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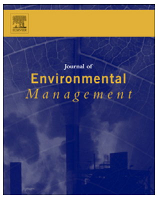

Research article

# Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada

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ABSTRACT

Coastal communities in tropical environments are at increasing risk from both environmental degradation and climate change and require urgent local adaptation action. Evidences show coral reefs play a critical role in wave attenuation but relatively little direct connection has been drawn between these effects and impacts on shorelines. Reefs are rarely assessed for their coastal protection service and thus not managed for their infrastructure benefits, while widespread damage and degradation continues. This paper presents a systematic approach to assess the protective role of coral reefs and to examine solutions based on the reef's influence on wave propagation patterns. Portions of the shoreline of Grenville Bay, Grenada, have seen acute shoreline erosion and coastal flooding. This paper (i) analyzes the historical changes in the shoreline and the local marine, (ii) assess the role of coral reefs in shoreline positioning through a shoreline equilibrium model first applied to coral reef environments, and (iii) design and begin implementation of a reef-based solution to reduce erosion and flooding. Coastline changes in the bay over the past 6 decades are analyzed from bathymetry and benthic surveys, historical imagery, historical wave and sea level data and modeling of wave dynamics. The analysis shows that, at present, the healthy and well-developed coral reefs system in the southern bay keeps the shoreline in equilibrium and stable, whereas reef degradation in the northern bay is linked with severe coastal erosion. A comparison of wave energy modeling for past bathymetry indicates that degradation of the coral reefs better explains erosion than changes in climate and historical sea level rise. Using this knowledge on how reefs affect the hydrodynamics, a reef restoration solution is designed and studied to ameliorate the coastal erosion and flooding. A characteristic design provides a modular design that can meet specific engineering, ecological and implementation criteria. Four pilot units were implemented in 2015 and are currently being field-tested. This paper presents one of the few existing examples available to date of a reef restoration project designed and engineered to deliver risk reduction benefits. The case study shows how engineering and ecology can work together in community-based adaptation. Our findings are particularly important for Small Island States on the front lines of climate change, who have the most to gain from protecting and managing coral reefs as coastal infrastructure.

## 1. Introduction

Shorelines change in a wide range of temporal and spatial scales from both natural and human-induced factors (Stive et al., 2002). Coastal erosion and flooding are major global problems but becoming more acute as climate change converges with coastal development and natural geomorphic changes (Hallegatte et al., 2013; Kron, 2013; Reguero et al., 2015a). For example, over 85% of

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the barrier beaches along the east coast of the United States have experienced erosion during the past century (Zhang et al., 2004), contributing to deteriorate a natural physical defense from flooding. In Hawaii, changes in sea level have been identified as the proximal cause of shoreline erosion (Romine et al., 2013). The risk of flooding and erosion is increasing from sea level rise, subsidence and coastal storms (Aagaard and Sørensen, 2012; Cazenave and Cozannet, 2014; Hinkel et al., 2013; Nicholls and Cazenave, 2010; Rosati et al., 2013; Wong et al., 2014).

Tropical developing nations in general and Small Island States in particular are the most vulnerable to the impacts of climate change due to population concentration in coastal areas, exposure to hazards, limited land space, geographic isolation, scarce freshwater supplies and significant dependence on tourism and fisheries (Kumar and Taylor, 2015; Nurse et al., 2014; Reguero et al., 2015a). They will be the most impacted by enhanced coastal flooding and erosion. For these small island nations, climate adaptation is essential now, regardless of the trajectory of future greenhouse gas emissions (Wong et al., 2014).

Increasing evidence indicates that coastal habitats protect coastal communities and could serve as effective adaptation and risk reduction strategies while also providing other valuable services (Cheong et al., 2013; Spalding et al., 2014; Temmerman et al., 2013). Coral reefs in particular constitute a first line of defense from erosion and flooding through wave attenuation and the production and retention of sand (Elliff and Silva, 2017; Ferrario et al., 2014; Pascal et al., 2016). Fringing natural reef crests function much like low crested breakwaters (Beck and Lange, 2016), dissipating wave energy and protecting the shoreline (Gallop et al., 2014; Rogers et al., 2013; Sheppard et al., 2005). Coral reefs also generate fine coral sand supplying shores with sand generated by physical forces as well as the biota (e.g. Bellwood, 1995).

Specific research exist on how reef parameters and geometry influence the geophysics of wave dynamics and wave energy attenuation (Buckley and Lowe, 2013; Costa et al., 2016; Lowe et al., 2010; Monismith, 2007; Monismith et al., 2013; Quataert et al., 2015; Torres-Freyermuth et al., 2012). Live coral provide the reef with shallower geometrical complexity and more surface roughness that dissipate wave energy through friction and wave breaking (Quataert et al., 2015). Correspondingly, coral mortality increase the wave energy reaching shores as the reef presents less friction to waves and the removal of the coral skeletons increases the depth of water over the reef flat (Sheppard et al., 2005).

However, direct knowledge on how coral reefs prevent coastal impacts such as erosion and flooding is scarcer. This paper investigates a possible direct link between reef condition and coastal protection. Only a few direct studies draw causality between coral reefs and shoreline stability (Frihy et al., 2004; Ruiz de Alegria-Arzaburu et al., 2013). Studies in the Maldives, Red Sea, Cancun (Mexico) and Bali (Indonesia) show that factors like coastal development, reef degradation and artificial defenses are related but causality is difficult to establish (Ferrario et al., 2014). This is partly because changes in coral reefs modify wave energy propagation, and in turn currents and sediment transport, in complex spatial ways beyond wave attenuation (e.g. Monismith, 2007). Furthermore, in many communities across small island nations other factors such as sand and coral mined for their use in construction further destabilizes the shoreline and damages the reefs through sedimentation, driving a perverse cycle. Linking coral reefs condition to coastal impacts has therefore been challenging given the multiple factors at play, the complexity of the coastal processes involved, and the lack of historical observations and data.

This study also presents an innovative project to use reefs in climate adaptation for both risk reduction and conservation. There is an urgent need of conservation and robust local action to tackle stressors, threats of climate change and to increase the resiliency of coral reefs (Bellwood et al., 2004; McGowan et al., 2016; Rinkevich, 2015, 2008). Degraded reefs can be structurally and functionally restored using both biological and physical techniques, including the use of artificial reefs. Artificial reefs are a combination of a submerged structure and natural reefs (Jaap, 2000); as submerged breakwaters, they mimic the protection and ecological benefits of a natural reef (Goreau and Trench, 2012; Pilarczyk, 2003) and exist in several forms and materials (Carlisle and Ebert, 1964). Artificial reefs have been used to favor conditions for diving, swimming and surfing, as wells as protecting beach areas for tourism and other recreational purposes (Black, 2001; Ranasinghe and Turner, 2006; Scarfe et al., 2009). Artificial reefs also serve as shelter and habitat for algae and fish, thus increasing the ecosystem resilience and marine biodiversity (Pickering et al., 1999). However, they have rarely been designed for coastal protection specifically at a scale comparable to traditional coastal structures and in a challenging energetic environment similar to natural conditions. Many questions remain on how to design and implement these projects (Narayan et al., 2016; Saleh and Weinstein, 2016). Despite existing favorable momentum for nature-based risk reduction, examples of reefs designed and engineered as natural infrastructure are practically inexistent.

This paper contributes to addressing these gaps by directly linking coral reefs with shoreline protection and outlining how reefs can be used as a tool for climate adaptation. First historical changes in coastal processes and the potential role that coral reef system have played on coastal impacts are examined in a Bay in the Caribbean, suggesting a direct link between coral reefs and shoreline stability in the Bay. Secondly, the design and field-test of an artificial reef aimed at providing joint benefits in risk reduction and conservation is outlined.

## 2. Field site description

Grenville is a fishing community located at the water's edge in the country of Grenada (Fig. 1). Adapting to existing coastal impacts is an immediate priority for the country emphasized in the National Adaptation Plan (Charles, 2000). The shoreline has been eroding in many parts of the country and coastal ecosystems degraded (Charles, 2000). The Intergovernmental Panel on Climate Change highlights the devastation wreaked on Grenada by 2004's Hurricane Ivan as “a powerful illustration of the reality of small-island vulnerability” (Box 16.3 in Mimura et al., 2007). Ivan, a category 3 hurricane, struck Grenada killing 28 people and causing damage of US$ 800 million, twice the nation's gross domestic product. As in other Small Island States, climate change adds further threats and stress to these coastal communities rendering the need to adapt a priority.

