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Coastline evolution modelling with ShorelineS to support climate resilient planning – An application to the Antigua and Barbuda Islands

Julien FORNASARI [1], Bas HUISMAN [2], Dano ROELVINK [2,3], Rémi CAILLIBOTTE [1], Tristan PLOUVIER [4], Camille LEQUETTE [1], Christophe BRIERE [1]

1. Egis Water & Maritime, 889 Rue de la Vieille Poste, 34965 Montpellier, France.
   Julien.Fornasari@egis-group.com
2. Deltares, Boussinesqweg 1, 2629 HV Delft, The Netherlands.
3. IHE Institute for Water Education, Delft, The Netherlands.

Abstract:

The need for sediment management of coastal areas is increasing, due to growing urbanization, reduction of sediment supply, and climate change related effects, such as sea level rise and storminess increase. Understanding coastal systems and defining relevant mitigation measures at a large spatial scale and long-term is essential.

To understand sandy system functioning and inform on possible solutions, modeling long-term shoreline evolution is an important diagnostic tool. Current 1D modelling through e.g. GENESIS, LITPACK, UNIBEST is however limited because the estimated morphological behavior of the coastline becomes fundamentally unstable for large wave angles more than 45°. ShorelineS is an open-source model based on relatively simple principles of alongshore transport gradient driven changes as a result of coastline curvature, including under highly obliquely incident waves (ROELVINK *et al.*, 2020).

A case study is conducted at Coco-Point (Barbuda) to explore ShorelineS capabilities. Calibration is carried out using digitalized coastlines (2009-2021) considering wave transformation, (incl. refraction) computed with TOMAWAC, over coral reefs and bathymetric irregularities, e.g. access channel, present in the Gravenor Bay. Shorelines are then projected on the 2021-2070 period taking sea level rise into account (Bruun formula) applying the CERC formula.

The long-term shoreline evolution modelling demonstrates ShorelineS capabilities to reproduce and predict shoreline changes in sediment poor environments (coral hard layer under the beaches). In addition, it shows the importance of accounting for refraction when reefs are present along the coastline.

Keywords:
Shore protection, Coastal erosion, Climate change, Sea level rise, Numerical modelling, ShorelineS.

1. Introduction

Coastal zones represent an undeniable natural, cultural and economic heritage. These areas are nonetheless exposed to natural hazards, such as flooding, coastal retreat, enhanced by sea-level rise (IPCC, 2021), that pose threats to people, properties and activities taking place in the coastal area.

This holds especially for sandy coastal areas present in islands with coral reefs. These areas are often relatively low-lying and therefore particularly vulnerable to sea level rise. In addition, the pressure is exacerbated by adverse impacts of human activities, such as wrongly designed coastal structures, coral reef destruction or sand extraction (BENDIXEN *et al.,* 2021). Poor management practice is often a result of a lack of understanding on how the coastal systems work (TUCK *et al*., 2021). An important element for protecting reefs and coastlines specific to islands is therefore to ensure a thorough understanding of the morphological system, and the way in which sediment supply and transport are influenced by anthropogenic activities.

In the realm of coastal management, numerical modelling tools can offer insights into shoreline evolution, considering the coastal system as a dynamic entity. By conceptualizing the coast as a 1D river of sediment migrating alongshore (THOMAS & FREY, 2013), these models describe not only the interactions within the system but also enable the computation of the anticipated rate of change. Numerous studies have showcased the efficacy of such models in evaluating erosion management strategies, analyzing both historical shoreline trends and projecting future evolution (e.g. TONNON *et al*., 2018). Over time, these models have evolved from rigid frameworks suited for uniform coastlines, like GENESIS (HANSON, 1989), to more versatile tools capable of handling complex foreshore dynamics, as demonstrated by ShorelineS (ROELVINK *et al.,* 2020). This advancement holds particular promise for reef-edged islands, as dealing with complex wave boundary conditions and accounting for the representation of diverse protective measures (e.g., sand nourishments, revetments, groynes, offshore breakwaters).

