the headlands at both sides of SMB and propagate further to the shore. As can be seen from the wave rose shown in Figure 7-1, these waves only represent a small fraction of all waves that approach the Cayman Islands. To illustrate this, a test was made where the propagation of a wide range of waves was simulated in the model. The wave heights, - periods and – directions cover the range of wave parameters observed in the available offshore data. The model results were extracted in the central part of SMB in a water depth of 5m. The results are shown in Figure 8-5. The figure shows the ratio of the inshore - and offshore wave height as function of the offshore wave direction. The results show that waves from East (90 degrees on the horizontal axis) practically do not reach SMB as their height, Hs, gets reduced to less than 5% compared to their offshore height, Hs0. Waves from North (0 degrees) are reduced to around 10 to 20 percent of their original height. Waves from West (270 degrees) are able to approach SMB unhindered (Hs/Hs0 ~1.0). Their height is not reduced by wave refraction. However, variations in wave height occur as a result of the wave period. High, short waves typically loose energy due to steepness breaking once they enter shallow water, (Hs/Hs0 < 1). Small, long waves increase in height as a result of shoaling, (Hs/Hs0 > 1).

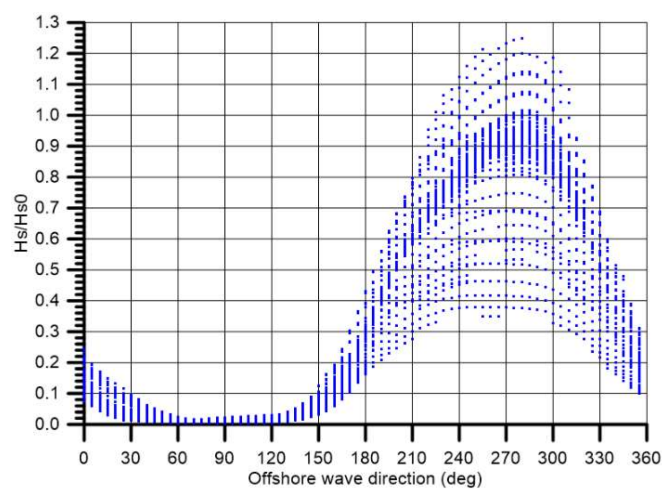

Figure 8-5 Simulated inshore wave height (in 5m depth) in the central part of SMB as function of offshore wave height and – direction.

8.3.1 Variations in annual nearshore wave statistics

From many other studies around the world, it is known that offshore wave conditions can vary significantly in time. Such variations occur on different time scales varying from single storm events and seasons to years and even decades.

To illustrate the importance of annual variations in wave conditions along SMB an analysis was made where only waves from the direction interval [NW – NNE] were considered. This direction interval is associated with the occurrence of winter storms from north-westerly directions, normally referred to as "nor' westers". Waves from all other (offshore) directions were excluded from this analysis.

Figure 8-6 shows the annual distribution of wave energy per wave height interval for the entire period covered by the data. The energy levels are given relative to the average wave energy over the entire period (1979-2022). A value of 100% thus represents an average year whereas values above and below 100% represent more energetic- and calmer years respectively. The red and purple colours indicate the events with high waves, normally associated with storms. The blue colours represent calmer conditions. The red line represent average conditions.

The analysis indicates that significant variations in wave energy occurred over the past decades. Years with relatively strong wave incidence, with a pronounced contribution from the highest (storm) waves, were 1984, 1989, 1993, 2002 and 2006. The data suggests that the intensity and/or frequency of nor' westers has reduced since the early 2000s, especially over the past 10 years. These variations have a pronounced impact on the littoral sediment transport and coastal sediment balance for SMB as will be shown in section 10.

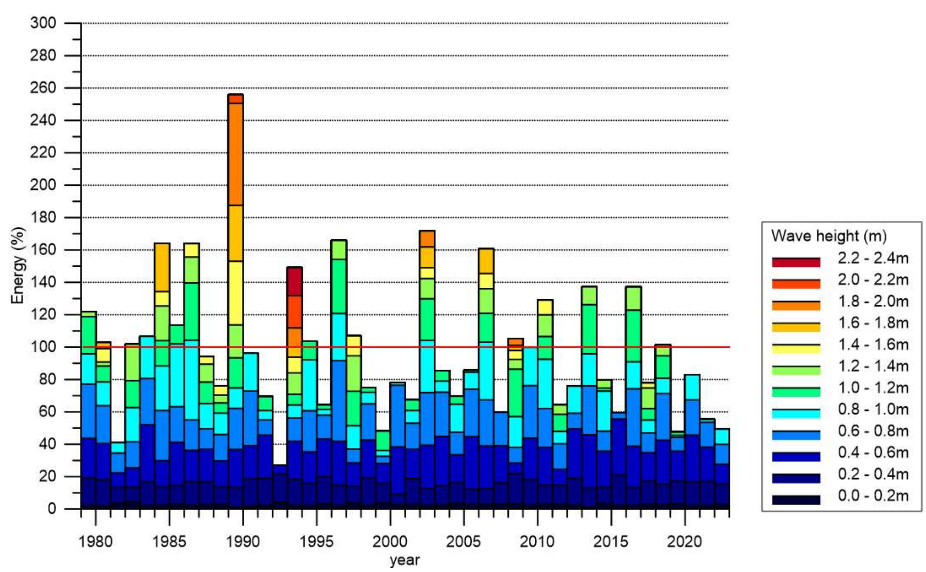

Figure 8-6 Simulated annual distribution of wave energy per wave height interval for the period 1979 – 2022 in the central part of SMB (water depth: 5m). Only offshore waves from the direction interval [NW-NNE] were considered.

It is noted that the data presented here only include wave events during normal conditions, including nor´westers. The data does not include hurricanes, which will be analysed separately in the next section.

9 Waves and coastal hydrodynamics during Storms and Hurricanes

Storms and hurricanes play an important role for the coastal sediment balance and shoreline dynamics along SMB. In this section waves, currents and water levels generated during the most important storm events since 2000 are analysed.

9.1 Generation of wind fields

The generation and evolution of wind - and wave fields during hurricanes occurs on spatial scales that are small compared to the spatial resolutions applied in global wave models. Therefore, wave data provided by Oceanweather, that was used in the previous studies are not optimal to represent waves generated by hurricanes.

In order to analyse the effect of storms and hurricanes on the hydrodynamic conditions at the project site, simulations were made using the Cyclone Wind Generation tool that is included in DHI’s MIKE 21 model suite. This tool allows users to compute wind and pressure data due to a tropical storm or hurricane. Wind and pressure data generated by a hurricane can be described by simple parametric models based on few parameters like position of the cyclone's eye, radius of the maximum winds, etc. These parameters are available through the hurdat2 data base provided by the hurricane research division of the National Oceanic and Atmospheric Administration (NOAA). More detailed information is found at https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html.

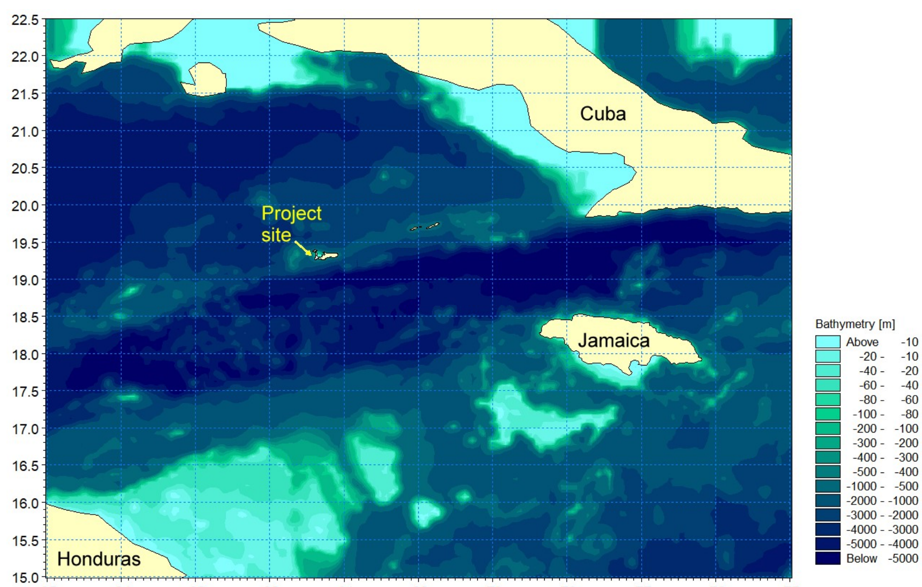

Figure 9-1 Regional-scale model for generation of wind and wave fields

The data base provides the geographical coordinates (longitude, latitude) of the storm at various time steps. For each time main parameters such as pressure at the eye of the storm, maximal wind speed and radius of the storm are given.

These parameters are then used in MIKE 21's tool to calculate wind and pressure fields in a regional-scale model that covers a large area around the Cayman Islands. The model domain is shown in Figure 9-1. An example of a wind field generated using MIKE 21 is shown in Figure 9-2.

The figure shows the wind speed at 4 different time steps during Hurricane Ivan (2004). The model results indicate wind speeds exceeding 60 m/s at grand Cayman during the peak of the storm.

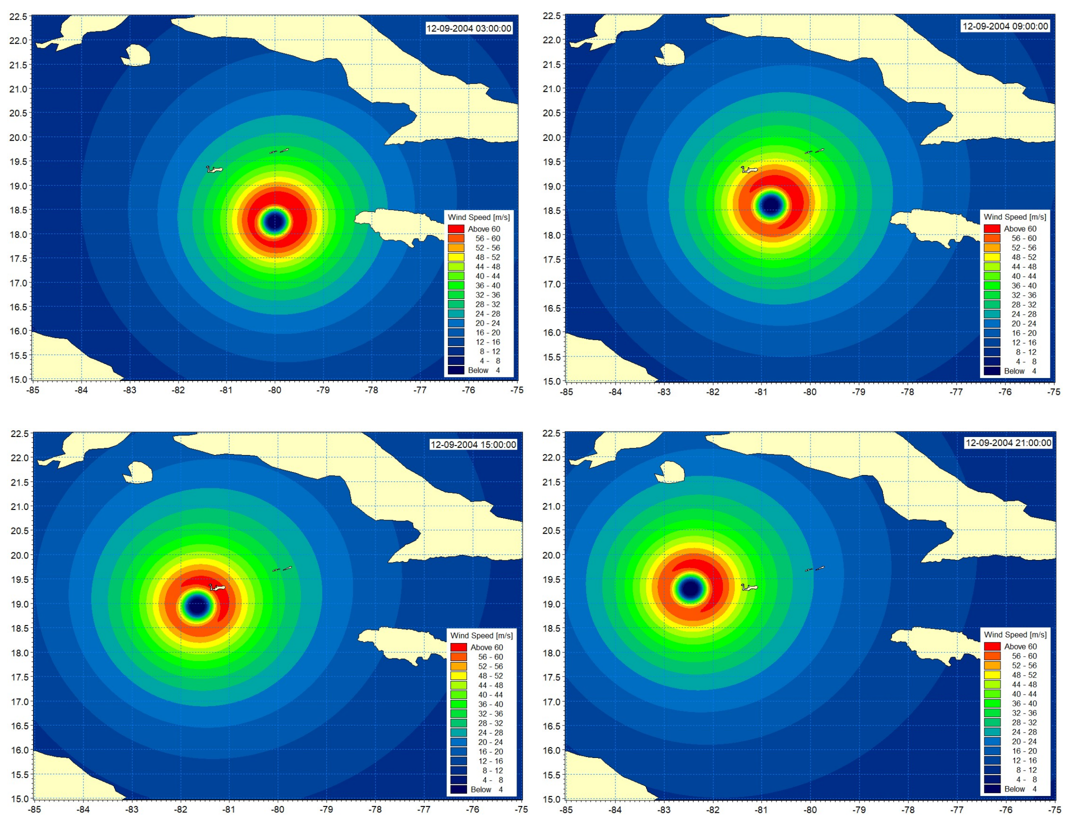

Figure 9-2 Simulated wind fields during Hurricane Ivan (2004)

Obviously, the representation of complex meteorological conditions by a few key parameters is a serious simplification of reality. Therefore, the calculated wind fields must be considered indicative only. The objective of the present analysis is not to simulate wind and pressure fields during storm events in great detail but rather to get a rough impression of the wave conditions at SMB during these events. The wave conditions and associated sediment transport rates during hurricanes are then compared to normal conditions. On the basis of this comparison the importance of hurricanes on the coastal sediment balance for SMB can be analysed, both on short and long time scales.

9.2 Generation of waves and currents

In the present study, wind generated waves, currents and water levels were simulated using a hydrodynamic model that runs simultaneously, and dynamically coupled, to the spectral wave model.

During storms, the wind exerts a force on the sea surface. This wind force is responsible for the generation of waves, currents, and water level variations near SMB. The wind stress causes elevation of the water surface at the coast (wind set-up). In addition, variations in air pressure during storms can cause additional water level elevation near the coast. Finally, the hydrodynamic forces associated with wave breaking (radiation stress) cause elevation of the water level across the wave breaking zone (wave set-up).

The generated wind- and pressure fields were used as forcing mechanisms for the coupled hydrodynamic model (MIKE 21 HD FM) and spectral wave model MIKE 21 SW FM.

9.2.1 Wave generation and propagation

At the seaward model boundary of the hydrodynamic model, water level variations, derived from DHI's global tidal model were imposed. Forces exerted by wind as well as wave generated forces (radiation stress gradients) were included as forcing mechanisms in the models.

Bed resistance was defined by means of the Manning number, which was set with a domain constant value of 40 $m^{1/3}/s$.

The wave model was applied in non-stationary, fully spectral mode, enabling the simulation of the detailed spatial – and temporal evolution of wave fields generated by the storm. The simulations were carried out in two steps, first water levels and wind generated wave fields were simulated in a regional-scale model that covers a large part of the Caribbean Sea (see Figure 9-1). Simulated water levels and wave spectra were stored along the boundary of a second, local-scale, model with a higher spatial resolution.

Figure 9-3 and Figure 9-4 show snapshots of the simulated wave fields during Hurricane Ivan (2004) in the area around Grand Cayman. The model results show that SMB is sheltered for waves during the peak of the storm when the highest wind speeds hit the Island, see Figure 9-3. After the eye of the storm has moved further towards west, SMB gets fully exposed to waves from west, see Figure 9-4.