Grenville bay faces the North Atlantic wave climate and can be considered a high-energy environment (a wave climate description can be found in the Results and Supplementary Information). However, the shoreline is protected by a system of coral reefs (Fig. 1-c). The bathymetry presents deeper banks and shallower zones near shore, which alternate sand and seagrass beds (Fig. 2). Hard coral framework and reef rubble alternate with algae cover over the most exposed areas of the Bay, while algae presence is predominant closer to shore and in the shallowest areas (Fig. 2-b). Benthic algae and corals are among the main groups competing for space on coral reefs (Fong and Paul, 2010). Favorable conditions for algal growth are created by the reduced abundance of herbivorous fish due to overfishing and eutrophication resulting from the unsustainable use of coastal areas (Hughes, 1994). However, the benthic survey shows large areas still dominated by live coral in the Bay (Fig. 2), despite signs of historical loss in sections, in particular

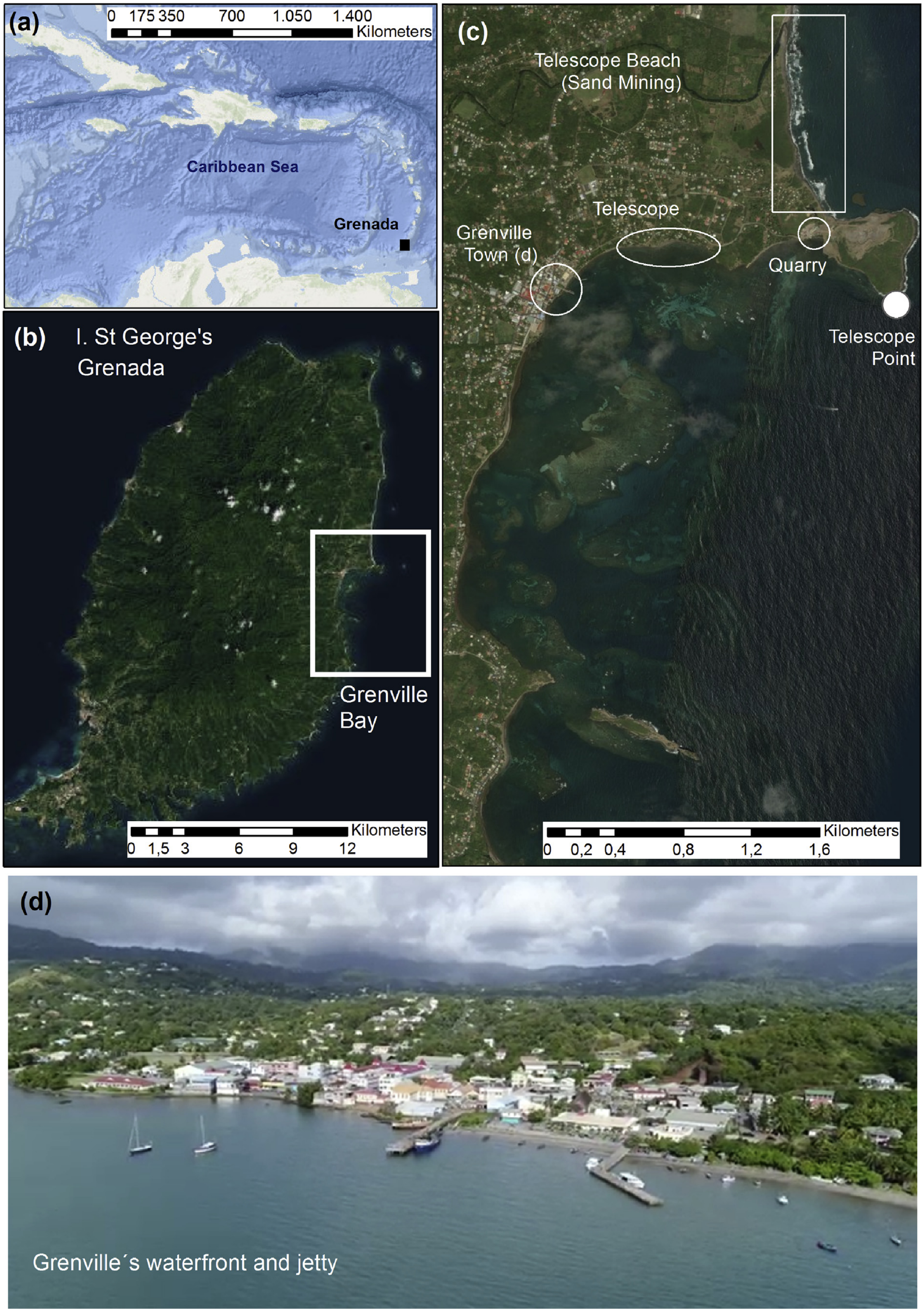

**Fig. 1.** Location and regional setting of Grenville Bay.

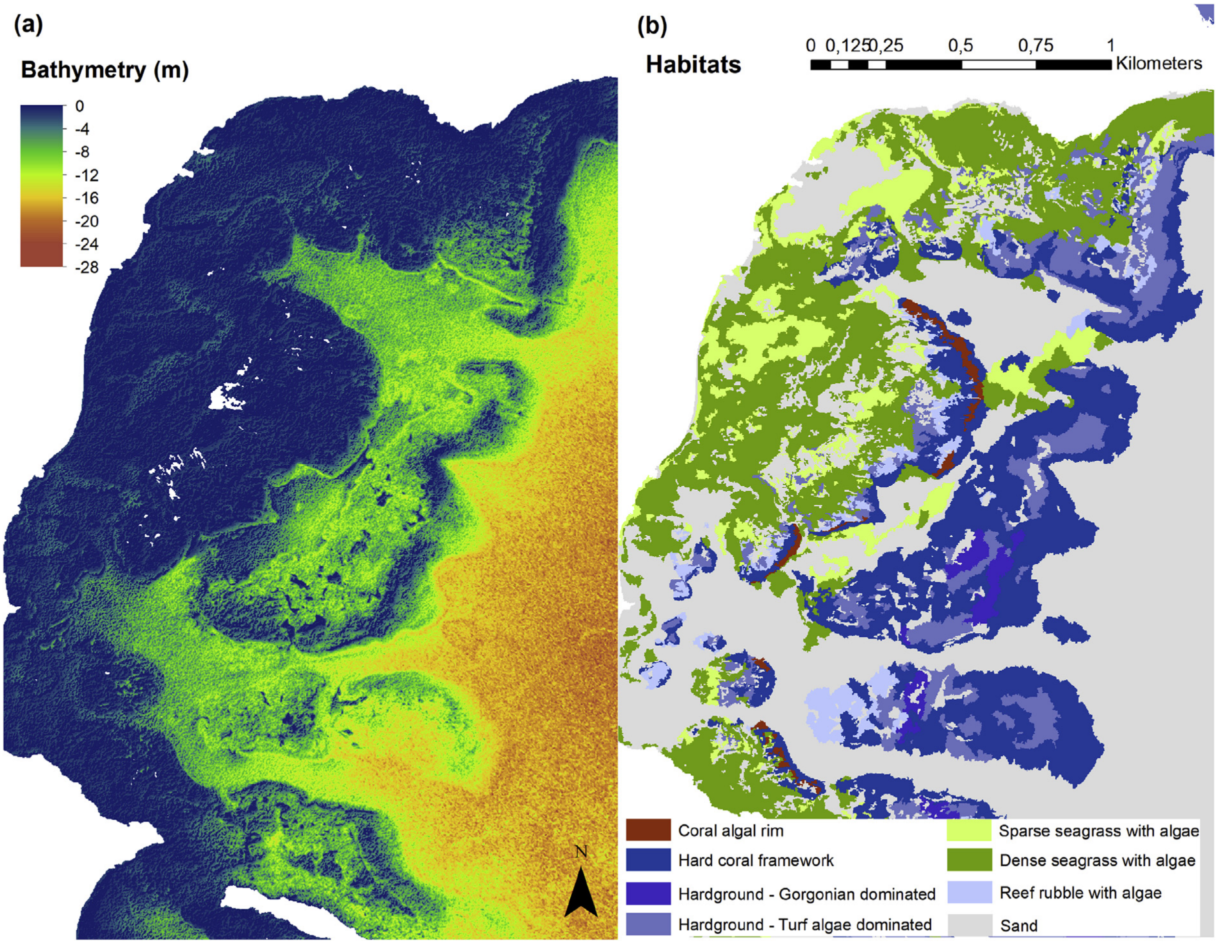

**Fig. 2.** (a) Bathymetry data, with resolution 2 × 2 m. (b) Distribution of benthic data. Survey was done in year 2012.

the northern lobe.