The focal point of this publication lies in assessing the physical dynamics at Gravenor Bay coastline (Coco Point, Barbuda) where an integrated coastal management strategy is investigated to sustain a healthy ecosystem. Utilizing the ShorelineS model (ROELVINK *et al*., 2020), the study aims at quantifying the long-term shoreline evolution, thereby demonstrating the suitability of the model to address complex coastal projects.

2. Methodology

The method to better understand the Gravenor Bay (Coco Point) system morphological behaviour and to predict the shoreline evolution, entails data analysis, wave modelling, morphological modelling and analyses.

2.1 Site description and data collection

Coco-Point is located on the Barbuda Island (Caribbean). The site, which once housed the luxury resort Coco Point Lodge, was devastated by Hurricane Irma in 2017. Currently, the area includes shallow ponds that are part of a mangrove restoration project proposed with the objective to boost economic activities locally.

In the frame of the restoration project, data collection is performed aiming at the analysis of the local wave conditions with a field campaign in 2022, and of the bathymetry of the shoreface and coastlines with the Modular Inversion Program. The complexity of reef coast morphologies is evident in these data. For instance, the analysis of the irregularities in the surfzone bathymetry reveals the presence of semi-hard substrate and fringed beaches encircling the island perimeter. Moreover, the beaches display undulations as a result of nearshore wave conditions variability. The morphologically active zones (i.e. the depth at which significant changes occur) can be discerned by analysing the presence of sand along the fringed beaches and the shoreline configuration.

2.2 Modelling approach

The bathymetry of the bay (and ponds) is inferred using 2021-2022 SENTINEL-2 satellite imagery validated using the latest available single-beam echo sounder profiles collected in 2018 (Figure 1). Wave transformation is then first studied to inform a shoreline evolution modelling, with ShorelineS.

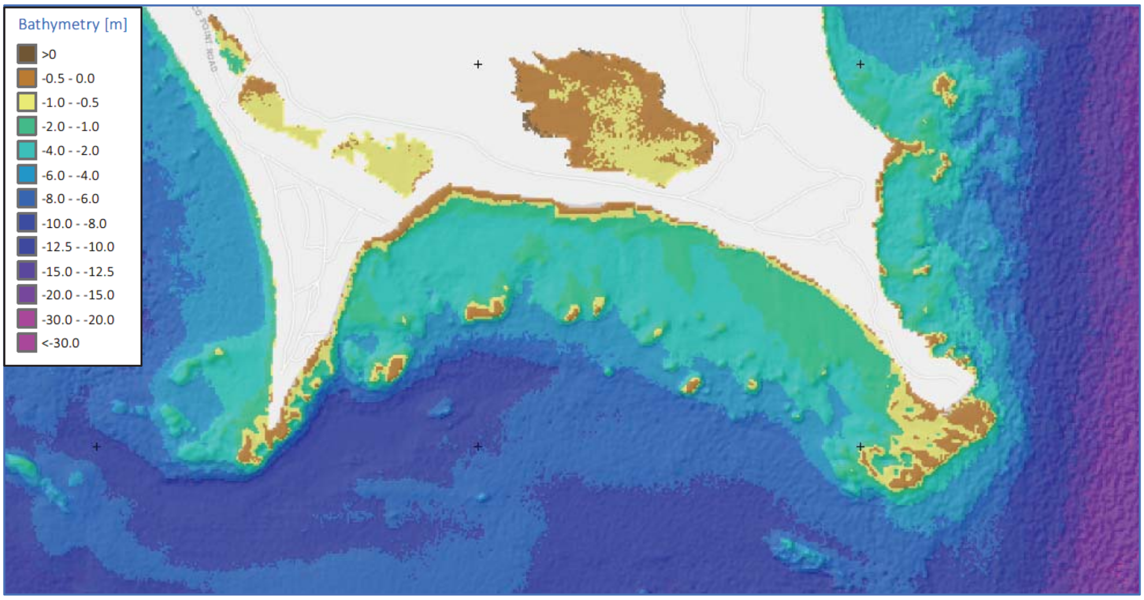

Figure 1. Satellite-Derived Bathymetry South of Barbuda Island obtained by 2021-2022 satellite imagery analysis (EOMAP) and corrected by 2018 single-beam echo-sounder data in the Gravenor bay (elevation data are given in mMSL = mLAT – 0.3m).