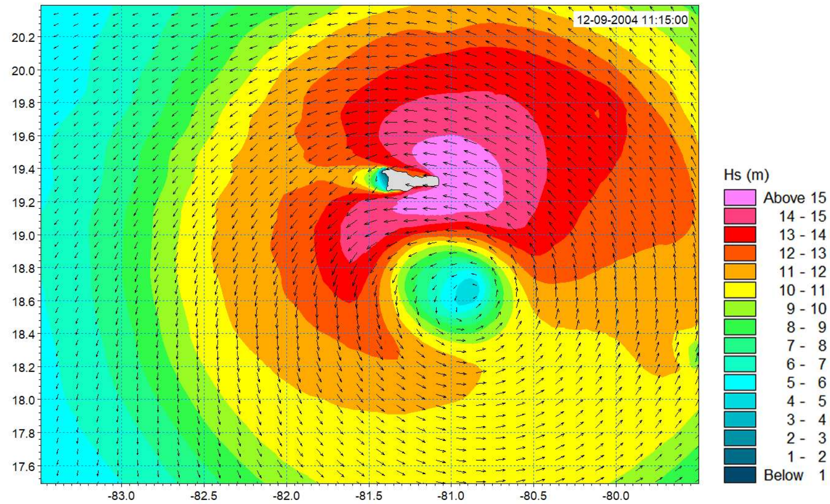

Figure 9-3 Snapshot of the simulated wave field during the peak of Hurricane Ivan (2004). The SMB is sheltered from direct wave attack.

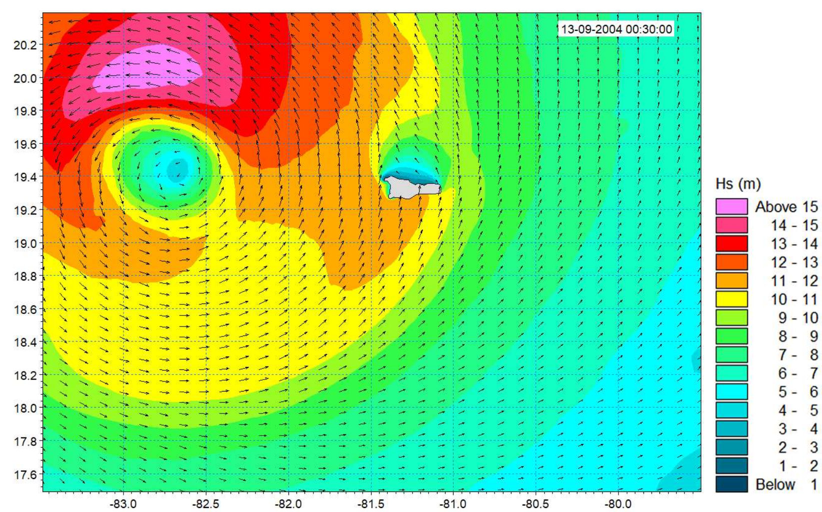

Figure 9-4 Snapshot of the simulated wave field after the passage of the eye of Hurricane Ivan (2004). The SMB is exposed to direct wave attack from west.

The propagation of waves across the reef and the shallow waters in front of SMB were simulated using a local-scale model with a high spatial resolution. The model domain of the local-scale model is shown in Figure 9-5.

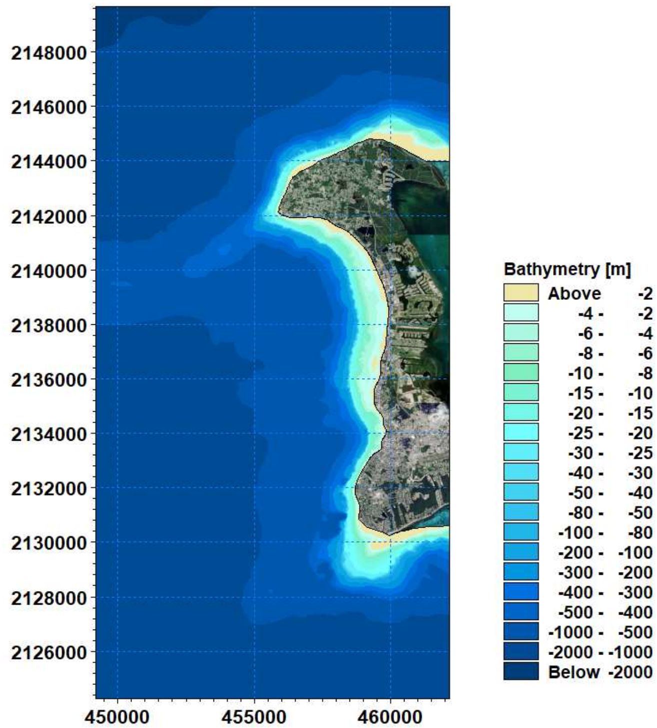

Figure 9-5 Model domain for local-scale model.

In the local-scale model, waves, water levels and currents were simulated in the same way as in the regional scale model, by dynamically coupling wave and hydrodynamic models. In this way, the effect of water level elevations during storms can be simulated in detail, including the combined effect of wind and wave generate forces on the water surface.

A detail of a simulated wave field during Hurricane Grace (2021) is shown in Figure 9-6. The model results show quite complex wave patterns that are determined by the bathymetry. Rocky outcrops in the nearshore zone cause local wave breaking. In the gaps in between the rocky areas, waves are able to penetrate further towards the shoreline. The figure clearly shows how the reef and shoal provide protection against wave attack on the shore. For the present case, the wave height just seaward of the reef is around 3.5 m. Near the shoreline the wave height has reduced to around 0.5 m as a result of wave breaking on the shoal. It is clear that the water surface elevation plays a crucial role in the amount of wave energy that is able to cross the shoal and reach the shoreline.

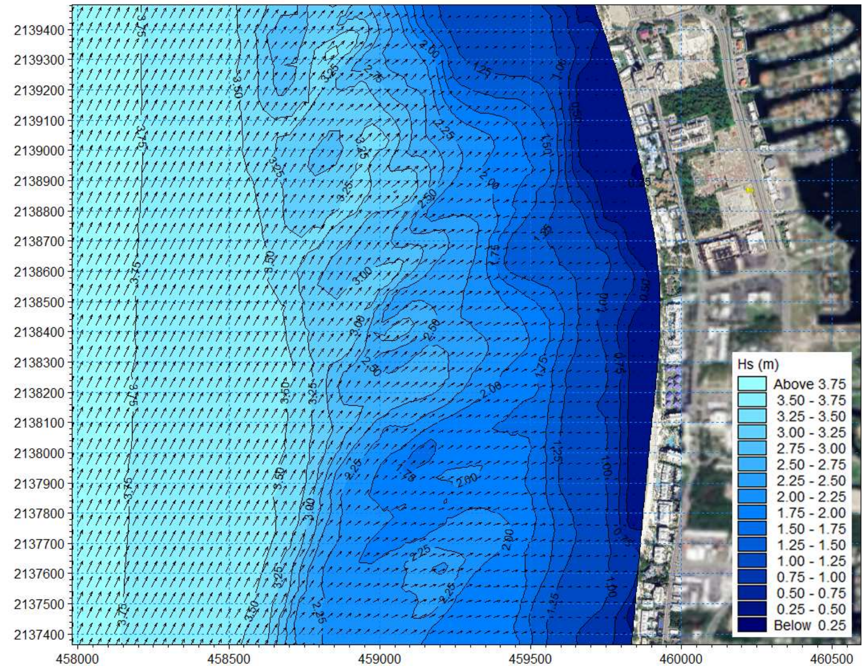

Figure 9-6 Detail of simulated wave field during Hurricane Grace (2021)

An example of the nearshore flow conditions during a storm is shown in Figure 9-7. The vectors represent the flow speed and – direction in a small area along SMB. The model results show complex flow patterns across the shoal. Just like the wave conditions, flow patterns are strongly determined by the local bathymetry.

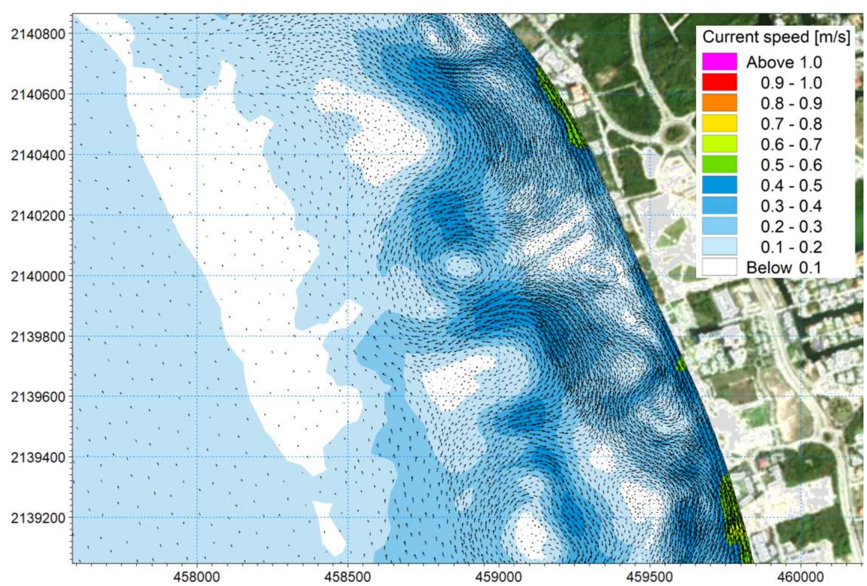

Figure 9-7 Complex wind- and wave driven flow patterns as a result of nearshore bathymetry.

It is important to notice that currents are often not directed parallel to the shoreline, as is the case for calm conditions. Several large scale vortices can be observed that stretch from the shoreline to several hundreds of metres further seaward. Such currents are able to carry sand from the shoreline to deeper waters in front of the beach. A part of this sediment will gradually be transported back to the shore during calm periods after the storm. However, under certain conditions the currents carry the sand too far from the shoreline. If the currents carry the sand beyond the edge of the reef, then the sand will be forever lost to deep water. Sand that has settled in relatively deep water (depth >10m) near the edge of the reef cannot be transported back to the shore by the waves and currents. This sand is likely to remain in this location until it gets pushed over the edge by the currents during a following storm event.

9.3 Example of Hurricane Ian (2022)

To illustrate the wave conditions at SMB during a hurricane an example is presented showing Hurricane Ian (2022). This has been quite a strong storm during recent years.

Figure 9-8 shows the time variation of the wind speed and – direction at SMB, calculated using the wind generation of MIKE 21 as mentioned above. The calculated wind speed reached values of around 35 m/s and the wind direction gradually changes from North to East and then further to South and finally WSW.

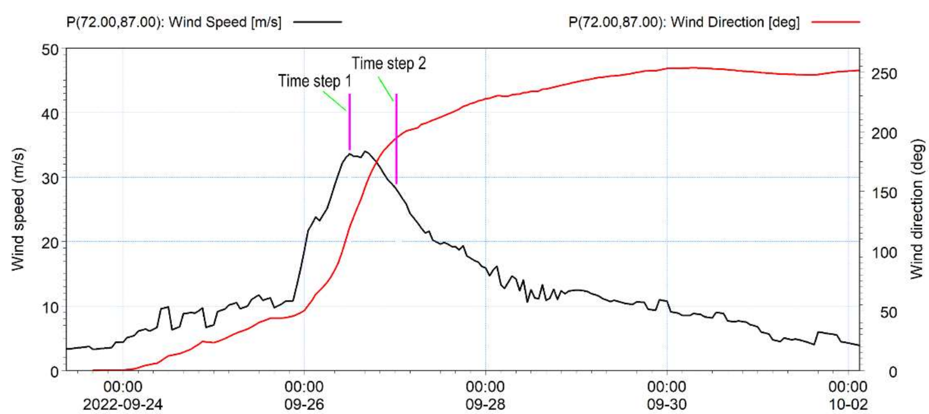

Figure 9-8 Time variation of wind speed and – direction at SMB during hurricane Ian (2022)

The generated wind field was used to generate waves using the 2-step approach presented above. Model results were derived in three locations along SMB, all in deep water e.g., where the waves are not affected by the seabed. The output locations are shown in Figure 9-9.

Figure 9-9 Output locations for wave parameters in front of SMB.

The time variation of the simulated significant wave height, peak wave period and mean wave direction are shown in Figure 9-10. The waves reach a maximum height of around 9 m with a corresponding peak wave period of around 14 s. The mean wave direction varies from S at the start of the storm to WNW.

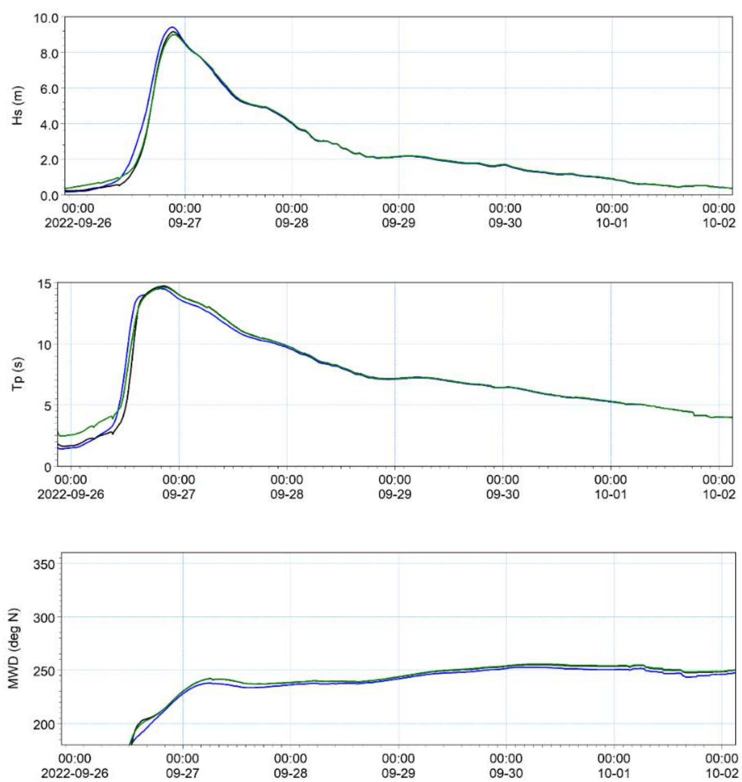

Figure 9-10 Time variation of wave parameters in from of SMB during Hurricane Ian (2022). Top: significant Wave height, middle: Peak wave period, bottom: Mean wave direction

Figure 9-11 and Figure 9-12 show the wave fields around Grand Cayman at two time steps during Hurricane Ian (2022). The time steps are indicated in Figure 9-8 and correspond to the peak of the storm and the moment after the peak with highest incident waves at SMB respectively.