The port of Grenville is located on the east coast of the island and is the second largest port on mainland Grenada. It functions as the main landing site for fishermen on the eastern side of the island and as a shipping facility for agricultural goods and services to and from Trinidad (Charles, 2000). There are two deeper navigation channels situated to the north and south of the well-developed and healthy central reef system, which are used by local fisherman to access the town waterfront and the market jetty.

The community in the *Telescope Area*, along the north-most section of the bay and east from Grenville's waterfront (Fig. 1-c), is currently suffering from erosion and flooding. Sediment eroded from this area is silting up the harbor and hampering operations at the market jetty (Fig. 1-d). The navigation channel now requires regular dredging to accommodate larger ships while land keeps eroding and habitat being destructed.

On the east, the Telescope Division quarry, in operation since 1944, is located approximately 1/2 mile from the town center and only a few meters away from the coastline. It currently mines at the site basalt rocks and manufacture concrete products (Gravel, 2009). Silica sand for construction is imported from Guyana nowadays. The importation started in January 2009 after the Government's banned the removal of sand from local beaches in Grenada. Prior to January 1st 2009, *Telescope Beach* (north of the Telescope point) was the only designated beach for sand mining in the whole country. Sand removal led to beach erosion and habitat destruction in the vicinity as well as outside the mining area (see location in Fig. 1-c).

## 3. Materials and methods

This paper studies the role of reefs in shoreline protection through a methodological approach that encompasses three main steps (see Table 1): (1) an analysis of the historical coastal changes; (2) an assessment of the current role that coral reefs play in shoreline positioning; and (3) the design of an artificial reef for coastal protection. The approach considers historical shoreline evolution and climate data over six decades. Based on modeling of wave energy, it implements a shoreline equilibrium model for Grenville bay to understand the role of present reefs and the historical impacts to the local community. Finally, an artificial reef solution is examined as an alternative to coastal armoring and conventional breakwaters, which is designed from a coastal engineering perspective and includes field-testing of pilot units.

### 3.1. *Analysis of historical changes*

A baseline survey was conducted in Grenville Bay in 2015. Benthic and bathymetry data were collected with at GPS-referenced transducer, side scan sonar, high definition underwater video and snorkel surveys. The bathymetry and habitat mapping data (Fig. 2) were complemented with WorldView-2 satellite imagery from September 1, 2012, to create a 2-m resolution bathymetry for the whole domain of the bay, following the methodology described in (Stumpf et al., 2003).

Background information on the social context, land uses and historical changes in the coastal zone was obtained from: Weis et al.

**Table 1**
Methodological approach and phases for studying the role of reefs in shoreline protection, outlining the data sources and analysis for each phase.

| | Phase I. Analysis of historical changes | Phase II. Assessment of the role of coral reefs in shoreline positioning | Phase III. Design a reef-based solution |
|---|---|---|---|
| Data sources | • Shoreline evolution (satellite and aerial imagery) – 1950 onwards<br>• Historical wave climate data – 1948 onwards<br>• Historical Mean Sea Level time Series – 1950 onwards<br>• Bathymetry and benthic surveys in year 2012.<br>• Meeting with stakeholders (Grenville Community)<br>• Social and Physical Planning information (Government of Grenada) | • Reef circulation based on numerical simulations of wave propagation: currents and wave heights<br>• Historical position of the shoreline<br>• Wave Energy Flux calculated from wave climate propagation | • Wave Climate propagation data<br>• Bathymetric and benthic survey<br>• On-site diving |
| Analysis | • Numerical modeling of hydrodynamics in the bay (wave heights and currents)<br>• Effects on wave height propagation and Annual Wave Energy Flux | • Changes in Wave Energy magnitude<br>• Changes in Wave Energy direction | • Changes in Wave Energy magnitude<br>• Changes in Wave Energy direction<br>• Run up calculation<br>• Design of structure section and modular baskets<br>• Design and implementation of pilot units<br>• Monitoring program: design and implementation |

(2016), the Grenada Physical Planning Unit and the Fisheries Department, in person meetings during 2014 and 2015 with community stakeholders, the First National Communication to the United Nations Framework Convention on Climate Change (Charles, 2000), and other adaptation programs in the country (e.g. ICCAS, 2016).

The historical position of the shoreline was digitized from aerial photos dated in 1951, and more recent Ikonos and Worldview-2 satellite imagery for years 2003 and 2012, respectively. The shoreline position was manually digitalized from the orthorectified imagery using visual references to landscape benchmarks using the pier, the Telescope point and the southern island. Landsat imagery (lower resolution) after 1980s was used to compare with most recent imagery and detect historical changes before 2003.

Tides were calculated from the TPXO global tides model as in Losada et al. (2013). The tidal regime in Grenville bay is micro-tidal, with the spring tide water level being approximately 0.3 m above mean sea level. Using measurements of beach profiles the influence of tidal variations in the coastline digitalization is estimated below 4 m, which is negligible compared to the observed changes in the northern bay (see Supplementary Information).

Historical time series of wave parameters (significant wave height, mean period and mean direction) were obtained from the Global Ocean Waves (GOW) reanalysis in the Caribbean (Reguero et al., 2013, 2012), which covers the period from 1948 to 2008 and includes information of altimetry measurements (Mínguez et al., 2011a, 2011b). The historical time series of astronomical tide, storm surge and historical mean sea level were obtained from Losada et al. (2013). However, the effect of astronomical tides in the propagation was not considered for being a micro-tidal environment (tidal range is approximately 0.6 m, see Supplementary Material). The 61-year wave and sea level data were used for wave propagation inside the bay and to assess long-term changes in offshore conditions. Long-term changes and the influence of the interannual variability were estimated from regression analysis of the mean significant wave height, mean wave energy direction and mean sea level time series, as computed and described in Reguero et al. (2013) for wave data and in Losada et al. (2013) for sea levels.

Waves were propagated in the bay using an hybrid dynamic propagation scheme (Camus et al., 2013, 2011a, 2011b) as follows:

i. The most representative offshore wave conditions were identified using a maximum dissimilitude algorithm (sea states were classified by significant wave heights, mean periods and directions). Given the small variation in wave direction and heights, 100 sea states were sufficient to represent the 61-yr hourly data (e.g. Reguero et al., 2013). See the Supplementary Material for a representation in a Self-Organizing Map.
ii. The selected sea states were propagated using a wave model that accounts for breaking, refraction and diffraction in nearshore areas (details of the numerical model below), considering a static mean sea level (the contributions of tides and non-hurricanes surges are relatively small). Details on the wave model and computation grids follow below.

The time series of significant wave height, mean period and mean wave direction were reconstructed at each point in the bay using multi-dimensional interpolation through radial basis functions on the set of propagated parameters.

The results of this propagation scheme are time series of hourly wave conditions in nearshore areas. Although the results only show wave and current fields for a specific sea state, the analysis of changes in the coastal hydrodynamics (i.e. waves and currents) is based on the information of wave climate for 61 years. Both high and low probability events are represented in the analysis because the approach selects sea states associated to their probability of occurrence.

The wave model used for the propagation was the *OLUCA-SP* (González et al., 2007), a weakly nonlinear combined refraction and diffraction model that solves the parabolic approximation solution to the mild-slope equation (Kirby and Dalrymple, 1983). OLUCA-SP was initially based on REF/DIF1 (Kirby and Dalrymple, 1992) and REF/DIFS (Kirby and Ozkan, 1994) models. It accounts for breaking, refraction and diffraction; all dominant processes in wave propagation in shallow water areas (Fan et al., 2012). The waves were propagated using two grids. An offshore grid with a resolution of 100 m covered 3 km in length from the shore. A finer grid was nested in the northern half of the bay with 20 m resolution to better resolve the nearshore processes. The model used as inputs the selected offshore wave parameters as explained above, and assumed a Jonswap wave spectrum with peak shape parameter of 3.3, a typical value for the North Atlantic wave climate.