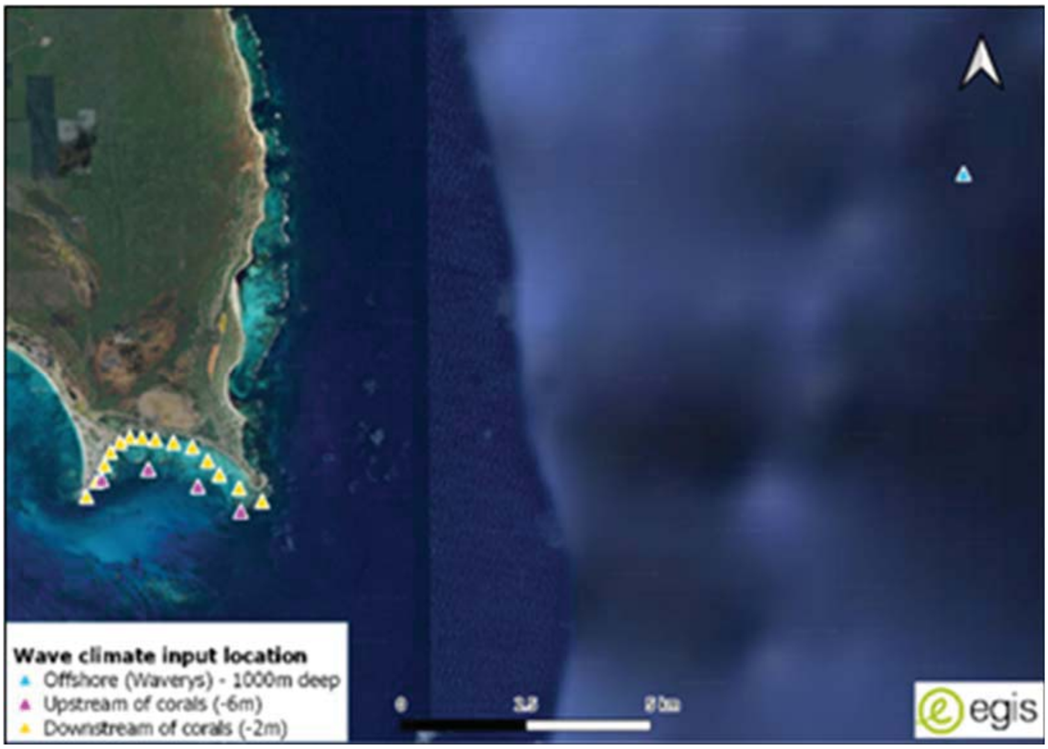

Figure 2. Location of input wave location and propagated wave locations (-2mMSL and -6mMSL isobaths for sensitivity).

A hydrodynamic model covering the offshore domain, the ponds and surrounding low-level areas, is constructed with the open TELEMAC-MASCARET solver suite. Offshore wave conditions, considering multi-directional, random offshore sea states, are propagated to the nearshore (depth of 2 meters, see Figure 2) using the 3rd generation wave model TOMAWAC. Wave propagation is carried out over the complex shoreface of the coral reefs and bathymetric irregularities. The unstructured mesh used by the model allows a fine representation of the coral reefs to ensure that propagation of waves, including refraction near the coast. Grid resolution ranges from 200m at the offshore boundaries to 7-50m in the bay and 2-3m in the channel.

The ShorelineS model (ROELVINK *et al.*, 2020), is then applied to compute actual transport rates at Coco-Point. This one-line model concept of ShorelineS consists of a shoreline evolution modelling tool based on a flexible, coastline-following grid, being a straightforward definition of a complex planform, freedom to allow coastal evolution in any direction, and the possibility to merge and split coastline sections where needed.