The model simulations show waves with maximal heights of around 13m approaching the Island from the South. The wave direction at the peak of the storm was SSE. This means that waves were propagating almost parallel to SMB. Consequently, SMB was quite sheltered from these waves at the peak of the storm.

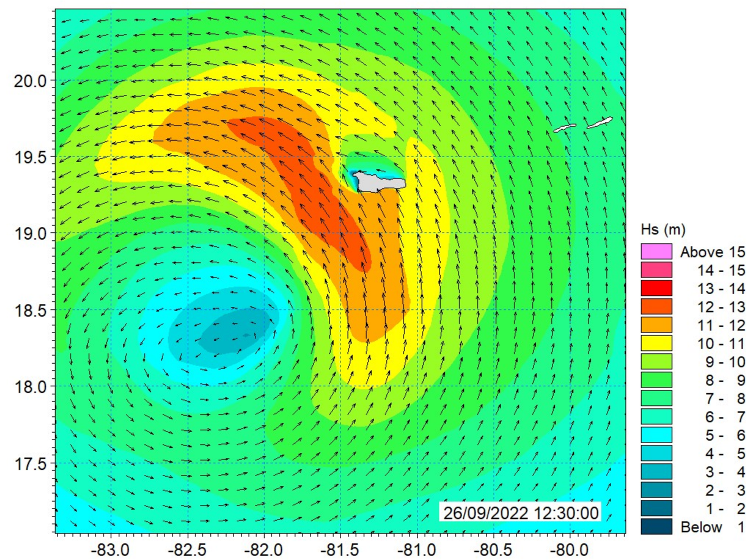

Figure 9-11 Waves during Ian (2022) – Peak of the storm, SMB is relatively sheltered for direct incident waves.

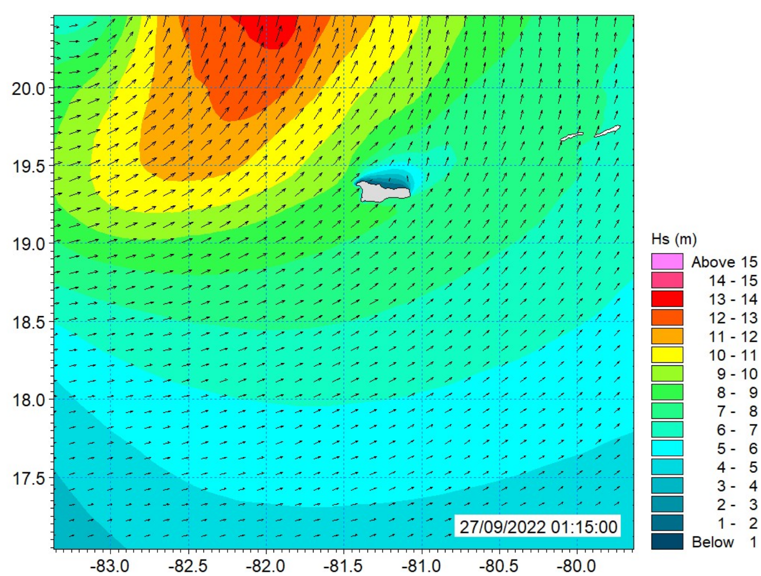

Figure 9-12 Waves during Ian (2022) – After the eye of the storm has passed Grand Cayman, SMB is fully exposed to large waves from SW.

Figure 9-12 shows the wave field approximately 13 hours later, when the eye of the storm had passed the Island and was now located NW of the Island. At this moment waves with heights of 8 to 9m approached SMB from SW, which corresponds to an angle of approximately 45 degrees with the shore normal in the central part of SMB.

The simulated wave fields at SMB are shown for both time steps in Figure 9-13. The strong reduction in wave height in front of SMB illustrates how the reef and the shoal provide shelter for large incident waves along SMB.

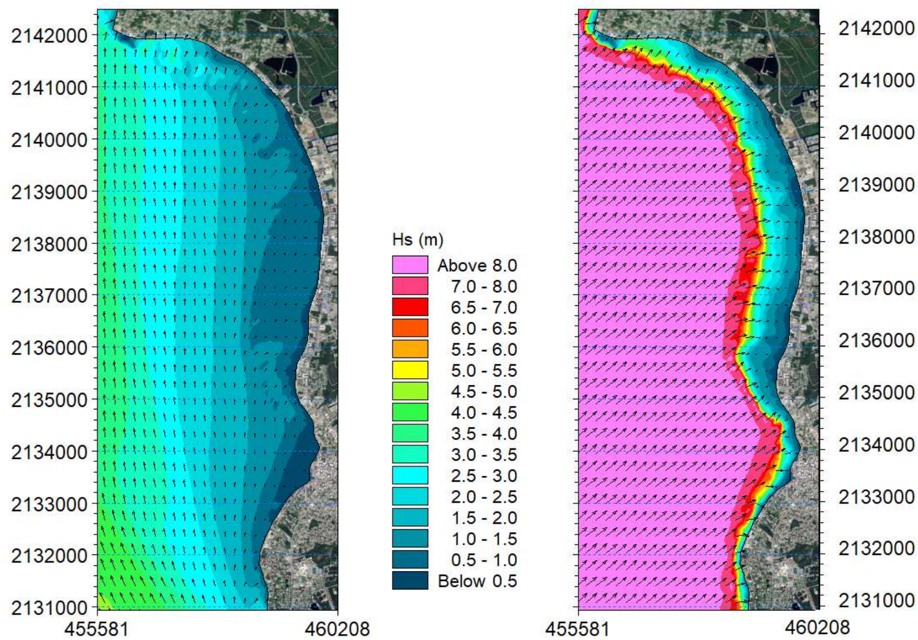

Figure 9-13 Simulated wave fields at two time steps during Hurricane Ian (2022), Left. Peak of the storm right: time step with maximal wave exposure at SMB (13 hours after the peak)

The elevation of the water surface is shown in Figure 9-14. The calculations show only very little elevation during the peak of the storm (left figure), possibly caused by the low air pressure. After the eye of the storm has passed, and waves approach SMB directly, the water surface elevation increased to around 0.9 m in the southern part of the beach and around 0.7 m in the north-eastern part. The relatively high water levels in the southern part (in front of Georgetown Villas and Sunset Cove) are due to the convergence of wave energy to this location, see Figure 9-13. The local bathymetry acts as a lens and causes a concentration of wave energy, which is reflected in an increased wave height. This results in a higher wave-setup than in other areas. The relative maximum in the north-eastern part of SMB is also mainly caused by waves. This is the location along SMB where the angle between the waves and the shore normal is smallest. Here the highest wave set-up can be expected.

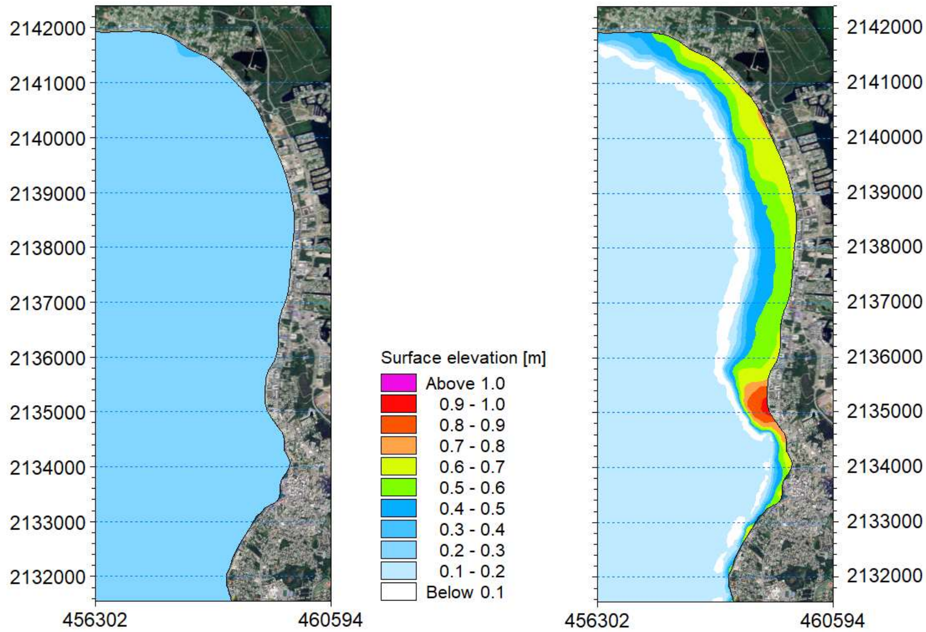

Figure 9-14 simulated water surface elevations at two time steps during Hurricane Ian (2022), Left. Peak of the storm right: time step with maximal wave exposure at SMB (13 hours after the peak)

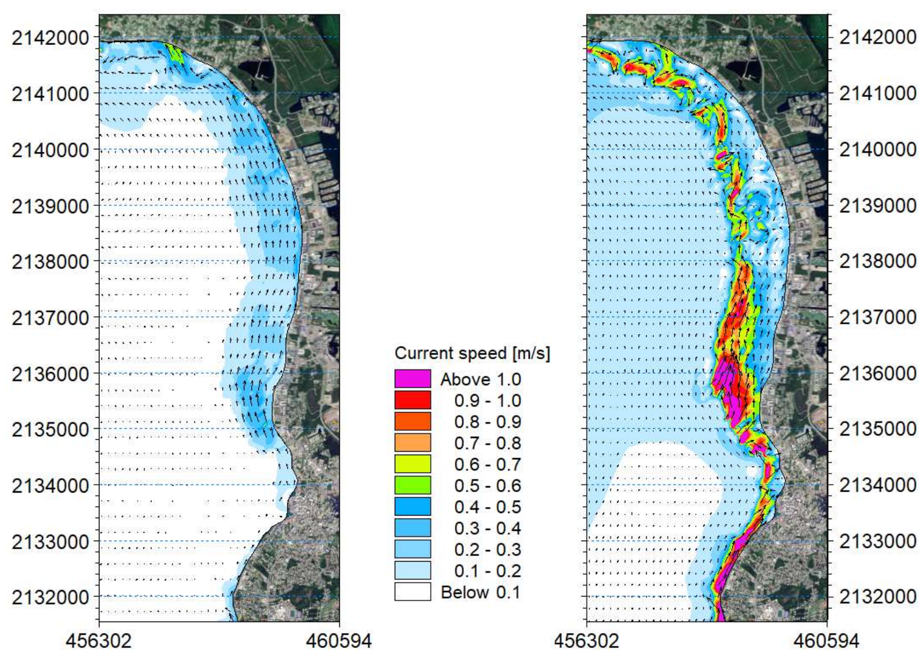

Figure 9-15 Simulated flow fields elevations at two time steps during Hurricane Ian (2022), Left. Peak of the storm right: time step with maximal wave exposure at SMB (13 hours after the peak)

The flow generated by the combined action of wind and waves is shown in Figure 9-15. The model simulations show an almost uniform current along the shore at the peak of the storm. This current is mostly generated by the wind, which is at its peak, while waves are relatively small. In the period after the peak of the storm the current pattern becomes increasingly irregular. In the southern part of SMB, the current is mostly concentrated around the edge of the reef, where current velocities locally exceed 1 m/s. Further towards north, large-scale vortices can be observed that range across the entire width of the shoal. This current is mostly generated by breaking waves. The irregular patterns of the flow occur due to local variations in wave breaking intensity. These variations are caused by the irregular bathymetry (i.e., rocky outcrops and sandy areas).

10 Coastal sediment balance and shoreline dynamics

In this section sediment transport along SMB is analysed. A distinction is made between sediment transport under normal conditions and during storm events.

10.1 Longshore sediment transport under normal conditions

Sediment transport rates were simulated using DHI's littoral sediment transport modelling system LITPACK. This model resolves the wave propagation and breaking in the surf zone, the wave-generated longshore currents, and the littoral sediment transport due to the combined wave-current motion. LITPACK is a so-called line model that assumes local uniform conditions along the shore. This is justified for the present situation with a relatively long and undisturbed shoreline. The advantage of the LITPACK model is that it is not as computationally demanding as a full 2D model. This allows for a very high spatial resolution in the model and a large number of simulated wave events, representing the period of data availability 1979-2022 at 1-hr intervals. The sediment model is highly deterministic where all dominant physical sediment transport processes are resolved in detail. This makes LITPACK a very reliable and robust engineering tool, that is significantly less depending on calibration procedures using local measured data than other modelling systems.

The available offshore wave data does not resolve the occurrence of hurricanes very well. The reason for this is that the computational grid used to simulate these offshore data is too coarse to resolve the dynamics of a single storm. The diameter of the storms is of the same order of magnitude as the spatial resolution of the grid. Therefore, wave generation and sediment transport during these events were analysed separately.

The calculations were made using a typical cross shore profile, derived from available bathymetric data. The simulated mean annual sediment transport for a section in the central part of SMB is shown in Figure 10-1. The calculations represent average values over the past 10 years. The black line represents the annual mean longshore sediment transport. The model calculations indicate a small net transport towards south. The accumulated northward and southward directed sediment transport rates are represented by the green - and blue curves respectively.