### *3.2. Assessment of the role of coral reefs in shoreline positioning*

In a novel application, the role of coral reefs in maintaining Grenville bay's shoreline is studied through a shoreline equilibrium model usually applied in coastal engineering for protected shorelines (e.g. Hsu et al., 2010). The equilibrium beach concept, both in planform and profile, has been widely used in coastal engineering practice (González et al., 2010) for morphological modeling on macro-scales (hundreds of meters to kilometers and years to decades). This model is applied here to coral reefs on the grounds that they induce wave refraction and diffraction patterns similarly to natural (e.g. headlands) and human-designed obstacles to wave propagation (e.g. breakwaters). The methodology in González and Medina (2001), proposed for static equilibrium shoreline in bays, is here adapted to reef environments to examine if coral reefs help to stabilize the shoreline in a similar manner than natural headlands and human built infrastructure.

The curved periphery of protected shorelines (e.g. beaches in the lee of natural headlands or breakwaters) adopt a parabolic shape at equilibrium (Hsu and Evans, 1989), in response to the diffraction and refraction of waves (González and Medina, 2001; Hsu et al., 2010; Jackson and Cooper, 2010). Wave refraction is the shifting of waves induced, primarily, by bathymetry changes; while diffraction is a transfer of wave energy from high towards low wave heights (i.e. protected areas) along a wave front (Dean and Dalrymplea, 1991). These shorelines may reach static equilibrium and remain stable without sediment supply from updrift and/or a riverine source within its own embayment (Hsu and Evans, 1989). González and Medina (2001) obtained that the downcoast straight shoreline alignment was parallel to the resultant wave front associated with the mean Wave Energy Flux (WEF) at certain control points and proposed a simple model for static equilibrium shoreline in bays. These points, referred hereafter as 'control points', can be identified from diffraction patterns as represented in the wave and current fields (e.g. Fig. 3-b and Supplementary Fig. 6). The methodology in González and Medina (2001) describes how to obtain the shoreline equilibrium position using information of the local WEF at these diffracting control points. The WEF can be calculated from time series of wave data as (Dean and Dalrymplea, 1991; Reguero et al., 2015b):

$$\overrightarrow{WEF} = E\cdot\overrightarrow{C_g} = \left(\frac{1}{8}\rho g H^2\right)\cdot\overrightarrow{C_g} \tag{1}$$

where $H$ is the significant wave height, $\overrightarrow{C_g}$ is the wave group velocity vector and $\rho$ the water density.

For hard emergent structures, these points are visually evident: they coincide with obstacles such as breakwaters and natural headlands (e.g. Hsu et al., 2010; Jackson and Cooper, 2010). However, the propagation of waves through submerged structures such as coral reefs is more complex and makes the prediction of the 'control points' more challenging. Therefore, to apply this equilibrium model in reef environments, the methodology in González and Medina (2001) is adapted in a sequence of steps:

i. A draft planform equilibrium shape for the sand beaches is first adjusted to the stable historical shoreline positions (i.e. sections that did not significantly changed since the 1980s), following the methodology described by González and Medina (2001) and Hsu et al. (2010) and using the using the Coastal Modeling Software in González et al. (2007). This step gives draft locations for the 'control points'. The draft equilibrium shapes are adjusted using the satellite imagery but also through the identification of diffraction patterns as represented in the wave and currents resulting from the propagation of waves in the bay (see example of a currents field in Fig. 3-b).
ii. For the adjusted equilibrium models, the direction of the corresponding mean WEF is calculated at these draft 'control points' using also the software in González et al. (2007), i.e. $WEF_{ii}$.
iii. The WEF at the same draft points is recalculated using the local wave time series at each point through equation (1), giving $WEF_{iii}$.
iv. The direction of the WEF vectors, $WEF_{ii}$ and $WEF_{iii}$ from steps ii and iii, are then compared. If both directions differ, the draft points and shoreline model from step i are readjusted maintaining the direction of $WEF_{iii,}$ the propagated WEF.
v. Steps ii to iv are repeated until the directions of the WEF vectors coincide in each control point, with the exception of control points very close to shore (less than 100 m from shore). In those areas the resolution of the numerical model (20 m) and the bathymetry are not detailed enough to represent the hydrodynamics adequately and the WEF vectors are considered affected by greater uncertainty. These areas can be identified from the final model adjustment but also considering points that fall between a few nodes from the shore (e.g. less than two wavelengths from the shore).

WEF is a determinant factor in the planform equilibrium model, but is also a key component of both long- and cross-shore sediment transport. The potential long-shore sediment transport rate (the movement of beach sediment along the coast), dependent on an available quantity of littoral material, is most commonly correlated with the so-called long-shore component of the WEF (USACE, 1984):

$$WEF_L = WEF_b \cos\alpha_b \sin\alpha_b \tag{2}$$

where WEF is the wave energy flux per unit width of wave crest and $\alpha_b$ is the angle of wave approach at the breaking point (denoted by *b*). Therefore, changes in the WEF magnitude and direction can be interpret as changes in the potential sediment transport (similar to the shoreline equilibrium model): wave energy more orthogonal to the shore represents less potential sediment transport; while wave energy parallel to the shore increase sediment transport. Longshore sediment transport has been shown to be proportional to the value of $WEF_L$ with a value of 0.77 (Komar and Inman, 1970). Although other formulations show that this proportion may also depend on other factors, for example the sediment size (e.g. del Valle et al., 1993), the direction and intensity of WEF can used to understand and explain changes in sediment transport.

Similarly, the cross-shore equilibrium beach profile shape is the result of the constructive and destructive forces acting on a beach profile. One of the most popular models to estimate the equilibrium beach profile is to consider the time-averaged WEF equation across shore:

$$\frac{dWEFs}{dx} = -\varepsilon \tag{3}$$

where WEFs is the net shoreward energy flux per unit width and $\varepsilon$ is the energy dissipation rate per unit area (e.g., Thorton and Guza, 1983).