The one-line model equation that conserves the sediment in ShorelineS can be represented as follows:

$$\frac{\partial n}{\partial t} = -\frac{1}{D_c}\frac{\partial Q_S}{\partial s} - \frac{\Delta SLR}{\tan\beta} + \frac{1}{D_c}\sum q_i \qquad (1)$$

In this equation n is the cross-shore change, s the longshore coordinate and t is time. The coastline properties are represented by the active height of the profile (Dc), the transport rate in alongshore direction (Qs in m^3/yr), the average slope of the beach profile of the active zone (tan β), the rate of sea level rise (ΔSLR in m/yr) and the supply or reduction of sediment in the system (q_i in m^3/m/yr) due to sand nourishments, sand mining and/or cross-shore transport.

The ShorelineS model computes the transport rates (Qs) based on the CERC formulation (CERC, 1984). This equation accounts for the wave characteristics at the depth of closure (Significant wave height, wave period and wave direction), and a calibration parameter *qscal* [-], as:

$$QS = \mathrm{qscal} \cdot \mathrm{b} \cdot {Hs_{br}}^{2.5} \cdot \sin 2\varphi_{br} \qquad (2)$$

Parameter b is set to 2150$m^{1/2}$/yr, and *qscal* is used as a calibration factor.

For this purpose, the wave conditions are specified at the point of wave breaking, which first required a transformation over the shoreface from the depth at which the coast is still sandy (i.e. approximately the depth-of-closure) to about 2 m depth using the TOMAWAC model. The berm height is set to 1m, considering the local topography, and the closure depth is set to 1m as defined by the Birkemeier formula. This value is consistent with the geomorphology of the coastline, as the coral reefs are located at approx. 2m depth. The Snell law is then applied for the transformation of the wave height and direction change due to refraction. Diffraction in ShorelineS is computed using the ROELVINK *et al.*, (2020) formulation.

3. Results

3.1. Historical trend analysis

The beach of Gravenor Bay is relatively stable in the long term – out of episodic cyclonic events. It is found to be in slight accretion over the period 1984-2016 (up to +1.6m/yr) (LUIJENDIJK *et al.*, 2018), but with irregularities (JAMES, 2017) that might be due to the influence of the local tropical cyclone activity. The beaches near the study area are then considered as quite stable, leading to low sediment availability.

3.2. Wave propagation modelling

The TOMAWAC model is validated against field measurements taken during a summer campaign in 2022, comparing water levels and wave heights in the bay near the entrance to the channel. Wave propagation modelling outputs are extracted at -2mMSL isobath and -6mMSL isobath points for sensitivity tests. Results obtained at -2mMSL are displayed in Figure 3. Offshore WAVERYS wave time series are extracted to prescribe deep water wave boundary conditions accounting for 64 classes (wave height, period, and directions) to represent the non-linearity of transmitted waves.