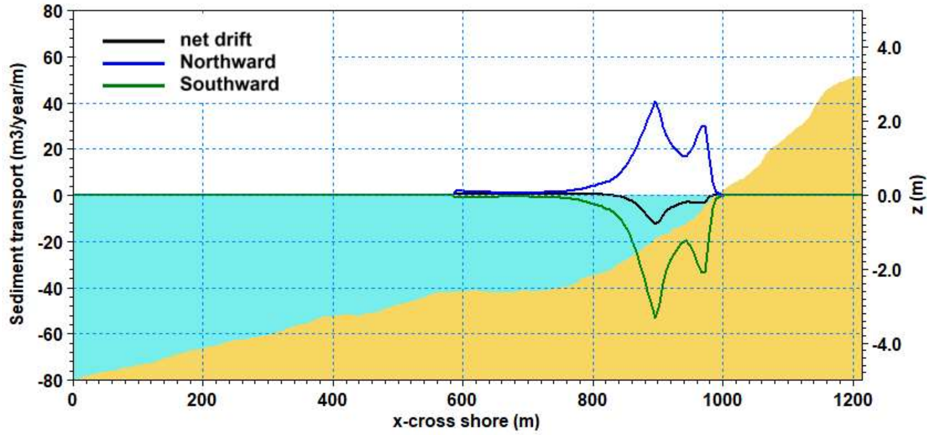

Figure 10-1 Cross-shore distribution of annual longshore sediment transport (littoral drift)

The model results show that the bulk of the annual transport under normal conditions occurs in a narrow zone of around 150 m from the shoreline in water depths less than 2 m.

Figure 10-2 shows the calculated annual variation in the littoral drift for the entire period (1979-2022). The red line represents the net annual sediment transport for each year. The blue and green histograms represent the annual north – and southward components of the annual transport respectively. The calculations indicate that the magnitude of the net annual drift has varied quite considerably over the past decades.

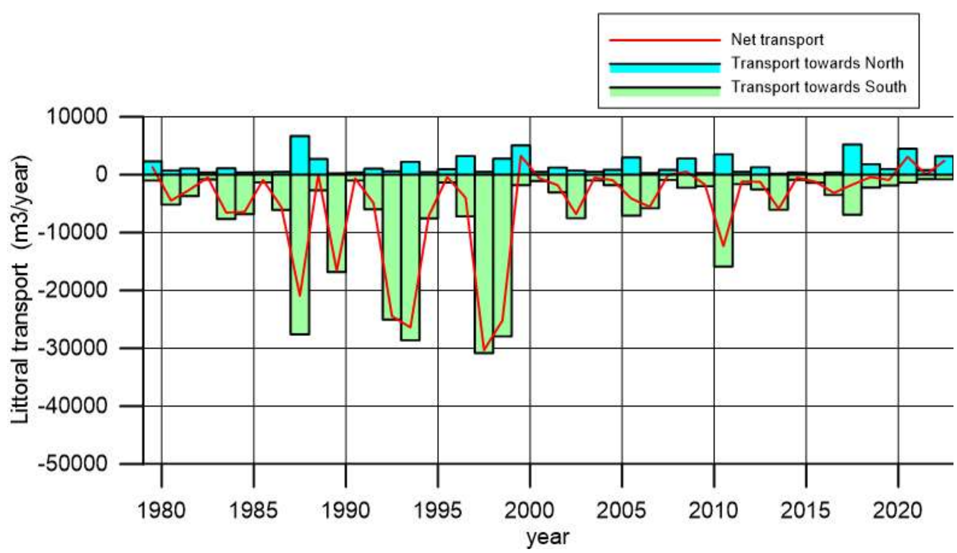

Figure 10-2 Annual variation in littoral sediment transport during the period 1979 – 2022

What is most noticeable are the peaks in southward directed transport during the 1980s and 1990s. These peaks in southward directed transport are likely to be caused by varying intensities of north-westerly storms. Apparently, the intensity of these events has reduced since 2000.

Significant variations in sediment transport occur throughout the year. Figure 10-3 shows the calculated monthly variation in sediment transport. The values represent average transport rates over the past 10 years. The calculations show that sediment transport is mainly directed towards North in September and October. In the period Nov-April the transport is mainly directed towards south. The months June and July are very calm months with very low sediment transport rates.

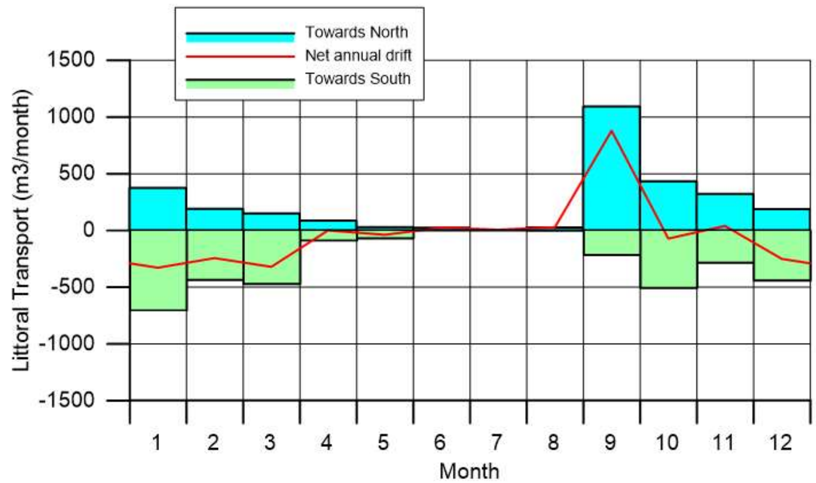

Figure 10-3 Monthly distribution of littoral sediment transport

Calculations of the annual longshore sediment transport were made for a series of cross sections along SMB. At the seaward boundaries of these sections, located along the 5m depth contour, wave data derived from the wave transformation model were specified. The location of the cross sections used in the calculations are shown in Figure 10-4.

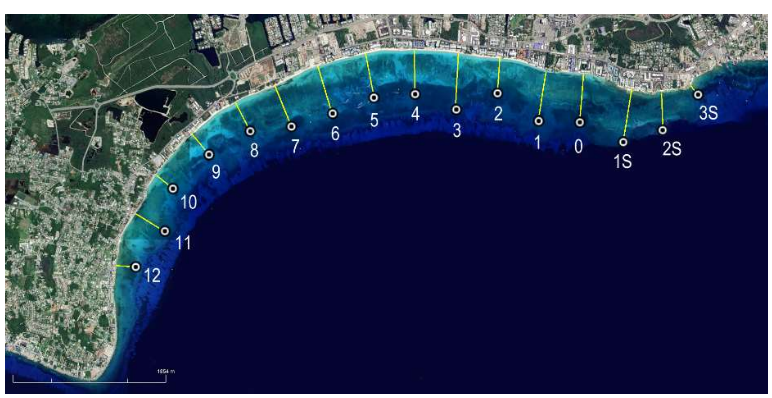

Figure 10-4 Location of cross sections used in the calculation of the annual sediment transport for normal conditions.

The variation of the net annual drift along SMB, under normal conditions, calculated over the past 10 years, is shown in Figure 10-5. The model simulations indicate that the net transport is relatively small with a slight tendency to southward transport. It is noted that the littoral transport at both ends of SMB are practically zero, because no sediment is observed in these areas, the coastline consists entirely of rock. In the northern end of SMB, a strong southward directed transport capacity was calculated. In the southern end the transport capacity is directed towards north. This means that, during normal conditions, the sediment is well confined along the main part of the beach, basically between positions 0 in the south and 12 in the north. In the outer areas sediment simply cannot be kept on the beach. In positions between 3S and 0 (see Figure 10-5) sediment will be transported towards north, in the area north of position 12 it will be transported towards south. The model calculations show that the net annual transport rates along the main part of SMB (e.g., between position 1 and Position 11) is practically zero.

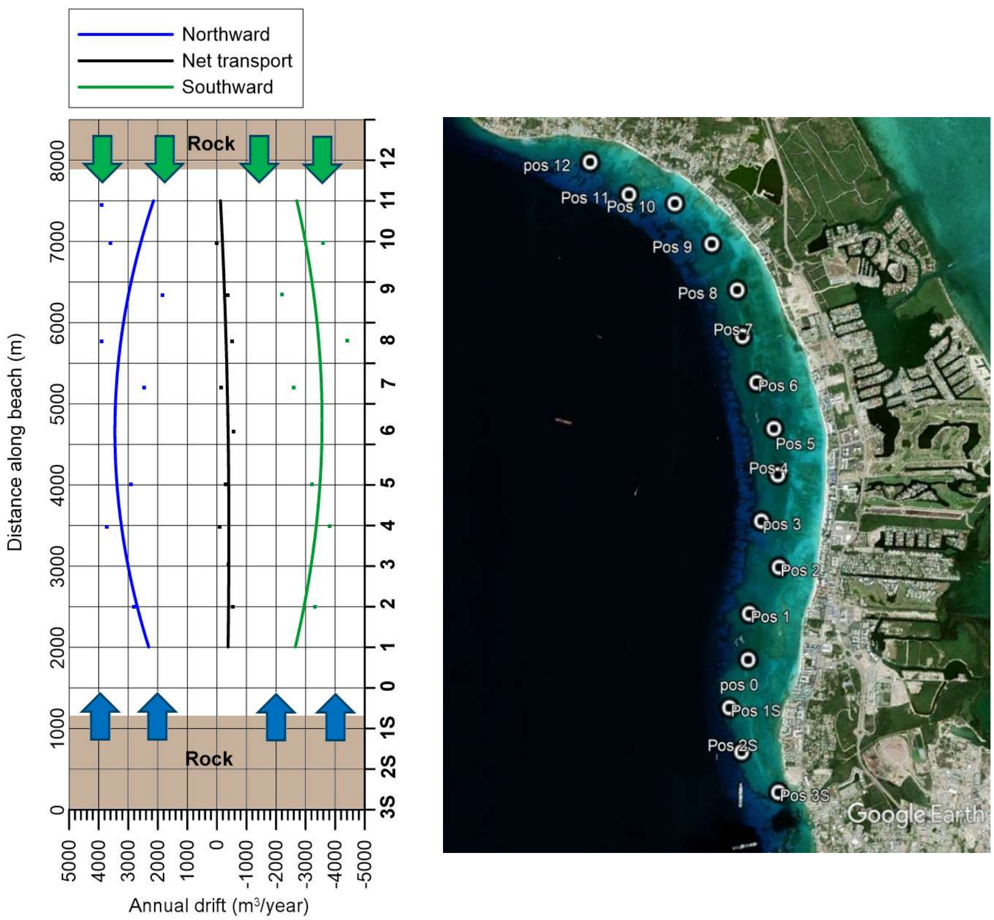

Figure 10-5 Calculated variation of net annual drift along SMB for normal conditions.

It is noted that the present calculations only include normal conditions without considering major storms and hurricanes. In the next section the effect of these storm events on the coastal sediment balance will be analysed.

10.2 Longshore sediment transport during hurricanes

The hydrodynamic simulations of the hurricanes listed in Table 7-1 has shown a typical pattern in the flow along SMB. In the first phase of the storm, the wind at SMB is typically directed towards south, causing a relatively weak southward directed current along the entire beach. Waves are still quite small at this stage. Therefore, longshore sediment transport is insignificant.

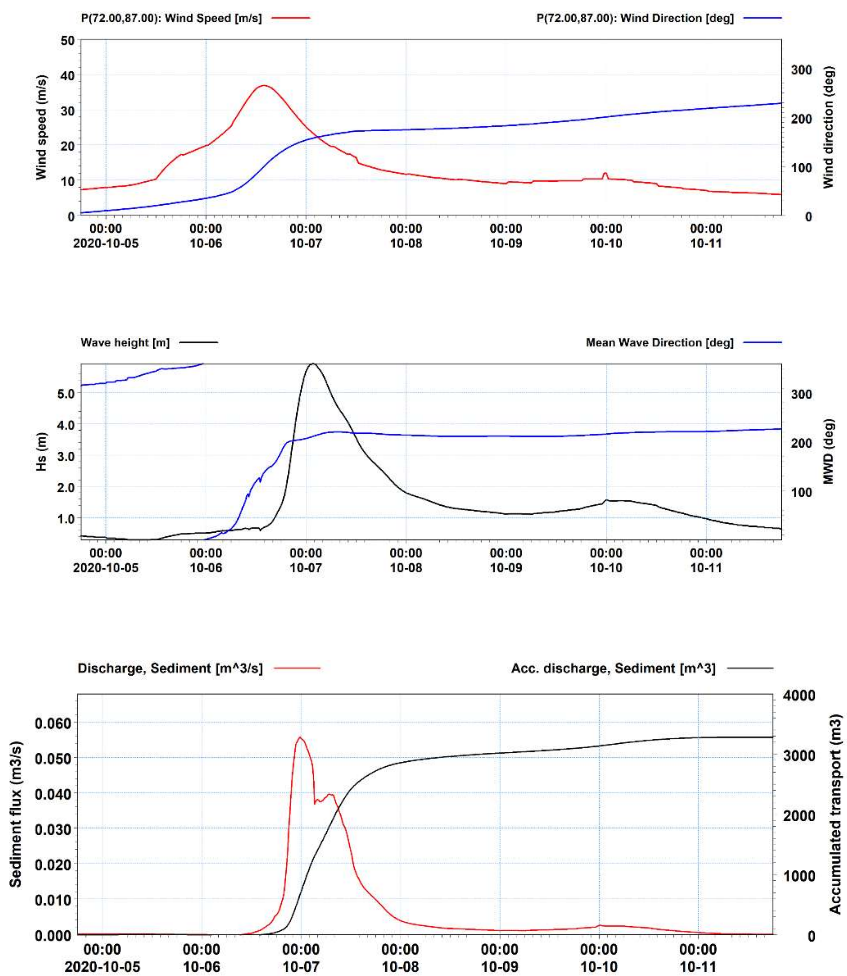

Figure 10-6 Time variation of key parameters in central part of SMB during Hurricane Delta (2020). Top: Wind speed and – direction, Middle: Wave height and – direction, Bottom: sediment flux and accumulated longshore sediment transport.

After the eye of the storm has passed Grand Cayman, the wind direction shifts towards S and SW. In this phase, large waves propagate towards SMB from south-westerly directions. The breaking waves cause strong littoral currents directed towards north. The combination of high waves and relatively strong wind- and wave induced currents cause significant longshore sediment transport towards north along SMB. Typically, the littoral current and associated sediment transport patterns are regular and uniform in the beginning of the storm, especially in the southern part of SMB. As the storm proceeds and waves get higher, the littoral current patterns become increasingly irregular and non-uniform. Often large-scale vortices can be observed that cover the entire width of the shoal.