Therefore, the WEF can be related with both long- and cross-

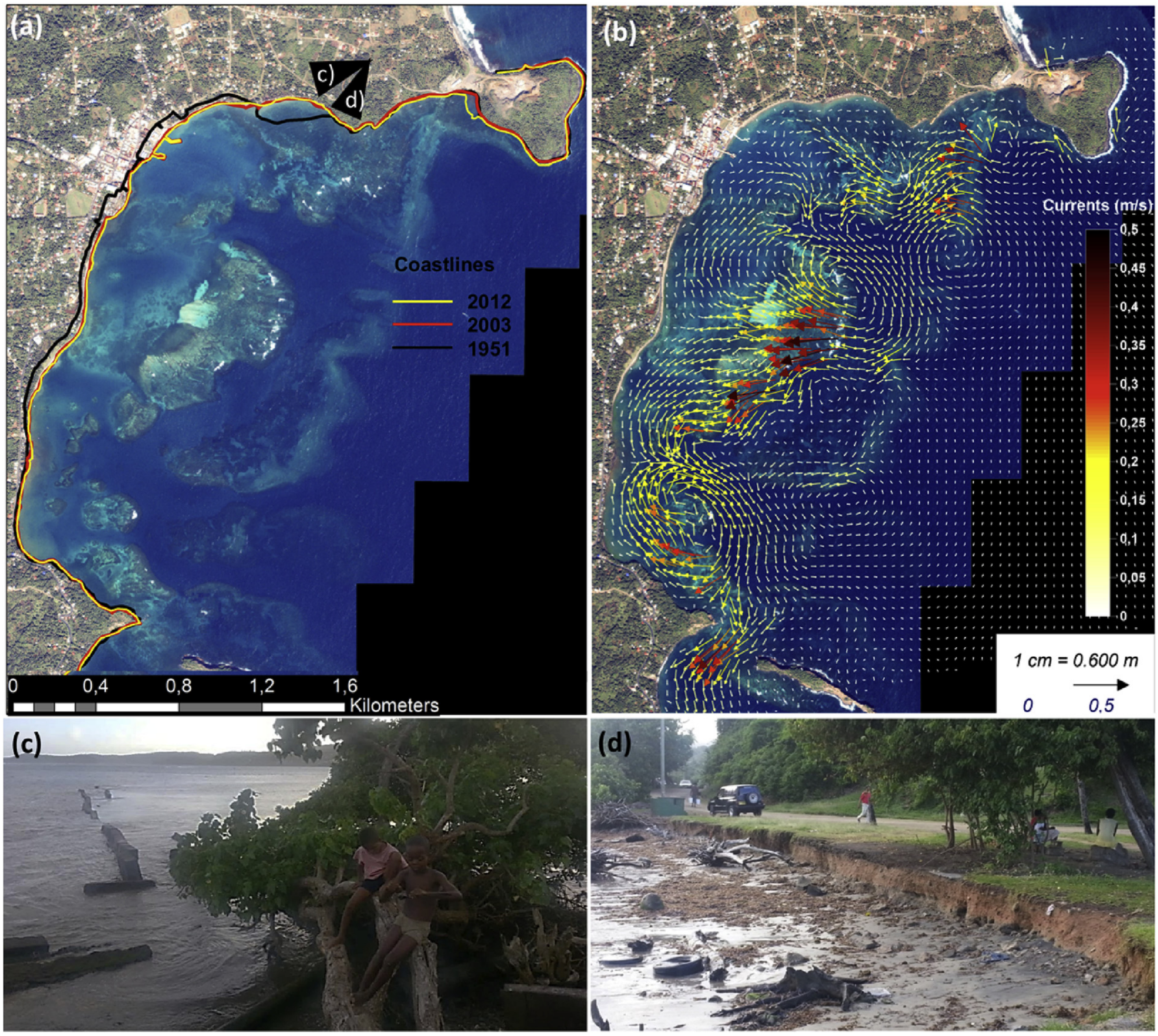

**Fig. 3.** Evolution of the coastline in Grenville Bay and circulation system. (a) Historical coastlines in Grenville: (black) coastline in year 1951 from aerial photos; (red), Ikonos 2003; and (yellow) Ikonos 2012; (b) Bay wave-induced currents associated with a north-eastern swell corresponding to Hs = 1.6 m, from the East, 7s, and occurring 2% of the time, velocity magnitude is indicated by the color and size of the arrows in the spatial map, only 1 out of 2 numerical grid points is represented in x and y directions; (c) and (d) January 2014 pictures of eroded coastal front in Telescope area, according to the orientations shown in panel (a). Panel (d) shows now submerged infrastructure that used to be inland and panel (c) the remnants and debris of local attempts to defend the shore. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

shore sediment transport and the long-term equilibrium of beach planform and profile. The changes in WEF (magnitude and direction) are used here as a proxy to investigate how the historical change in the reefs may have explained the observed erosion.

Since historical bathymetry information was not available, the WEF for two hypothetical plausible bathymetric settings are compared with the WEF for the current bathymetry to assess how the WEF would have been different in the past. The two bathymetry settings were informed by on-site diving inspections (2014 site survey) and testimonies from local stakeholders, and represented:

i. A flattened navigation channel: the navigation channel is nowadays about 4 m deep, and was created by human action in the 1980s. For comparison with the present bathymetry, the channel was reshaped and made shallower following the neighboring bathymetry contour lines.
ii. A shallower northern barrier reef crest: the outer reef, nowadays about 1–2 m deep and deeper at the southern end (bathymetric survey), is compared to a historical 1 m continuous reef crest. This reef section shows visual evidence of degradation, loss of coral cover and storm blasting and breaching. The present and historical situation of the reef that informs this scenario is further discussed in the results.

### 3.3. Design of a reef-based solution

This paper also presents the design of an artificial reef to help control erosion and reduce flooding currently impacting the coastal community in the area. The guiding principles for the design of the artificial reef in Grenville are:

i. Reduce the coastal erosion and storm coastal flooding in Grenville's waterfront and the Telescope area, by restoring the former wave shifting and attenuation characteristics of the reef, lost by degradation of the natural reefs.

ii. Provide a stable substrate for coral colonization and habitat restoration to facilitate the reestablishment of coral growth and ecological functions of natural reefs, in areas where benthic algae are not yet dominant and to prevent they overgrow live corals.
iii. Design a solution that is modular, adaptable to varying depths and seabed configurations, easy to ensemble on-site, stable, with enough porosity for habitat enhancement, replicable elsewhere, and suitable for local implementation in small island communities.
iv. Demonstrate the feasibility of a new eco-engineered reef design that can be installed utilizing local community labor, at lower cost and with higher ecosystem benefits than traditional grey infrastructure such as seawalls, rip rap, and conventional breakwaters.

For its adaptation goals, the design of the reef keeps an engineering emphasis. Its hydrodynamic performance is assessed comparing the WEF intensity and direction for two scenarios: with and without the 'reef'; similarly to the analysis of coastal changes. From a structural perspective, the reef is designed as a submerged breakwater able to withstand a high-energy environment and its cross-section resembles structurally a 'reef breakwater', i.e., a low-crested rubble-mound breakwater without the traditional multi-layer configuration (Ahrens, 1987). Structural stability analyses were performed to determine required weight of armor and the dimensions of the baskets. Since there are no stability formulas available for a modular design (in contrast with rubble-mound breakwater), the section was calculated using the Hudson formula as a 1-layer armor design (USACE, 1984) and with the highest water level and maximum significant wave height at the site, to be conservative. The rock size resulting from the stability analysis is assumed for the equivalent weight and size of individual baskets filled with material. The final design configuration is described in the Results section and more information accompanied in the supplementary material.

In September 2015, four pilot units were installed and monitored yearly to test the effectiveness of the design, implementation and construction methods, prior to a full reef array build. Data is being collected periodically on: stability and physical performance; corrosion; sandblasting; growth and mortality of coral transplants; coral recruitment; fish usage; beach profiles (water depth and distance from shore is registered for a total of 10 transects distributed equidistantly from the Telescope beach to Grenville's pier); wave transmission through the structure; and aerial survey. This information will be used to help refine the design and construction of the full reef array.

## 4. Results

### 4.1. Analysis of historical changes

#### 4.1.1. Shoreline evolution

The evolution of Grenville's coastline between 1951 and 2012 is shown in Fig. 3-a. Aerial and satellite imagery reveal large areas of shoreline retreat (of about 200 m) and mangrove loss in the north since the 1950s related to sediment removal from the area. Grenville's town waterfront has advanced, by about 100 m (Fig. 3-a), partially due to coastal armoring and construction at the water's edge. The southern section of the bay has remained largely unchanged.

An analysis of Landsat imagery shows that the approximately 200 m of shoreline retreat in the northern section shown in Fig. 3-a started only after the 1980s (Supplementary Fig. 7). Our monitoring data also shows that this pattern continues at present with erosion rates in the northern section of the bay, proceeding at approximately 0.65 m/year (measured during the year 2016). Surveys and meetings with Grenada's Ports Authority, the Fishery Commission and the Grenville community in 2014 and 2015 indicated that the eroded sediment from the northern side has been deposited along Grenville's town waterfront (Fig. 1-d) silting up the harbor. This sedimentation is hampering operations at the market jetty (Fishery Commission, Grenada Ministry of Agriculture), which has been requiring regular dredging (Grenada's Ports authority). Meanwhile, the circulation of waves and currents (Fig. 3-b) is producing erosion and storm flooding in the Telescope area on the north side of the bay, threatening housing and infrastructure (Fig. 3 – c, d).

#### 4.1.2. Hydrodynamic conditions

The largest waves come from the East to Northeast and reach up to 3 m of significant wave height and long periods (Supplementary Figs. 3 and 5). The most frequent incoming waves are easterly but present milder wave heights. However, sea levels and wave heights have been increasing since 1950s (Table 2 and Supplementary Fig. 8). Historical changes in mean sea level (panel a) have been moderate (Losada et al., 2013), but projections by the end of the century estimate about 0.5 m of sea-level rise for the southeastern Caribbean (Slangen et al., 2014). There have been sustained changes in both wave heights and wave directions (Table 2 and Supplementary Fig. 8- b, c). Mean wave heights increased moderately and the mean wave direction slightly shifted northwards (at about 0.7°/decade, see Table 2, during 1948–2008). Both signals show also statistically significant long-term trends while inter-annual changes (e.g. El-Niño) are small (Reguero et al., 2015b, 2013). These variations are negligible in terms of wave energy changes in the bay and, alone, are not sufficient to explain the magnitude and the concentrated location of the erosion.