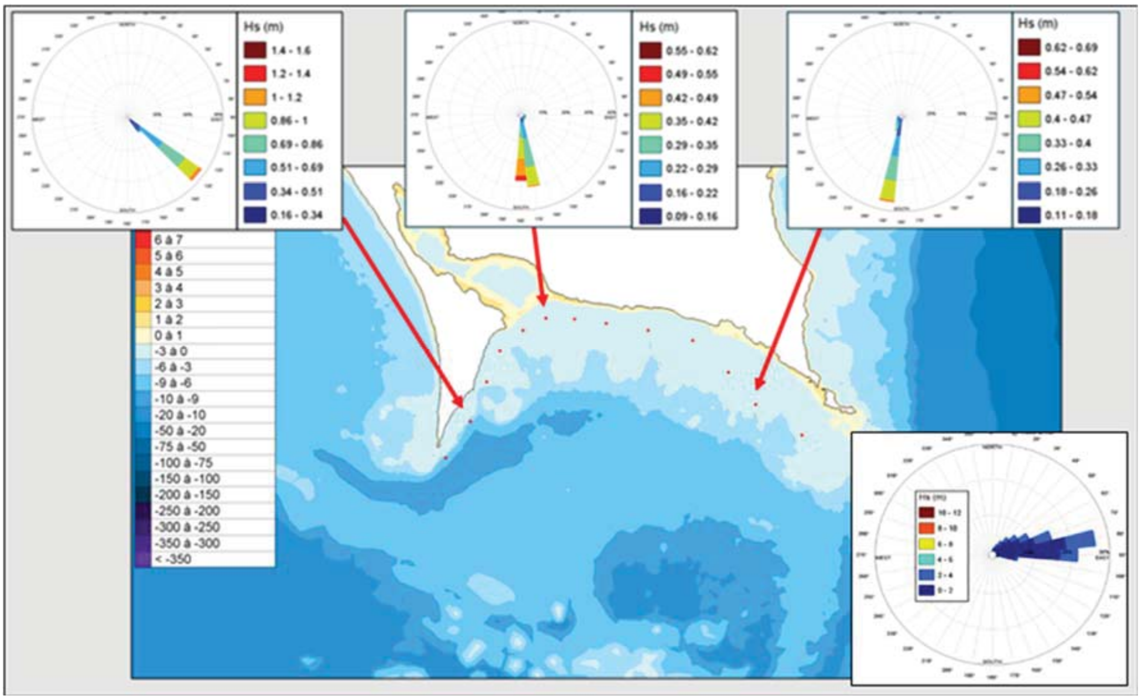

Figure 3. Nearshore propagated waves to -2mMSL isobath through TOMAWAC and offshore wave rose [bottom right corner] (WAVERYS 1993-2020, 17.6N 61.6W ~1000m deep).

3.3. <u>ShorelineS modelling</u>

The sea-level-rise (SLR) is taken into account in the simulation as a constant rate of +6mm/yr between 2020 and 2070 (IPCC, 2022). Erosion due to SLR is computed based on the Bruun rule (1962), considering a representative beach slope of 7% (that could be less at the SW and SE points of the bay).

The channel connecting the salt pond to the ocean is set to 20m wide and kept open by the model during the entire simulation, moving westward or eastward depending on the evolution of the sand spits.

Nearshore wave timeseries are aggregated in ShorelineS to have a representative wave state for each time step, with the shoreline resolution chosen to be 10m and the time step 1 day.

For calibration purpose, ShorelineS is run from 2009 to 2021, and results are compared to shorelines digitalized from Google Earth images.

Comparison of model behavior shows that modelling results are sensitive to wave input locations. Taking the offshore wave climate (-1000m deep) as input leads to almost no evolution along the bay (Figure 4), because the wave incidence is higher than 90° on the eastern part of the bay, and the south-eastern tip shades almost the entire coastline.

Wave propagation to the -6m isobath only implies that waves are not sufficiently refracting, and numerical instabilities appear in the eastern part of the bay (Figure 4b) with oscillations of 10 meters amplitude. A gentle slope and the influence of reef patches between the -6m isobath and the coastline, which induce wave refraction and attenuation, are then included in the TOMAWAC wave modelling.
Wave propagation to the -2m isobath is then performed to ensure the most accurate input to the ShorelineS model downstream of coral reefs. The south-western tip is less sensitive to the location of the wave climate input due to its orientation and the presence of coral only closer to the shore (Figure 4a).