The time variation in wind - , wave -, and sediment transport conditions during Hurricane Delta (2020) are shown for a location in the central part of SMB in Figure 10-6. The wind reaches a maximum speed of around 40 m/s. At the peak of the storm the wind direction is SE. The wave height is small (<0.5m) at this stage but reaches a maximum value of around 6m approximately 12 hours after the highest wind speeds occurred. Sediment transport started to increase in line with the increase in wave height and shift in wave direction towards SW.

The accumulated longshore sediment transport was calculated for all major hurricanes in the period 2000 - 2022. Transport rates were derived in a series of cross sections along the SMB. The total longshore transport, integrated over all simulated hurricanes are shown in Figure 10-7.

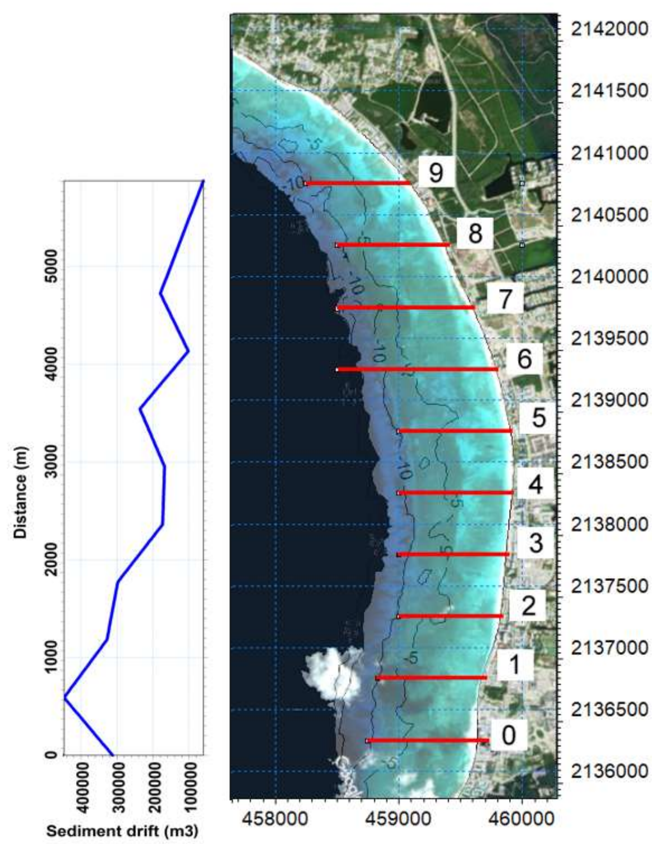

Figure 10-7 **Left: Total integrated longshore sediment transport for the most important hurricanes in the period 2000-2022. Right: Positions of control sections for calculation of longshore sediment transport.**

The red lines in the right figure represent the cross sections used in the calculations. The blue line in the left figure indicates the total integrated longshore transport.

It is noted that the sediment transport volumes presented here are based on potential transport rates as sediment was assumed to be available in the entire model domain. In reality, sediment transport volumes will be somewhat lower as parts of the seabed are covered by rock.

The calculations indicate maximal sediment transport volume in the order of 400,000 m^3 in the southern part of SMB. This corresponds to an average transport rate of around 18,000 m^3/year. Further towards north the transport rates are decreasing. In the upper part of SMB, the total sediment transport volume was calculated to be around 100,000 m^3, which corresponds to an average transport rate of around 4,500 m^3/year.

A ranking was made of all simulated hurricanes. The hurricane with the strongest impact on the coastal sediment balance for SMB was Hurricane Michelle (2001). Hurricane Ivan (2004) was the second most important hurricane and Hurricane Ian (2022) came in third place. The results and ranking for all simulated hurricanes are shown in Table 10-1.

Table 10-1 Ranking of most important hurricanes for the coastal sediment balance at SMB. Period: 2000 - 2022

Rank	Name	Year	Indicative Transport rate (m^3)
1	Michelle	2001	31398
2	Ivan	2004	14761
3	Ian	2022	11306
4	Isidore	2002	9143
5	Wilma	2005	9077
6	Paloma	2008	-5730
7	Delta	2020	4481
8	Zeta	2020	3715
9	Emily	2005	3397
10	Ida	2021	2181
11	Eta	2020	2055
12	Marco	2020	1369
13	Lili	2002	1250
14	Gustav	2008	1235
15	Dean	2007	1035
16	Laura	2020	512
17	Dennis	2005	504
18	Charley	2004	-328
19	Claudette	2003	218
20	Iris	2001	205
21	Helene	2000	151
22	Bonnie	2004	76
23	Grace	2021	43

The reason why Hurricane Michelle (2001) has a larger impact on the sediment balance for SMB is that this storm passed west of Grand Cayman, see Figure 7-6. Most other storms passed the island from east to west. The rather unusual track of Michelle (2001) caused high waves directly propagating towards SMB, causing very significant longshore transport during the entire passage of the storm. The modelling studies showed that for most hurricanes, the largest waves at SMB do not coincide with the peak of the storm but occur after the eye of the storm has passed the Island. For Hurricane Michelle (2001) this was not the case.

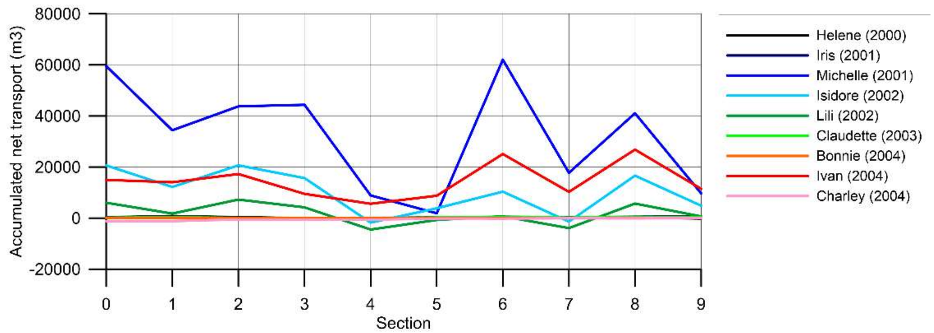

Figure 10-8 Integrated longshore transport rates during hurricanes during 2000 and 2004.

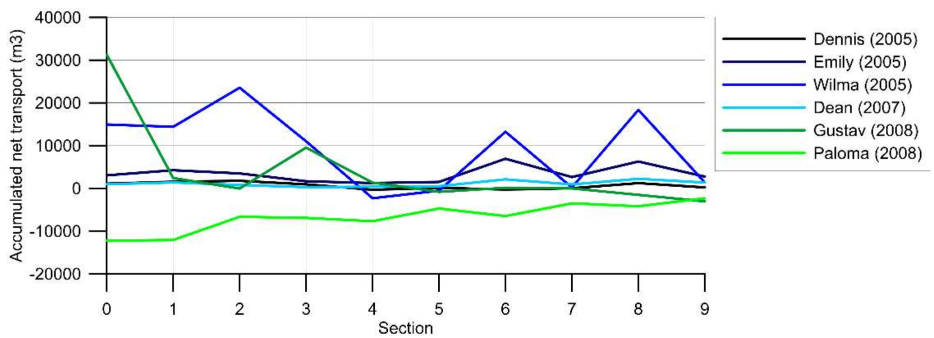

Figure 10-9 Integrated longshore transport rates during hurricanes during 2000 and 2004.

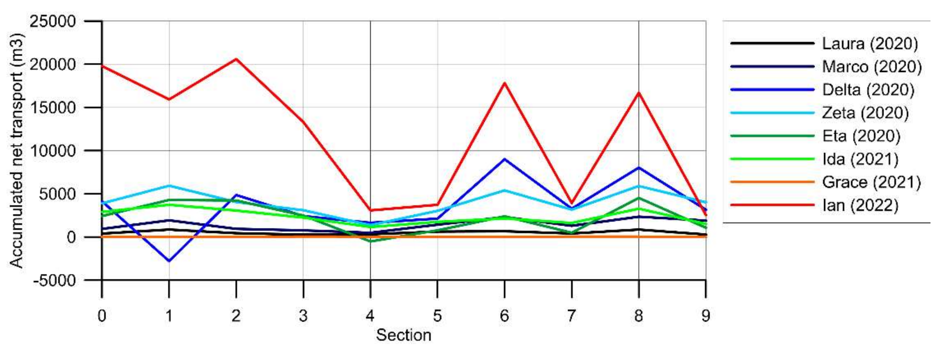

Figure 10-10 Integrated longshore transport rates during hurricanes during 2000 and 2004.

The calculated transport rates for all analysed hurricanes are shown graphically in Figure 10-8, Figure 10-9, and Figure 10-10. Large variations in transport rates were found among the analysed hurricanes. The total transport rates were integrated for three different time periods : [2000-2004], [2005-2010], and [2020-2023]. The results are shown in Figure 10-11. In is noted that no major hurricanes were recorded during the period 2011-2019.

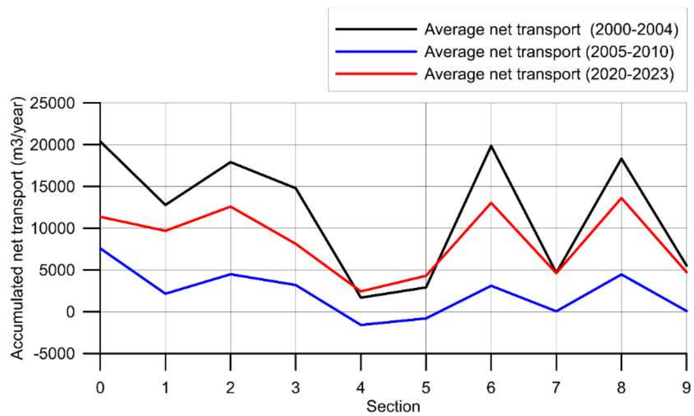

Figure 10-11 Integrated longshore transport rates during hurricanes for three different periods.

The model calculations indicate that the highest average sediment transport due to hurricanes occurred in the period between 2000 and 2004. The lowest average rates were observed for the period between 2005 and 2010. Roughly, the annual longshore sediment transport along SMB due to hurricanes varied between 2000 m^3/year to 10,000 m^3/year. Obviously, strong variations occurred from one year to the next. However, some important trends can be observed.

From the calculations it appears that high transport rates occurred in the early 2000s. In the years between 2005 and 2010 the rates started to decrease. Then, during the following 10 years there were no major hurricanes that affected SMB significantly. Presently, since 2020 the hurricane activity seems to be increasing again.

10.2.1 Loss of sediment to deep water

The flow patterns observed during hurricanes contribute to the loss of beach sediments to the offshore zone. This is illustrated in Figure 10-12 that shows a satellite image of the nearshore zone superposed by the simulated flow field (black vectors). The yellow arrows indicate the transport of sand from the beach towards the reef. If sediment is carried beyond the edge of the reef, it cannot be transported back to the shore and is lost permanently.

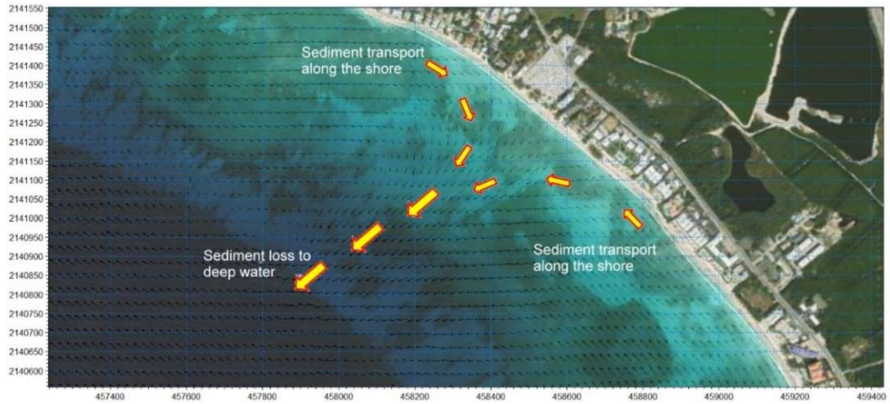

Figure 10-12 Detail of the wind- and wave generated currents in the northern part of SMB during Hurricane Ian. The vectors indicate the transport of sand from the shoreline towards the edge of the reef.

The model results show that the flow patterns during storms are quite different from the patterns observed during calm conditions. Under calm conditions wave breaking is confined to a narrow band along the water line. The littoral current is weak (< 0.5 m/s) and uniformly follows the shoreline. During storms, waves start breaking at the edge of the reef and travel as turbulent bores across the shoal before reaching the shoreline. The hydrodynamic forces associated with wave breaking cause complex current patterns across the entire shoal. These current patterns are highly determined by the underlying bathymetry. Generally, the areas where the seabed is covered by rock are located somewhat higher than the areas with sand on the seabed. Sometimes the elevated areas provoke stronger wave breaking and more intense littoral currents. At other occasions the rocky areas mainly act as increased roughness elements on the seabed, causing the littoral currents to flow around these areas.

As a result, complex flow patterns occur that vary along the shore and during the storm. Quite often, the littoral currents are directed away from the shoreline and cause sediment transport across the shore. In some cases, the cross shore currents can be so strong that sediments are transported all the way towards the edge of the reef. Once passing the reef, the sediment is lost forever to deep water. When sediment is deposited near the edge, in water depths between 5m and 20m it will be difficult, and it will take a long time, for the sediment to be transported back to the shore.

To analyse the potential loss of sediment to deep water, the cross shore transport of sediment was calculated along a section that more or less coincides with the 5m depth contour. This water depth was chosen because it corresponds more or less to the so-called closure depth of the beach during calm conditions. The closure depth indicates the maximal water depth at which waves and currents are able to mobilize sediment at the seabed. During calm conditions, with waves typically in the range of 0.2m to 0.8m, sediment transport is confined to water depths smaller than 5m. During storms, waves and currents are able to mobilize and transport sediment across the entire shoal. Therefore, a realistic estimate of sediment loss to deep water can be obtained by calculating the offshore directed flux of sediment across the 5m depth contour.