#### 4.1.3. Coral reef condition and evolution

The health and condition of the reefs vary throughout the bay. The southern reefs are very shallow (approximately mean sea level), while the northern section shows less coral cover and overall reef degradation. Monitoring surveys in 2014 and 2015 showed that reefs north of the navigation channel has only around 2% live coral cover at present (most outer reef). The inner northern reef also shows low coral reef cover and overall reef degradation. Historical aerial and satellite imagery also indicate changes in the seabed configuration and coral cover (Supplementary Fig. 9). Furthermore, local stakeholders reported (as of January 2014) that the northern reef system was shallower in the past and could be walked at low tide, which indicates more abundance of corals and reef substrate.

Reef degradation is widespread, particularly across the Caribbean, due to many factors. The exact causes in Grenville Bay are uncertain but surveys and in person meetings pointed to a variety of factors. It is likely that sea water warming, disease and overfishing have all played roles. It is also possible that beach sand mining, whose impacts have been publicly acknowledged (Gravel, 2009), could have damaged the reefs through sedimentation. Furthermore, direct physical damage to coral has likely occurred too, both from coral mining and storm-wave action, similarly to other regions of the Caribbean (e.g. Bjorn et al., 1986; Lirman et al., 2001; Scoffin, 1993; Woodley et al., 1981). Meetings with the community confirmed corals from the north Grenville reef were also historically harvested and burnt for lime production by the local villagers. Although the exact causes of coral damage (and their relative impact) remain uncertain, plausible causes include a combination of: sedimentation, high nutrients from untreated wastewater, overharvesting of reef fish, coral mining and storm damage.

**Table 2**
Historical changes in wave climate and sea levels. (*) Statistics calculated on the monthly time series.

| | Period analyzed | Mean value | Long-term trend | Standard deviation of the annual time series | Original Data Source |
|---|---|---|---|---|---|
| Historical Sea Level Rise | 1950–2008 | – | 0.2 cm/yr | 3.5 cm (*) | Losada et al. (2013) |
| Mean Significant Wave Height | 1948–2008 | 1.1 m | 0.21 cm/yr | 0.09 cm | Reguero et al. (2013, 2012) |
| 95% percentile of Significant Wave Height | 1948–2008 | 1.9 m | 0.33 cm/yr | 0.18 cm | Reguero et al. (2013, 2012) |
| Direction of Mean Energy Flux | 1948–2008 | 75.9 Degrees North | 0.07 Degrees North/yr | 3 Degrees North | Reguero et al. (2013, 2012) |

### 4.1.4. Potential factors for erosion

Heavy sand mining has been occurring in the island for its use in construction up to December 31st 2008, when the ban on beach sand mining was stamped across the island after devastating ecological damages. Until 2009, the Telegraph quarry near Pearls, St. David, along the Telescope Beach, outside and north from the bay, was the only location in Grenada designated for beach sand mining (Grenada Action Forum, 2013). It remains uncertain if beach mining could have increased sedimentation on reefs in Grenville Bay, south from the extraction area, but downstream from the prevailing wave climate at the mining site.

However, sand mining is an unlike cause of the heavy erosion in the Telescope area because it is: (i) outside the designated area in the bay, (ii) close to inhabited areas and (iii) not consistent with the pace of the most recent erosion after the mining ban (as measured during year 2016). Similarly, coastal armoring cannot explain the coastal erosion because it only happened in the town waterfront (outside of the circulation system, see Fig. 3-b). However, changes in the bathymetry and seabed configuration could have potentially led to changes in the wave propagation patterns and had induced shoreline changes. Some of such bathymetric changes could have been driven by reef degradation. Research shows that when the coral cover is reduced to less than approximately 10%, reef growth is no longer sufficient to keep up with erosion and the reef gradually becomes deeper (Perry et al., 2013). This hypothesis is assessed in the next section.

## 4.2. Assessment of the role of coral reefs in shoreline positioning

The reef configuration in the bay drives characteristic hydrodynamic circulation with important effects on shoreline positioning, as seen in Fig. 3-b for the currents associated to one of the most frequent sea states. Waves experiment breaking, refraction and diffraction induced by the reef shallow water depths. Reefs create major breaking areas (surf-zones) in the northern, central and southern section (large arrows and hot colors in Fig. 3-b) in characteristic circulation gyres that move water onshore and back offshore through channels between the large reef systems. Characteristic refraction and diffraction of waves can be identified at the bay scale associated with these circulation gyres (Fig. 3-b and Supplementary Fig. 6).

The bay beach equilibrium planform model (e.g. Hsu et al., 2010) in Fig. 4 shows that over 50% of the sandy coastline in Grenville bay is controlled by the effect on hydrodynamics of the large coral reef systems in the bay. The largest effect is found at the center of the bay, points C and D that are the farthest from the shore. These two points receive 13.3% and 22.1% of the offshore WEF, respectively, and their effect, as seen in currents in Fig. 3-b, keep the shoreline stable. The southern coastline is controlled by a sequence of smaller reefs, with three control points: E, F, and G, which receive 26.1%, 19.5% and 62% of offshore wave energy respectively.

The northern coastline receives comparatively less wave energy (8.9 and 9.9% of offshore wave energy at points A and B respectively, see Fig. 4). At point A, reefs maintain the most northeastern shoreline stable. However, at point B the WEF direction is approximately parallel to the adjacent shore. This is the section that has experienced the largest erosion and was still eroding as in year 2016. Remarkably, the erosion in this section is consistent with the equilibrium planform at point B because the model does not reach this eroding stretch (see Fig. 3-a) indicating that is not yet in equilibrium. Indeed, the erosion of the Telescope area is occurring between two equilibrium shapes (A and B).

Other minor circulation patterns influence the north-west coast (west of point B in the Figure). In locations very close to the shore (approximately in the first 150 m from the shoreline, i.e. points not marked with letters in the Figure), despite some control points showing good alignment between WEF vectors, no conclusions should be drawn because the resolution of the numerical model (20 m) is insufficient and the bathymetry not detailed enough to resolve the local processes in the vicinity of the beach. However, at these locations the effect of reefs is local and of a smaller scale as compared to the large circulation patterns found further from shore.

Lastly, is worth noting the deep navigation channel is exposed to higher wave energy and to the action of large waves from storms. Points P1 and P2 receive more energy than the shallower areas where coral reefs induce breaking of waves and the characteristic circulation of currents described above. For example, at point P1, only a 40% percent of the offshore wave energy gets dissipated during the propagation.

Based on this characteristic link between the coral reefs and the shoreline long-term equilibrium, one way to assess the influence that reef degradation had in the historical erosion is by assessing how the bay circulation could have been different in the past. This can be analyzed by comparing the WEF in the present bathymetry (baseline scenario) with two different bathymetry settings (see Methods): (a) before the creation of the navigation channel (i.e. a shallower channel), and (b) the degradation of the northern reefs (i.e. shallower reef). Fig. 5 compares the WEF intensity and direction for the two scenarios. The creation of the navigation channel (currently over 4 m deep) had a large effect on the central system of reefs, where WEF would had been 4 times the baseline values (in black). These changes do not significantly modify the WEF in the most northern points. Comparatively, a shallower outer reef would have had two key effects: (i) attenuation of the larger waves in the north section (e.g. 40% reduction in point P3) and (ii) a clockwise rotation of the WEF. Smaller waves and more orthogonal to shore represents less sediment transport. This effect can also be seen in the wave propagation field in Fig. 6-a.