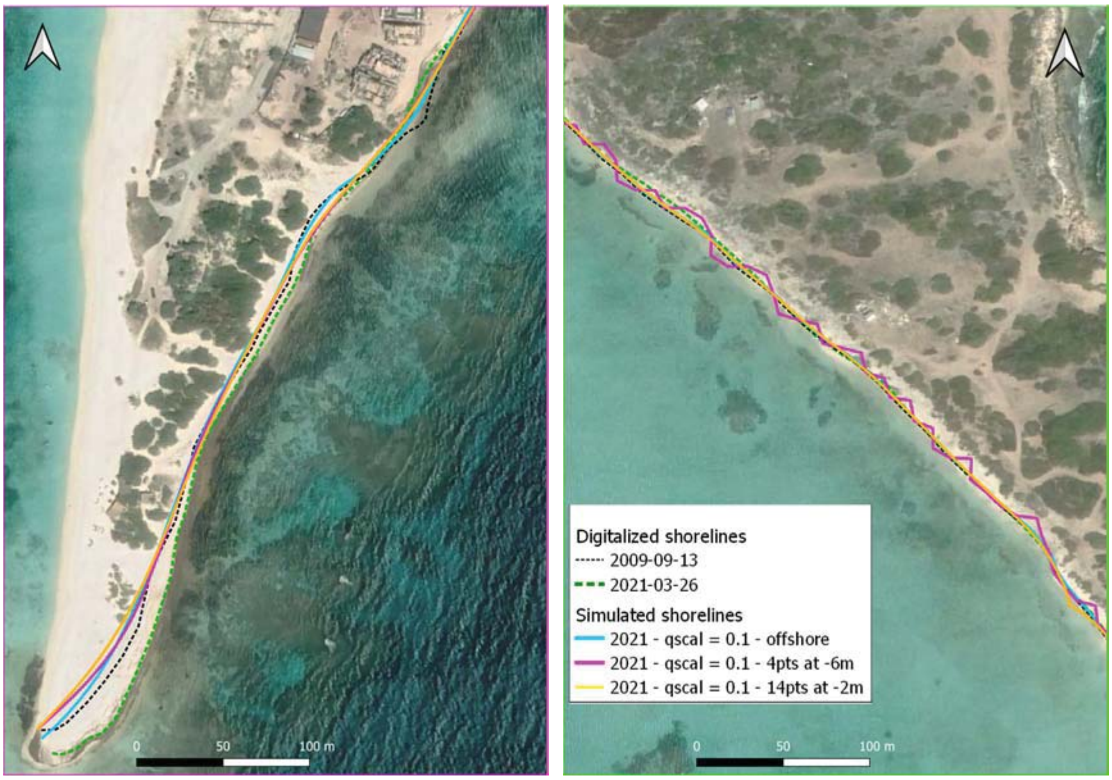

Figure 4. Simulated shorelines (2009-2021) for different wave input: not propagated (offshore climate into ShorelineS directly), propagated to 6m depth, propagated to 2m depth.

The value of the calibration factor *qscal* = 0.1 best reproduces the true evolution rate, and was chosen after a sensitivity test among values of *qscal* between 0.05 and 0.5. This value represents a good compromise between consistent evolution rates (max +/-0.5m/yr immediately west of the channel, and max 0.25m/yr immediately east of the channel) and shape behaviour for local coastal features. However, some features, such as the erosion trend southwest of the channel, are not reproduced.
Typical sediment transport rates are found in the range of 100 to 1 000m^3/yr, higher on the southwestern side of the bay (mainly from west to east) due to the reduced protection

of the coastline by the coral reefs. In the centre of the bay, sediment are either deposited, implying coastal accretion, or are transported offshore by a cross-shore current. A convergence pattern can be seen around the entrance to the channel, with longshore transport directed from both the western and eastern sides of the bay (see Figure 5 as final results). This is consistent with simulated current maps where wave-induced currents dominate over wind-induced currents. Note however that such currents cannot be reproduced by 1D shoreline models like ShorelineS.