Figure 10-13 (left hand side) shows the total offshore directed sediment transported integrated over all analysed hurricanes in the period 2000-2022 (see Table 10-1). The yellow line in the figure on the right hand side coincides more or less with the 5m depth contour and indicates the line across which the transport was calculated. The results show some offshore sediment loss along the entire section. However, a clear peak was observed in the northern end of SMB, in the area of the Kittiwake shipwreck. The location of this peak corresponds to the location where the littoral current is directed offshore, see Figure 10-12. This observation is agreement with the model results presented in section 9 that indicate that the longshore current usually is directed towards north during the main part of the storm. The variation of the offshore directed transport and the water depth along the control section (e.g., the yellow line in Figure 10-13) are shown in Figure 10-14. The figure shows that the water depth along the control section is around 5m except for the most northern part where the water depth is somewhat larger.

The total potential sediment loss to the offshore zone for all hurricanes combined is approximately 380,000 m^3. This corresponds to around 17,000 m^3/year on average. The real volume could be somewhat lower. Firstly, because some of the sediment could be transported back to the shore during a storm. Secondly, the calculations were performed assuming mobile sand across the entire shoal. In areas where the seabed is covered by rock the calculated offshore directed sediment transport may be overestimated.

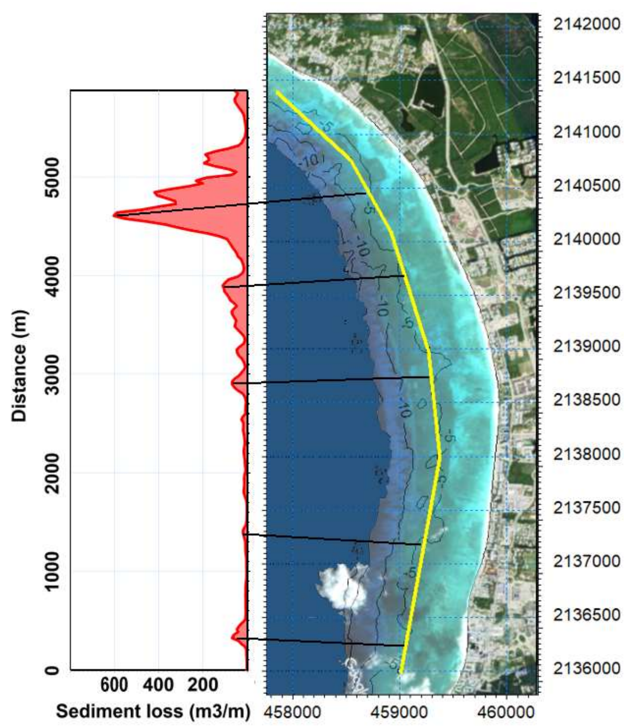

Figure 10-13 Offshore sediment loss along SMB during hurricanes. The highest sediment losses occur in the northern part of the beach.

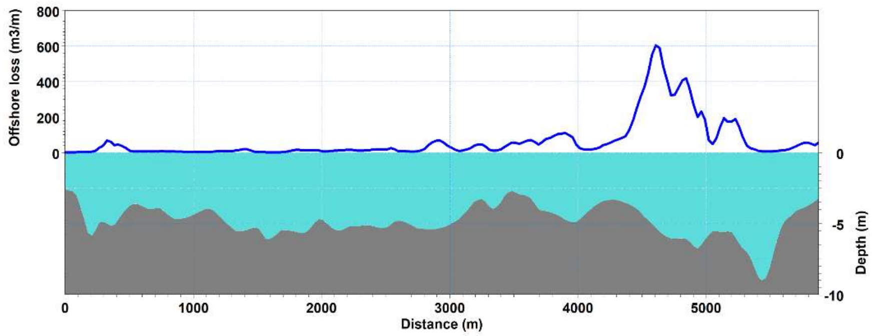

Figure 10-14 Variation of water depth and offshore directed sediment transport along a control section represented by the yellow line in Figure 10-13.

The area where the peak of offshore directed transport was observed is shown in Figure 10-15. The yellow vectors indicate areas close the edge of the reef where the seabed seems to be covered by sand. The satellite imagery seems to indicate that these areas with sand covered bed are wider and denser than similar areas further south. This could confirm the finding of the modelling study that during storms sand is transported towards north and a part of the sand is transported towards, and beyond, the edge of the reef.

Figure 10-15 Nearshore sand accumulations northern part of SMB

The accumulated sand near the edge of the reef is typically found in water depths between 10 m and 20 m. Figure 10-16 shows the sand accumulations in the central part of SMB.

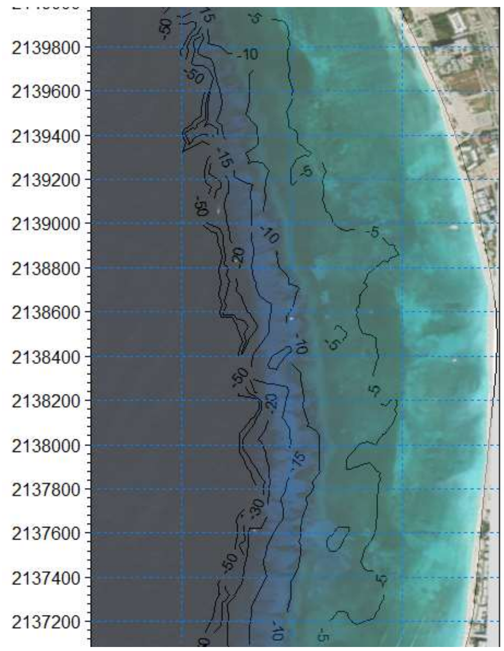

Figure 10-16 Nearshore sand accumulations central part of SMB

10.3 Shoreline dynamics due to cross shore sediment transport.

A coastal profile consisting of sand is continuously being modified by the action of the incoming waves. Particularly in the breaker zone bars can be built up, shifted about, or levelled out by the wave-induced cross-shore sediment transport. Prediction of the profile development, and more specifically, the maximal shoreline withdrawal during storms, is important for the definition of set-back lines aimed to minimize the risk of damage to properties.

During storms the sediment transport across the beach profile is dominated by wave breaking and the associated offshore-directed flow near the bed, the so-called undertow. Under these conditions, relatively large volumes of sand can be transported from the shoreline and deposited in deeper water further away from the shoreline. Storms are often associated with increased water levels (surge) caused by the combined action of wind and breaking waves. The increased water levels allow waves to propagate further up the shore and cause erosion of the upper part of the beach. This phenomenon is often referred to as acute erosion. It occurs rapidly and can cause severe damage to properties that are located close to the water line. The mechanism is illustrated in Figure 10-17.

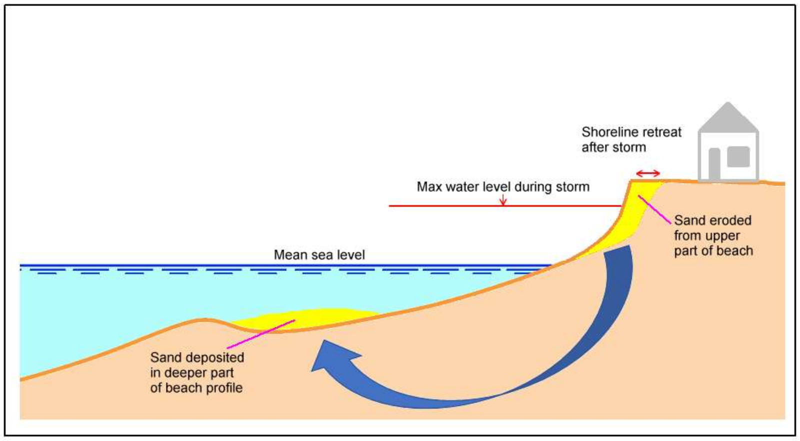

Figure 10-17 Destruction phase (storms, hurricanes): Erosion of upper part of the beach profile during periods with high water levels (surge) and high waves. Time scale: hours to days

During the following period with calm conditions, the sand is gradually transported back to the shore, see Figure 10-18. Normally, it takes much longer for the beach to recover after a storm than it takes to erode it.

Figure 10-18 Recovery phase (calm periods): Gradual transport of sand from the shoal back to the water line. Time scale: weeks, months, years

To estimate the acute shoreline erosion during storms a series of model simulations were made of the cross-shore sediment transport during storms and the resulting dynamics of the beach profile. The model simulations were performed using DHI's beach profile model LITPROF. The model simulates the propagation and breaking of waves close to the shore. In case of oblique incident waves, the wave-driven longshore currents are calculated from the hydrodynamic forces (radiation stress) associated with wave breaking. The model resolves the vertical distribution of the flow, turbulence, and sediment transport in great detail. Further technical information about DHI models is provided in Appendix A.

The model simulations were performed for three sections in the southern, central, and northern part of SMB. The sections are indicated in Figure 10-19.

Figure 10-19 Cross sections used in the simulation of crops shore profile dynamics during storms.

An example of a simulation of the cross shore profile during hurricane Wilma (2005) is shown in Figure 10-20. The upper panel shows time variation of the significant wave height and water level in the central part of SMB at a depth of 5m (Pos C in Figure 10-19). The data was derived from the 2D model simulations presented in section 9. The duration of the storm was approximately 6 days. During this period the wave height in Pos C reached a maximal value of around 2.4m. The maximal water level elevation was around 0.25m. It is noted that the wave and water level shown are derived outside the area where most wave breaking occurs. As a result, water levels at the shoreline will be higher than shown in the figure due to the effect of wave set-up. The wave se-up at the water typically reaches values in the order of 25% of the wave height at breaking point. For the present case, water levels at the shore of around 0.7m to 1m can be expected. As a result of the run-up of individual waves instantaneous water levels reach even higher values.

In the model simulations the presence of rock was included. The area where the seabed consist of rock is represented by the light-grey area in Figure 10-20.

The lower panel shows the cross shore profile at different time steps during the storm. The model results indicate that, at the end of the storm, a considerable portion of the upper part of the beach was eroded. At the same time, sediment accumulations are observed in the form of two sand bars located further seaward. The area in between the two bars was not eroded because the seabed here consists of solid rock. No detailed information about the composition of the seabed was available. The distinction between rock and sand was based on the shape of the cross shore profile and on observations made on the site.

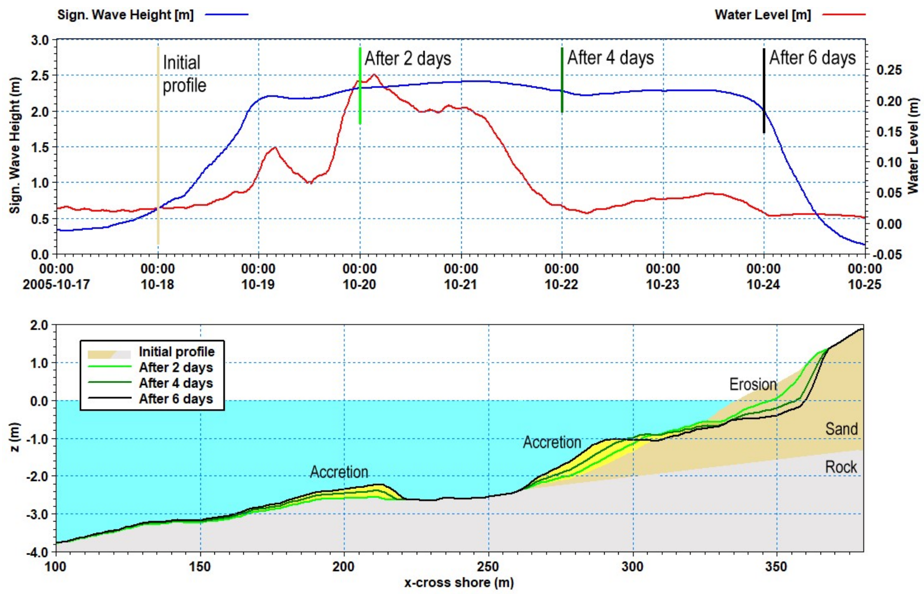

Figure 10-20 Simulated cross shore profile dynamics during hurricane Wilma (2005). Upper panel: Time variation of wave height and water at seaward boundary. Lower panel: Cross shore profile at start of simulation and after 2,4, and 6 days.

The profile dynamics were simulated for the 10 most severe hurricanes in terms of sediment transport as listed in Table 10-1. No measured data was available to provide detailed calibration of the model. The main objective of the profile modelling was to get an idea of the magnitude of acute erosion during extreme events.

The results obtained from these exercises are combined with calculated longshore sediment transport rates as presented in the previous section. The calculated cross shore profiles for the top 10 hurricanes form the period 2000-2022 are shown in Figure 10-21, Figure 10-22 and Figure 10-23 for the southern, central and northern part of SMB respectively.