## 4.3. Design of a reef-based solution

### 4.3.1. Hydrodynamic design

How reefs naturally modify wave propagation and currents in the bay were used to design an artificial reef to protect the shoreline in the northern section of the bay. The reef-based design

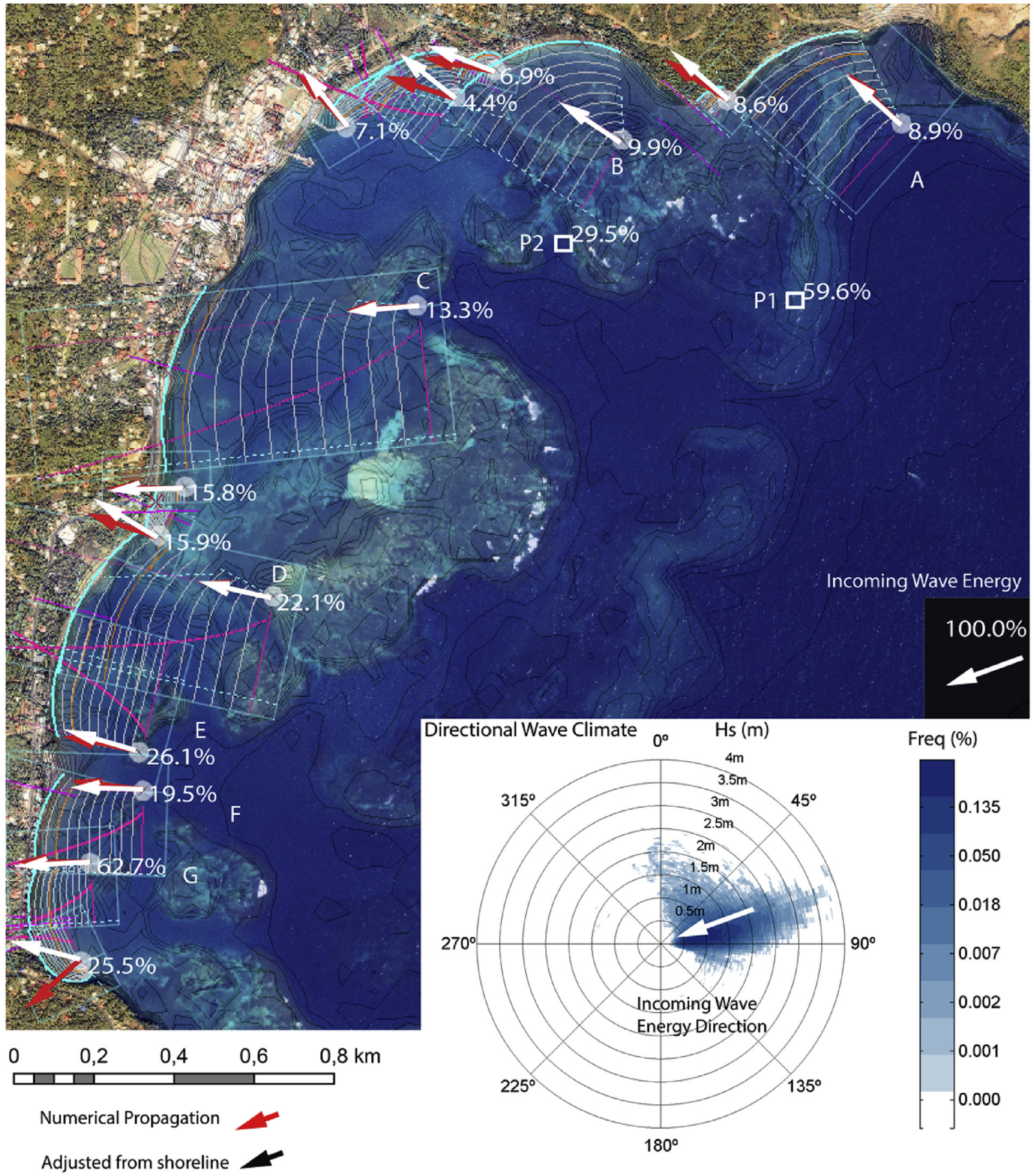

**Fig. 4.** Shoreline equilibrium planform model for the bay: control points are indicated by white circles and the dynamic equilibrium shoreline shapes are represented by the blue polygons. The arrows indicate the wave energy flux vectors for the historical coastline position (white arrows), and calculated from the wave propagations at the control points (red arrows). The percent values represent wave energy percentage with respect to the offshore total incoming mean annual wave energy (100%). The wave rose shows the directional distribution of significant wave heights. Points P1 and P2 (squares) represent points closer to the deeper navigation channel for comparison purposes. The resolution of the wave propagation model is 20 m. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

resembles a submerged breakwater but it differs from one in key features. First, the design is comprised of an array of individual reefs (between 20 and 30 m –long each) that total 350 m in length. Each reef unit is formed by interconnected and modular gabion steel baskets (1.2 m long, by 0.6 wide and 0.45 m high). This modular design allows the individual reef units be grouped with variable height, width and alignment helping to adapt to the seabed but also providing adequate hydrodynamic performance and facilitating inter-reef channels and ecological flow of water and nutrients. The final location and alignment resulted from a tradeoff between an adequate hydrodynamic performance and the suitability of the topography of the seabed.

Fig. 6 compares the significant wave height fields between the present situation (panel a) and the designed reef (panel b). At present waves reach the north of the bay tangentially to shore causing sediment transport (Fig. 6-a). The artificial reef could

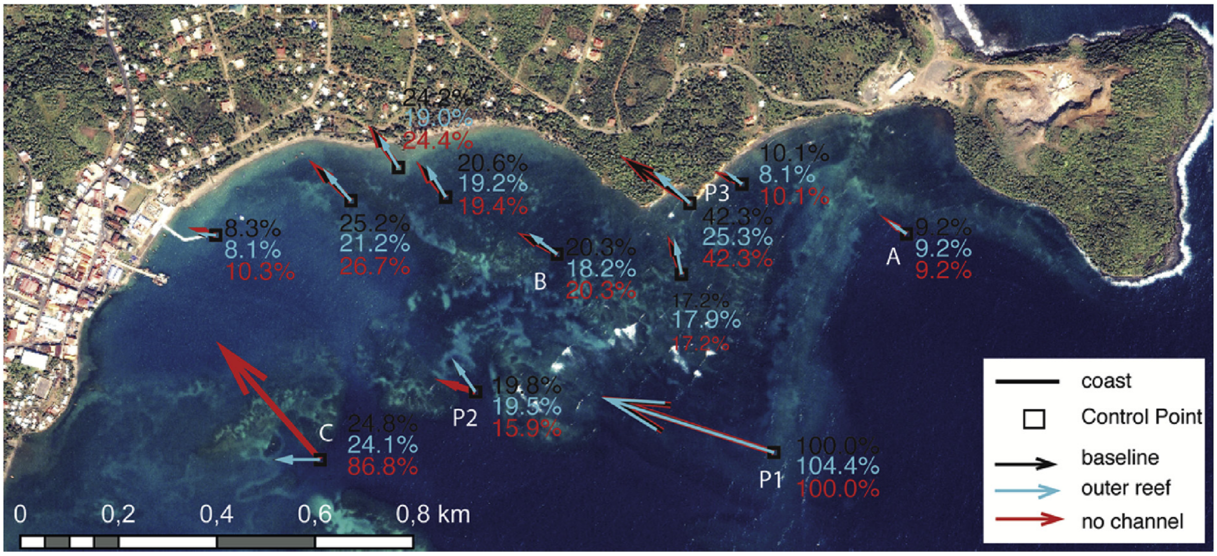

**Fig. 5.** Effect of historical bathymetry changes. Arrows indicate the mean wave energy flux for: black – baseline case, the historical wave climate with 2012 bathymetry blue - a shallower outer reef, approximately 1 m deep from point P1 to A (at present this section varies between 1 and 2 m); and red - a shallow navigation channel (red), representing the situation before the creation of the channel for navigation. Percent values indicate the wave energy flux with respect to the incoming mean annual wave energy at point P1 (baseline case). The points' locations and names correspond to those indicated in Fig. 4 for the equilibrium planform model. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

attenuate waves and, more importantly, shift the direction of the energy clockwise towards the north-east shore; both effects beneficial for erosion control. Fig. 6-c illustrates how with the reef the WEF will be attenuated and rotated clockwisely so the wave energy would approach the coastline more orthogonally than at present. This effect could help to control the sediment transport along the northern section. By attenuating the waves, the reef also reduces flooding. Wave attenuation ratios and run-up reduction results are available in the supplementary material.