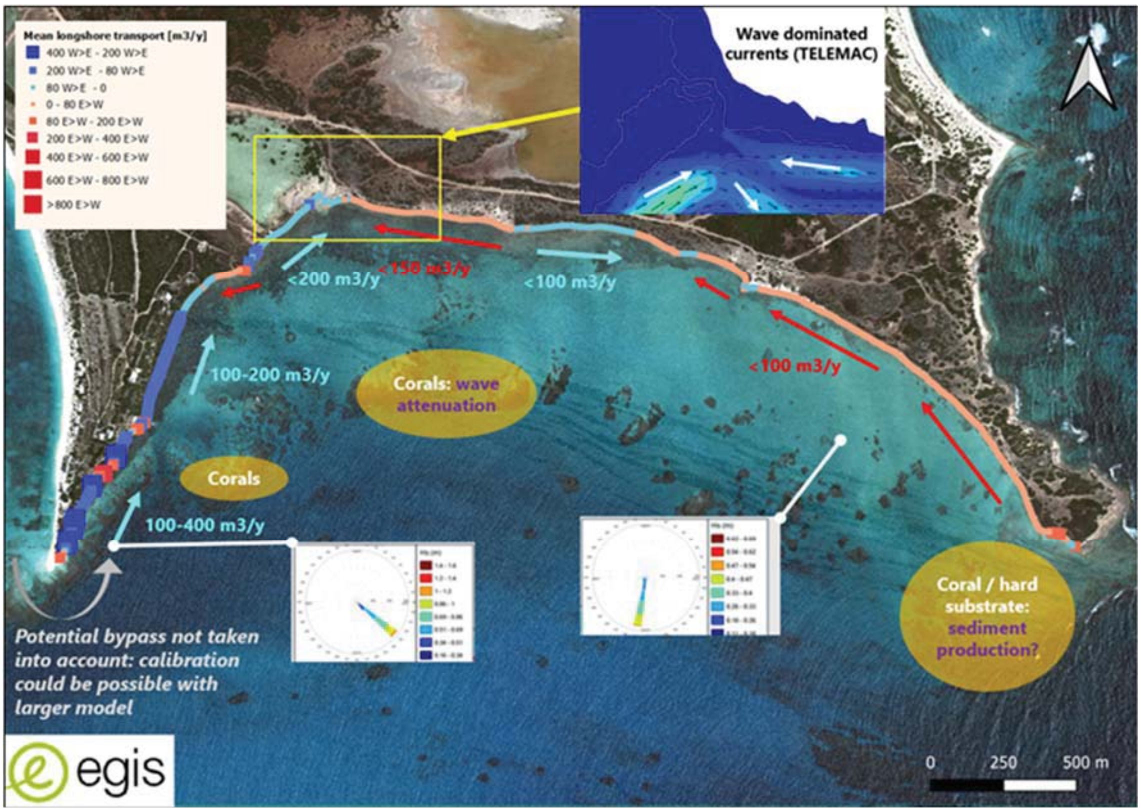

Figure 5. Conceptual figure representing mean annual computed longshore transport, against wave input examples, location of coral reefs.

3.4 <u>Limited sediment availability</u>

Sediment availability is difficult to estimate at Coco Point. Sand by-pass could potentially occur occasionally from West to East, resulting in additional sediment availability from SW of the bay. Sediment could also be supplied by reef-corals’ erosion (especially at the SE tip) and from seagrass fields. Still, as beaches are made of a thin layer of sediment over a hard-coral layer, sediment transport capacity is therefore limited.

3.5 <u>Long-term evolution</u>

Long-term shoreline evolution is computed with ShorelineS for the 2070 horizon (Figure 6). Sea level rise (SLR) is accounted for, inducing erosion at a about 4m rate over all the period. The channel is kept open, and remains stable, slightly widened due to SLR. Local coastline features appear rather smoothed. The modelling results are consistent with those obtained in the calibration phase and show that the coastline is not expected to retreat more than 10 meters close to the pond entrance (-0.2m/yr).