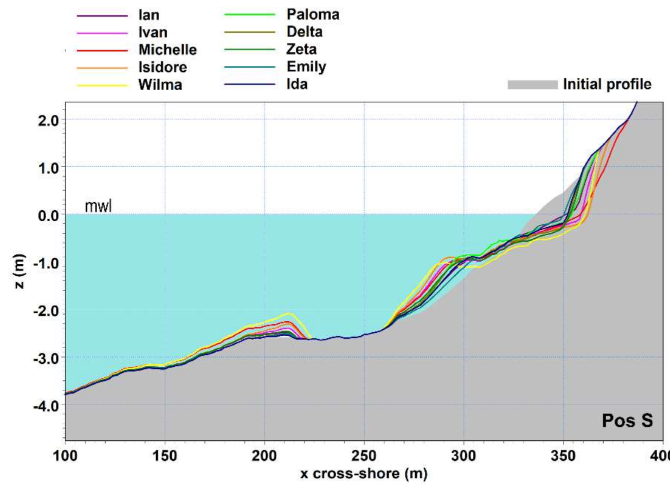

Figure 10-21 Simulated cross shore profiles during recent hurricanes Position S

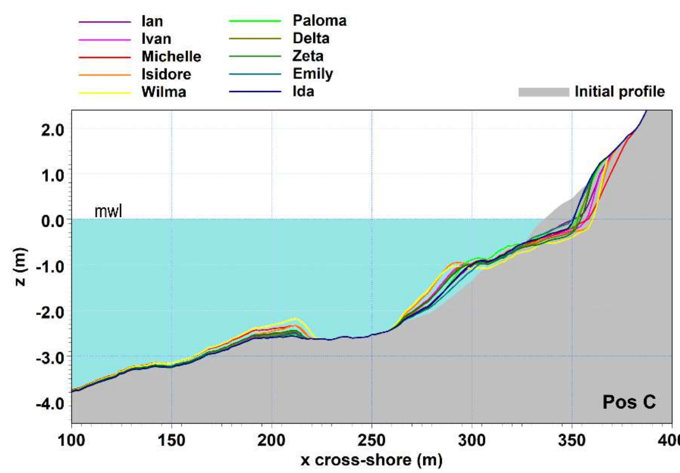

Figure 10-22 Simulated cross shore profiles during recent hurricanes Position C

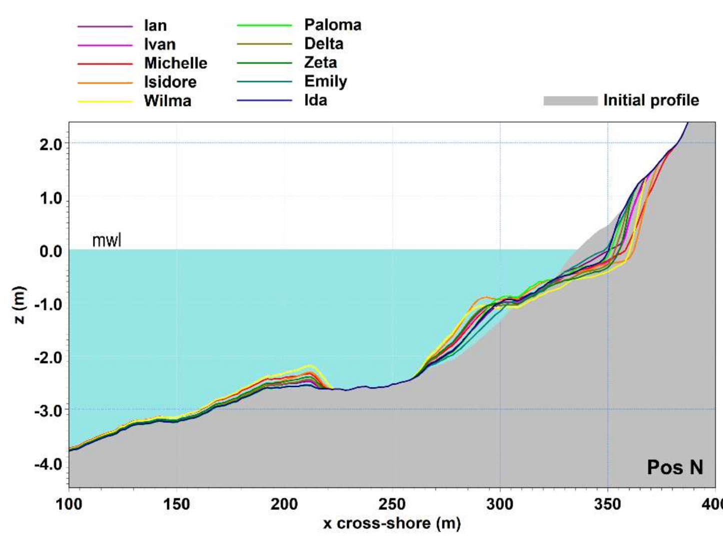

Figure 10-23 Simulated cross shore profiles during recent hurricanes Position N

The model simulations show a clear pattern of erosion of the upper part of the beach and sediment accumulation on sand bars in front of the shoreline. Variations can be observed between the different storms. These variations are mainly the result of 1) the intensity of the storm, 2) the duration, and 3) the water levels. For some storms the beach erosion resulted in a strong horizontal retreat of the shoreline. For others it caused pronounced vertical reduction of the beach level. Table 10-2 shows the horizontal withdrawal of three different depth contours (0.0m, 0.5m, and 1.0m) for all storms in the three analysed cross sections.

Table 10-2 Calculated maximal withdrawal of nearshore depth contours during recent hurricanes in three positions along SMB.

	Depth contour : 0.0 m			Depth contour : 0.5 m			Depth contour : 1.0 m		
Hurricane	**Pos S**	**Pos C**	**Pos N**	**Pos S**	**Pos C**	**Pos N**	**Pos S**	**Pos C**	**Pos N**
Ian	-12.8	-13.2	-12.8	-7.5	-7.4	-7.5	-0.8	-4.5	-0.8
Ivan	-21.4	-19.1	-16.7	-9.2	-10.2	-7.3	-3.1	-4.3	-0.6
Michelle	-21.7	-22.1	-21.8	-13.8	-15.0	-11.1	-9.6	-7.2	-7.9
Isidore	-25.9	-23.9	-20.5	-13.7	-11.5	-12.4	-8.1	-6.0	-3.3
Wilma	-23.4	-23.8	-23.9	-11.2	-11.7	-12.0	-2.6	-2.9	-3.0
Paloma	-18.0	-15.8	-12.7	-8.2	-5.8	-7.1	-1.3	0.0	0.0
Delta	-15.4	-15.0	-14.7	-6.5	-6.0	-5.8	0.0	0.0	0.0
Zeta	-14.7	-17.8	-16.6	-5.9	-5.2	-8.5	0.0	0.0	0.0
Emily	-13.9	-13.9	-11.4	-3.9	-3.6	-3.7	0.0	0.0	0.0
Ida	-15.9	-13.4	-13.7	-7.1	-4.1	-4.6	0.0	0.0	0.0
Average	**-18.3**	**-17.8**	**-16.5**	**-8.7**	**-8.1**	**-8.0**	**-2.6**	**-2.5**	**-1.6**

The results show that the strongest withdrawal was observed for the 0.0m depth contour. The highest value was 25.9 m and was observed during Hurricane Isidore (2002). The strongest horizontal erosion of the 1.0m depth contour was observed during Hurricane Michelle (2001). For all cases the erosion was found most severe in the southern part of SMB and mildest in the northern part. On average, the set back of the 0.0m depth contour was 18.3 m for the southern part and 8.7m and 2.6m for the central - and northern part respectively. Similarly, the average retreat of the 1.0m depth contour was 16.5m for the southern part of SMB and 8.0m and 1.6m for the central - and northern part respectively.

The values of beach erosion in terms of volumetric values are listed in Table 10-3. The volumes were calculated from the difference between the initial beach profile and the profile at the end of the storm along the inshore part of the profile where the beach erosion was observed. The strongest erosion rates in terms of volume, were observed for Hurricane Wilma (2005) where a total of 34.9 m^3/m sediment was eroded from the beach in the southern part of SMB. In the central – and northern parts of SMB the erosion rates were 32.5 m^3/m and 32.9 m^3/m respectively.

Table 10-3 Calculated volumes eroded along the shoreline during recent hurricanes in three positions along SMB.

Hurricane	Erosion (m^3/m) Pos S	Pos C	Pos N
Ian	-15.4	-15.3	-15.4
Ivan	-22.4	-21.0	-20.1
Michelle	-30.8	-27.6	-27.2
Isidore	-29.1	-26.9	-27.6
Wilma	-34.9	-32.5	-32.9
Paloma	-16.6	-14.3	-13.5
Delta	-15.2	-16.5	-17.9
Zeta	-17.7	-19.3	-21.4
Emily	-10.0	-9.8	-8.9
Ida	-12.8	-11.8	-12.0
Average	**-20.5**	**-19.5**	**-19.7**

Finally, the maximal vertical erosion rates for each analysed hurricane are listed in Table 10-4. Maximal values of around 1m were observed, typically at a distance of 15 m to 25 m from the shoreline.

Table 10-4 Calculated maximal erosion depths during recent hurricanes in three positions along SMB.

	Pos S		Pos C		Pos N	
Hurricane	Maximal erosion (m)	Distance from shoreline (m)	maximal erosion (m)	Distance from shoreline (m)	maximal erosion (m)	Distance from shoreline (m)
Ian	-0.6	18	-0.6	16	-0.6	18
Ivan	-0.9	20	-0.8	16	-0.7	16
Michelle	-0.9	22	-0.8	22	-0.8	20
Isidore	-1.1	24	-1.0	22	-1.0	20
Wilma	-1.1	22	-1.0	22	-1.0	20
Paloma	-0.7	14	-0.6	12	-0.6	8
Delta	-0.7	10	-0.7	12	-0.7	10
Zeta	-0.7	10	-0.8	10	-0.8	12
Emily	-0.5	10	-0.5	10	-0.4	10
Ida	-0.6	12	-0.6	10	-0.6	8
Average	**-0.8**	**16**	**-0.7**	**15**	**-0.7**	**14**

An example of the vertical erosion is shown in Figure 10-24. The photo shows the stairs in front of the Marriot Beach resort that seems to be “hanging in the air”.

Figure 10-24 Beach erosion in front of the Marriot Beach Resort. Notice the stairs at the beach “hanging in the air”. Photo: DHI, March 2023.

11 Cause of beach erosion and mitigation measures

In this section the cause of the observed beach erosion at SMB is analysed and the most adequate mitigation concept is identified.

11.1 Cause of observed erosion

The present modelling study finds that the coastal sediment balance at SMB is determined by two main factors: 1) – Extratropical cyclones (nor'westers) that cause wave-driven currents and sediment transport from north to south along SMB and, 2) Tropical storms and hurricanes that mainly drive sediment from south to north.

The analysis of historic wave data (1979-2022) suggests that the intensity of the nor'westers has decreased significantly since the late 1990s. This has led to a decrease in sediment transport from north to south along SMB. At the same time, no major hurricanes with direct impact on SMB were recorded in the period between 2008 (Paloma) and Laura (2020). As a result, both northward and southward directed transport rates were reduced. Consequently, no major changes in the sediment balance occurred.

Since 2020 a series of storms and hurricanes have hit Grand Cayman and caused excessive sediment transport from south to north.

The net northward directed transport during the past years has caused a sediment deficit in the southern part of SMB. This has resulted in beach erosion. The sediment deficit, and the associated shoreline retreat, is migrating along SMB towards north.

Model simulations showed that, during tropical storms and hurricanes, waves and strong winds cause complex sediment transport patterns across the entire shoal. Generally, a net northward directed sediment transport is observed during these events. In addition, a part of the sediment is transported across the shoal towards the edge of the reef.

Sand along SMB is of organic origin (carbonate sand) and is produced by organisms living on the reef. During periods with high hurricane activity, the loss of sand to deep water could exceed the production of new sediments, leading to a net loss of beach material in the coastal system.

It is possible that the balance between northward and southward components of the annual sediment transport is re-established naturally in the coming years, either by an increase in nor'westers or a decrease in tropical storms and hurricanes. However, if the present trend continues, then chronic erosion along the entire SMB is expected for the coming years/decades.

Global sea level rise will have an additional negative effect on the shoreline dynamics at SMB. First of all, an elevation of the mean seal level will cause shoreward migration of the beach profile. This corresponds to a net beach erosion that is proportional to the sea level rise and the mean slope of the beach. Secondly, for higher water levels, waves will easier cross the reef and shallow area in front of SMB and will therefore be larger when they reach the shore than they are nowadays. Even though the sea level rise will have a pronounced effect on the shoreline on a long time scale, it is a slow process and its impacts on shorter time scales (10 – 20 years) are expected small compared to the effects of a single hurricane or severe nor'wester that could occur on short notice. The present study has shown that the shoreline dynamics at SMB are highly event driven. This means that large impacts occur during short term events (i.e., storms) rather than long term processes. Therefore, the recommendations regarding the shoreline management of SMB are mainly focussed on these short-term events. The long terms effects of sea level rise can be dealt with along the way.

11.2 Mitigation measures

The analyses presented in the previous sections have concluded that the beach erosion observed along SMB is the result of an imbalance between northward and southward components of the annual sediment transport along the shore. Sediment is removed from the southern part of SMB and transported towards north. In addition, a part of the sand was transported perpendicular to the shoreline during recent hurricanes and is now partly stored on the shoal and partly lost to deep water.

In order to mitigate the erosion, and re-establish a stable beach, a number of mitigation concepts could be considered. The choice of mitigation measure depends on a variety of factors. First thing to consider is what are the functions of such mitigation. Is it only for protection of coastal infrastructure or are there other factors to consider ?

Economic considerations are key here. From a coastal engineering viewpoint, mitigation solutions are always available, but these may turn our very costly. The cost of coastal protection must be held up against the value of the coastal infrastructure and economic activities in the area. If nothing is done, then the risk arises of loss of income as tourists would stay away if there were no beach. Furthermore, the safety for the people living in coastal communities could be compromised. In many countries, planning and management of the shoreline is a matter for the government to handle. Especially in a case where multiple interests are in play and poorly planned solutions by individual owners could cause significant damage both to the environment and to other stakeholders.

In the following sections a number of mitigation concepts are presented and discussed.

11.2.1 Managed retreat

A so-called "managed retreat" could be considered, where human occupation and activities are gradually drawn further away from the beach. This is an excellent strategy for areas that are not yet fully developed for urban use. However, given the economic importance of the established coastal infrastructure this option seems hardly viable. Managed retreat is not a mitigation measure in itself but rather an adaptation. It does not require any coastal engineering solutions and is therefore not elaborated further in this study.

11.2.2 Hard structures

The establishment of "hard" structures such as groins, breakwaters and revetments could be considered to halt the erosion and protect the coastal infrastructure. In many locations around the world coastal structures are the main component of coastal protection systems.

For SMB the use of hard structures is generally not recommended. The risk of this concept is that local-scale protective structures are constructed more or less ad-hoc. Each structure, or series of structures, is constructed to protect only one single property. As a result, the established structures could transfer the erosion problems to adjacent properties. This could initiate a cascade of poorly planned, local scale solutions.

Even if hard structures were implemented in a planned manner, covering the entire SMB, it would still be very questionable if such solution would provide the desired long term coastal protection. Erosion along SMB is often caused by cross shore sediment transport. For this type of erosion blocking structures such as groins would be meaningless. Finally, hard structures would have a significant negative visual impact and could even cause dangerous situations for swimmers.

However, there are locations along SMB where a sandy beach simply would not be possible without hard structures. In these locations the orientation of the coastline is such that any sand positioned here would rapidly be swept away by the waves. These areas include the southern – and northern limits of SMB. In these areas the coastline presently entirely consists of rock. During storms, both the southern - and northern limit of SMB are directly exposed to high waves. The configuration of the coastline in these areas creates a divergence point for sediment. This means that any sediment in this location would be transported away, either towards north or towards south. Sand can only be kept on the shore if it is protected on both sides by hard structures. The areas where hard structures could possibly be considered to create and maintain sandy beaches, are shown in Figure 11-1 and Figure 11-2.

Figure 11-1 Area where hard structures could be considered – Southern part of SMB.

Figure 11-2 Area where hard structures could be considered – Northern part of SMB.

An example of a mitigation measures aimed at keeping a sandy beach is already present in front of the Treasure Island resort in the southern part of SMB, see Figure 11-3.

Here, a so-called cove was constructed using two hard structures at each side of the compound. The structures practically cut off the area from the sea. Inside the area surrounded by the structures a sandy beach is constructed. This type of solution is only recommended in areas where no natural sediment is available nor could be kept in place by natural means.