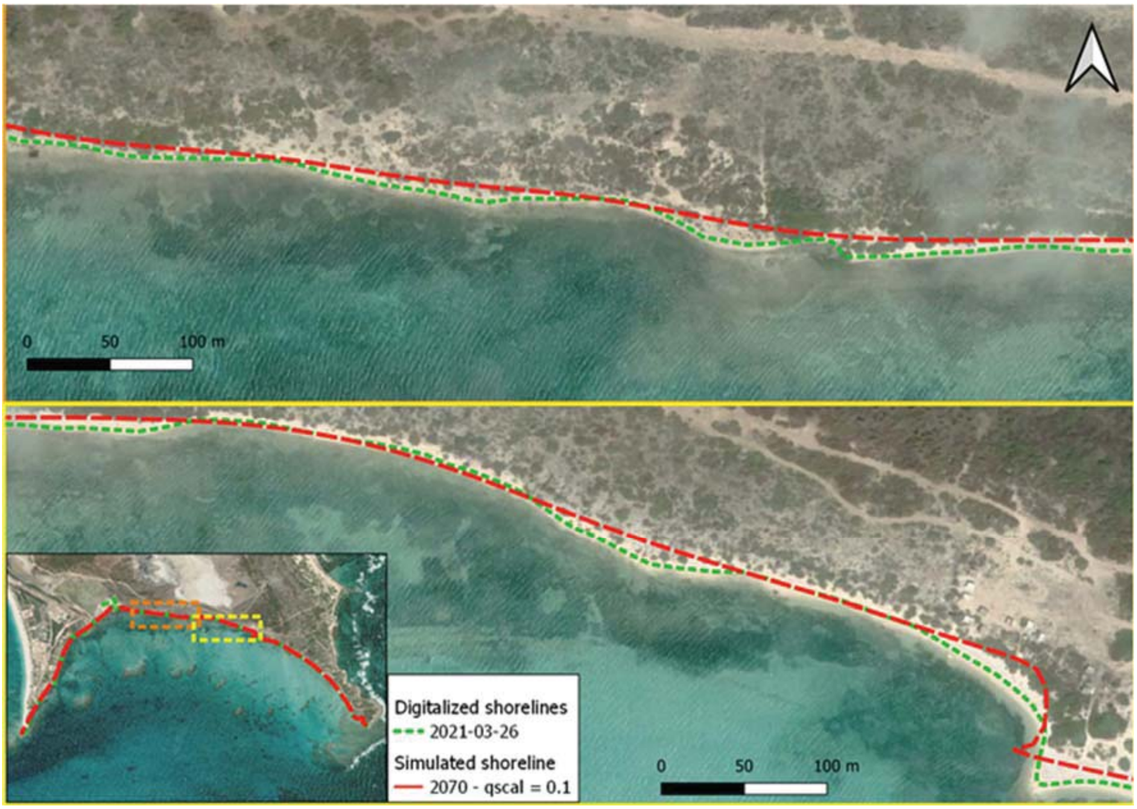

Figure 6. Long-term evolution predicted with ShorelineS model (2070 horizon) including SLR.

4. Discussion

The complex morphology of Gravenor Bay is closely linked to bathymetric irregularities caused by the presence of coral reef patches, primarily located in the central and south-eastern regions of the bay. Although ShorelineS is able to refract waves using empirical formulations and beach slope assumptions, wave transformation must be performed with TOMAWAC up to the nearshore point to better represent wave energy attenuation over coral patches and in the context of limited sediment availability. As such, the ShorelineS model accounts for spatially varying wave inputs.

Moreover, the representation of sediment supply and loss is of great importance when considering long-term trends and sensitivity to sea-level rise. A more precise definition of sediment availability could be proposed by establishing a theoretical erosion limit, similar to a seawall, perhaps aligned with the vegetation boundary. It would also be important to better understand the sediment production by coral reefs and seagrass beds.

No biological component is included in the model. Finally, a better understanding of the amount of sand bypassing at the southwest boundary could be beneficial. Extending the ShorelineS model to include the west coast of Coco-Point may be an idea to determine these bypass rates.

Besides, as ShorelineS focuses on long-term evolution, the short-term effects of extreme events (e.g. hurricanes) are not assessed in this study but would require attention, especially with regard to offshore-directed sediment losses.

In summary, improving the modelling approach to include beach slopes, sediment availability, and cross-shore currents promises more accurate predictions and would better prepare for managing the challenges of coastal erosion and sea-level rise challenges.

5. Conclusion

As part of the development of a coastal restoration project at Gravenor Bay, Coco Point, Barbuda, the long-term shoreline evolution model ShorelineS is being used to provide a better understanding of the physical system. Wave attenuation and refraction are addressed using TOMAWAC, so coupling the two models provides a better understanding of the dynamics associated with limited sediment supply in this coral reef environment.

At Gravenor Bay, the ShorelineS model projection suggests relative stability of the coastline over the coming decades, foreseeing a gradual smoothing of its characteristic features, assuming a sufficient sand availability. This can be explained by the wave attenuation over the reef, resulting in low sediment transport rates.

Furthermore, the model keeps representing the opening of the channel entrance to the pond where the restoration project is planned. However, a slight westward shift of the channel entrance is predicted, which should be taken into account in any coastal management project in this area.

Still, the integration of key parameters, such as the influence of sea level rise on wave dynamics and associated generation of rip currents, as well as a fine representation of sand layer thickness, could refine the predictions and better capture the complex interplay of factors influencing shoreline dynamics at Coco Point.

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