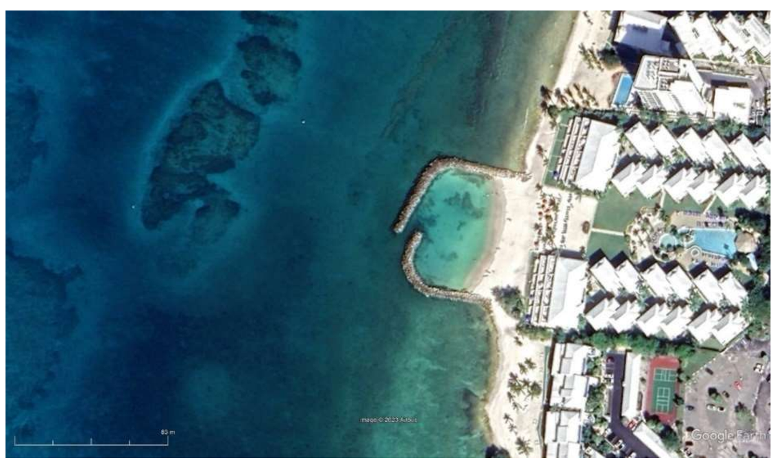

Figure 11-3 Coastal protection using hard structures: Cove at Treasure Island Resort.

11.2.3 Artificial Beach Nourishment

The philosophy behind beach nourishment, in a coastal protection context, is to artificially add sand to the beach in order to restore the beach' capacity to absorb the natural fluctuations of the shoreline. Apparently, the term "natural" here corresponds to "new natural" conditions as it seems that sea level rise and changes in offshore wind- and wave conditions are here to stay and likely even get worse in the future.

In many locations around the world beach nourishment is presently the preferred solution to coastal erosion problems. The main advantages of beach nourishment, compared to hard structures, are:

- The beach itself provides protection as long as sufficient volume of sand is present between coastal infrastructure and the sea.
- The beach will appear naturally and undisturbed and is suitable for leisure.
- No negative impact (lee side erosion) on adjacent areas.

A disadvantage of artificial beach nourishment is that it requires a large volume of sediment to establish. The acquisition of clean, good quality sand with the right granulometric characteristics can be difficult and costly.

Furthermore, nourishment requires maintenance in the form of periodic re-nourishment. For the case of SMB, the frequency and volume of such maintenance nourishment is not known beforehand but depends heavily on the occurrence and intensity of storms.

11.2.4 Nourishment scenario

For SMB the realisation of beach nourishment is not straightforward. There are several factors to consider such as :

- It must cause minimal disruption of ongoing economic activities (tourism)
- It must be planned carefully with regard to seasonality in Meteomarine conditions.
- The optimal volume of the nourishment must be defined.
- Maintenance activities must be planned.
- The nourishment scheme must be flexible and adjustable as corresponding to continuously changing meteomarine conditions.

The most severe beach erosion was observed in the southern part of SMB. The modelling studies have shown that sediment generally is transported from south to north. To adopt a “Building with Nature” concept, it is recommended to place the sand concentrated in one or a few spots in the southern part of the beach. These so-called sand engines provide sand for the entire beach further towards north by gradually releasing sand as the result of wave driven sediment transport. In this way, the only maintenance activity required to keep the system working is to keep the sand engine at sufficient capacity to continue to feed sand to the beach. Such practice will have minimal impact on the ongoing economic activities along SMB. There will be no need for bulldozers, excavators, and other heavy machinery on the beach. Sand is pumped to the nourishment spot from sea by a pipeline.

The system is illustrated in Figure 11-4. The sand is placed in two areas. The first area is located on the boundary between Crescent Point and Plantation Village. In this location the natural sediment transport is almost exclusively directed towards north.

The second sand engine is located in front of Canal Pont Drive (Meridian Hotel) at approximately 1500m north of the first engine.

The advantage of using two sand engines instead of one is that a larger area along the beach gets protected right away and the initial beach widening in each location gets smaller.

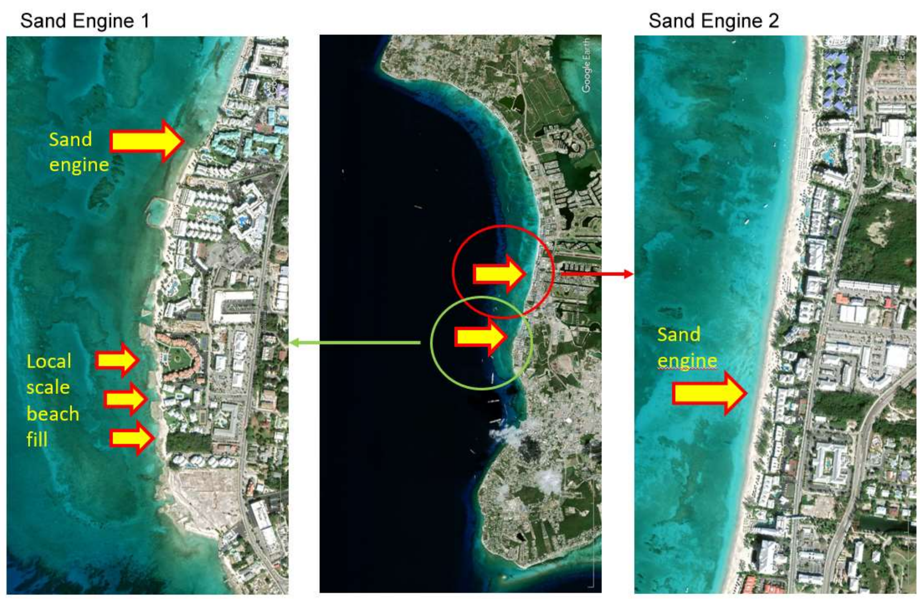

Figure 11-4 Beach nourishment layout with local scale beach fill in the southern part of SMB and two sand engines along the south/central section of the beach.

If desired, local scale mitigation measures could be taken in the southernmost area of SMB, see three arrows in the picture on the left hand side of Figure 11-4. If additional sand is placed in these locations, it is likely that it will be eroded at the next storm unless local-scale protective structures such as the ones found at the Treasure Island resort are established. From an aesthetic point of view, such solutions are not recommended as they would have a negative visual impact on the landscape.

The volume of the nourishment must be decided carefully. Large volumes of sand are very costly and may not be the most effective way in the long term. On the other and, the nourishment volumes must be large enough to provide protection and not require maintenance nourishment every year.

The model simulations in section 10 indicate that longshore sediment transport rates due to tropical storms and hurricanes are typically in the range of 10,000 to 30,000 m^3/year on average. This volume corresponds well with the calculated transport rates caused by “normal” conditions including the nor’westers in the period before the year 2000.

The profile evolutions studies presented in section 10.3 show that volumes in the range of 20 m^3/m to 30m^3/m can be eroded during a single hurricane. Some of the sediment may be transported back to the shore, but a part will be taken away by the currents. From historical records we know that as many as three storms/hurricanes can occur in one year. Including a safety margin to account for uncertainties in the data, then a reasonable estimate of the volume required to withstand a “design year” of Meteomarine conditions would be around 100,000 m^3 for each sand engine. This volume corresponds to an average increase in beach width of around 5 m if it was distributed evenly along SMB. However, not all of SMB is craving sand at this moment. The strongest deficit was found in the southern part of SMB. Therefore, it makes sense to start recovering the beach in the south and let areas further towards north gradually take advantage of the material injected by the sand engines in the south.

We recommend distributing the sand in each engine equally along the beach over a longshore distance of around 500m. This gives an initial nourishment volume of 200 m^3/m at the engine. The initial extension of the beach width in each sand engine will be around 40m, assuming an active depth of 5m. The newly formed protuberances along the shore will immediately start to provide sand to adjacent beaches and their forms will gradually be smoothened out by the action of waves.

It is expected that the nourishment will last for around 5 years, before it needs to be replenished, depending on the weather conditions of course. This does not mean that the initial sand volume of 200,000 m^3 is lost after 5 years. It has just been fed to the beaches adjacent to the sand engines. These beaches will profit from the sand engines and will gradually increase in width in a natural way without use of heavy earth works machinery or sand disposals through pipelines on the beach.

A volume of 200,000 m^3 is quite small compared to nourishment volumes used on other tourist beaches around the world. However, we recommend starting the beach recovery using modest volumes. It is strongly recommended to initiate a shoreline monitoring that measures the beach width twice a year at the beginning and the end of the hurricane season. Good quality information of the sediment distribution along the shore makes the maintenance activities more efficient and easier to plan.

11.2.5 The use of sediment traps

Model simulations presented in section 10 indicate that, during tropical storms, sediment is transported across the shore and towards the edge of the reef. The cross-shore transport and resulting loss of sediment is most intense in the northern end of SMB, see Figure 10-15. If the sediment could be intercepted on its way towards deeper water, then it could be recycled and used again to nourish the beach.

If it is possible from a practical - and environmental point of view, it could be considered to establish one or more sediment traps. These are nothing more than, strategically positioned, dredged pits where sand will deposit during a storm. After the pit has been filled up, the sand can be removed by a dredger and fed into the sand engines presented in the previous sections. In this way a circular sand economy can be established where the loss of sand to the offshore zone is minimized. A suitable location for such sediment trap would be off the coast in front of the Cemetery in the northern end of SMB, close to the Kittiwake shipwreck. An example of a location for such sand trap is illustrated in Figure 11-5.

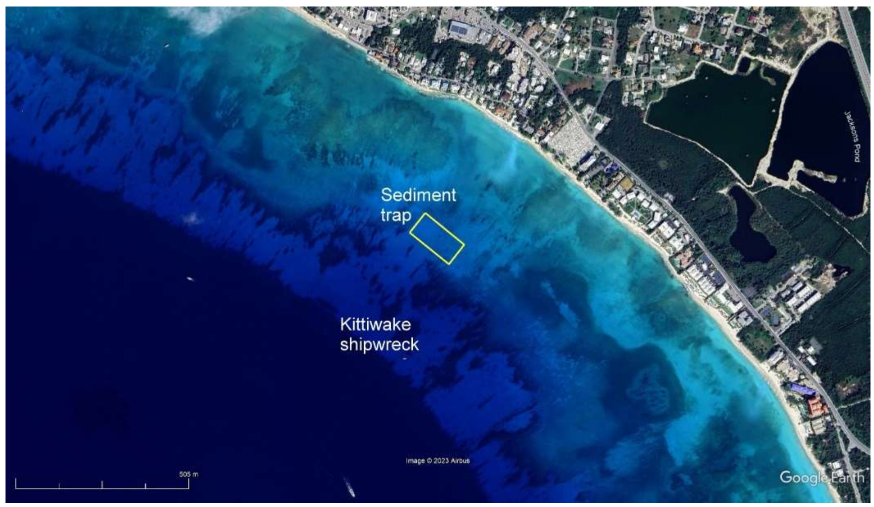

Figure 11-5 Possible location for a sediment trap

The depth inside the sediment trap must be larger than the depth in its surrounding areas. Depending on the thickness of the sand layer an initial excess depth of 2 to 3 meters is recommended. The sediment trap indicated in the figure has a cross sectional area of around 12,000 m^2. An upfilling of 2m would thus provide 24,000 m^3. This would already provide a substantial portion of the maintenance nourishment required to keep the beach safe and attractive.

More areas could be considered to capture sand and bring it back to the shore. Areas closer to the edge of the reef seem suitable for sand mining as well. Sand in these areas is located too deep to be transported back to the shore under calm weather conditions. It can only be moved by exceptionally large waves that only occur during hurricanes. Under such circumstance the sand would not be transported back to the shore but rather in the offshore direction by the undertow that typically occurs during such wave events. Therefore, the sand in these deep locations (between 10m and 20) are not available for the coastal sediment balance in a natural way and are only waiting to get pushed over the edge at the next storm. Therefore, it could be worthwhile to investigate the availability of these sand sources and assess possible environmental impacts associated to the retrieval of these sand sources for shoreline protection purposes.

12 Next steps

A logical follow-up of the present study would be to investigate the possibility to use sand on the shoal for nourishment. In this way, no sand needs to be imported from other areas and an (almost) circular sand economy could be established by capturing sand in a number of sediment traps and recycling the material by re-charging the sand engines along the shore. It could be a sustainable, environmentally friendly, and cost-efficient way to maintain the beach in the future.

Two main issues are related to this idea:

1) – Sand availability in the identified areas of the shoal
2) – Possible environmental impact of sand removal

12.1 Sand availability – sub-bottom profiling

The thickness of the sand layer across the shoal can easily be analyzed using a so-called sub-bottom profiler. A sub-Bottom Profiling system essentially works in a similar way to sonar, radar, and other reflective positioning systems.

Sub-profiling is a well-established technology and is offered by many survey companies around the world. It is fast, not intrusive nor polluting and can be operated from a smaller vessel. It utilises an acoustic or seismic energy source, to trigger a pressure wave which travels down through the water column and into the seabed. By recording the reflected returns of this sound, it is possible to build a picture of the subsurface structure and geology beneath the seabed.

The data recorded by sub-bottom profilers can be used for many different purposes, such as mapping subsurface structures, identifying corals and marine habitats, and provide data for mining and monitoring surveys.

There are a variety of different sub-bottom profiling systems available, some transmitting very high frequencies (pingers) capable of identifying small geological features in the shallow part of the seabed (less then 10m below seabed) and some transmitting lower frequencies (boomers) capable of identifying deeper geology and features.

12.2 Environmental impact

The possible negative environmental impact of sand removal must be investigated first by identifying the characteristics in terms om flora and fauna in the designated borrow sites. A site survey should be conducted to map out the flora and fauna in these locations and to evaluate the possible impact of sand removal. If necessary, mathematical modelling studies can be conducted to analyze the dispersion and accumulation of sand and other material during the operation. If the impacts are found unacceptable then perhaps alternative locations could be identified where the requirements regarding environmental impact can be met.

12.3 Licensing

If sand availability in the designated areas is sufficient and the environmental impact of sand removal in these areas is low, then the next step would be to obtain a license to initiate the operation.

13 References

/1/ DHI Assessment of Beach Rock Stability. Phase 2 and 3. Numerical modelling study. DHI report no 11823293. June 2020

/2/ Baird & Associates. Field Data Collection Report for the Cayman Island Government Cruise Berthing Facility. Executed by Smith warner International Limited. May 2015

/3/ ATM & CGA (2017), Coastal Engineering Support for a proposed redevelopment on Seven Mile Beach, Grand Cayman.

Appendix A Scientific Documentation of applied mathematical models.

Appendix A.1 MIKE 21 FM

Appendix A.1.1 MIKE 21 SW

Appendix A.1.2 MIKE 21 HD

Appendix A.1.3 MIKE 21 ST

Appendix A.2 LITPACK

Appendix A.2.1 LITDRIFT

Appendix A.2.2 LITPROF