### 4.3.2. *On-site implementation and construction*

Four pilot units were built in September 2015 to test the design, construction methods, and the stability and performance over time, prior to a full reef array build. The crest of each reef was kept about 0.25 m below mean sea level to ensure hydrodynamic performance. The pilot units were constructed as two pairs with a 1 m channel between each pair of pilot units. Fig. 7-a shows the locations of two of them as of March 2017 and the implementation and construction process in 2015 (panels b and c), including coral reef cover in 2016 (panels e and f), one year after the construction. The surface seabed was surveyed in support of the bathymetry data through field diving observations and geotechnical drillings of the substrate (details on the substrate can be seen in the Figures). Live coral falling within the footprint of the submerged breakwater was transplanted to an adjacent reef in advance of the construction to minimize the ecological impact. These coral fragments were later attached to the completed structures (Fig. 7-f, g).

Materials for the pilot units were assembled on land prior to the construction and included over 270 steel baskets fabricated by a team of local welders, cement cinder blocks, and large stones from the adjacent Telescope Quarry. The construction (4 units, 10% of length of the full reef array) was undertaken primarily by a team of 10 local fishers and overseen by a Grenadian commercial dive company, Underwater Solutions Ltd (1500 dive hours). The pilot units were formed from gabion baskets of a bent and welded steel rebar rod frame (15 mm) and filled with either local rock that has shown to host coral colonization or cement cinder blocks. The length of each pilot unit was approximately 8 m long by 5 m wide (a total of 30 m of reef), installed as pairs at two different sites, with half the length of each filled with stones (70 tons total) and the remaining half with concrete blocks (2400 units). The pilot units required 44,000 feet of 15 mm (5/8″) rebar steel. Individual basket units were welded together (41,000 welds). A small selection of baskets were cleaned to bare metal and coated with two coats of marine epoxy applied to the manufacturer's specifications, for comparison with uncoated gabion baskets.

### 4.3.3. *Monitoring*

Although the focus of this paper is not the analysis of the monitoring data in detail, some observations are worth noting because the monitoring has already provided crucial information that could guide construction of a full reef array (modeled in Fig. 6-b) and potentially reef restoration elsewhere. In the first 12 months after installation, there was good recruitment of Crustose Coralline Algae and coral to structures and fill. Recruitment rates of corals were up to 31 recruits per basket (Fig. 7-f, g). Survivorship of transplanted coral varied by species and orientation on the reef (seaward or lee side), suggesting that selection of suitable coral species will play an important role in the long-term success. Future monitoring will provide more insight in this regard. Fish usage is high, and continues to attract attention from the local fishers (particularly for octopus and lobster). The stability of the structure has not been compromised, but some modifications would be recommendable to prolong the expected life of the steel (e.g. marine epoxy coating). Future data will allow a better assessment of the structural and ecological performance in the long-term. The monitoring is confirming that each pilot unit constitutes a solid and wave resistant substrate on which to grow local coral species.

## 5. Discussion and conclusions

### 5.1. *The role of coral reefs in shoreline positioning*

The results outlined above show reef degradation is the probable cause of the observed shoreline erosion. Three lines of evidence indicate this link: (i) most of the shoreline in the bay is stable

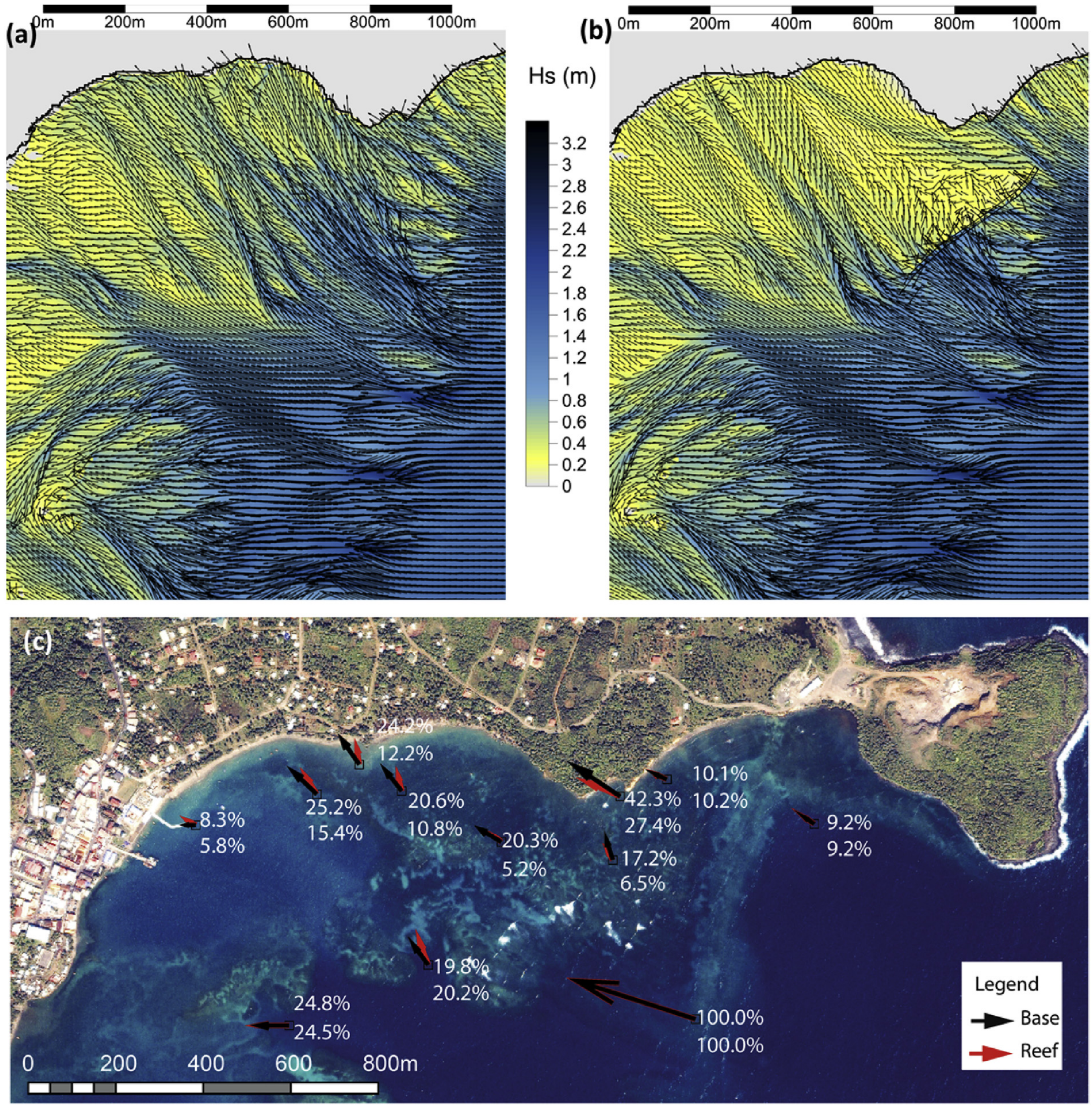

**Fig. 6.** Effect of the artificial reef on wave heights and wave energy. Wave propagation pattern and direction of significant wave heights (Hs) at present (panel a) and with the artificial reef (panel b), marked in black. The intensity of the colors indicates the significant wave height, the arrows indicate the mean direction. Sea state conditions: Hs = 1.6 m, East direction, 7s, and occurs a 2% of the time. Panel c: Mean wave energy flux at present (black) and with the reef project (red). The arrows indicate the magnitude and direction of the mean wave energy flux. The location of the points correspond to the control points of the shoreline equilibrium planform model in Fig. 4. The percent values represent the annual wave energy with respect values at point P1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(since the 1950s) but there is high erosion in northern part of the bay (Telescope Beach); (ii) historical imagery and anecdotal evidence indicates that there has been significant die-off and loss of height in the northern lobe of the reef while, in the south, reefs are shallow and healthy; and (iii) modeling of wave energy over 6 decades shows that the changes in the northern reef geometry are consistent with erosion along the northern coastline and of a greater magnitude than those derived from historical changes in the wave climate and sea levels. However, it is worth acknowledging that quantitative causality could only be inferred through historical bathymetry changes and sediment transport rates.

Analyzing the historical evolution of a reef-protected coastline for a number of decades is unusual but this study shows that studying the past is key to understand present coastal problems, and more importantly, provide effective solutions for adaptation. Furthermore, the application of the beach equilibrium planform model to reef environments is a novel approach to determine reef's role in coastal protection. Although the same concept has been traditionally applied in coastal engineering to study protected shorelines in equilibrium with incoming wave energy, its use for coral reefs is new. The approach has the potential to infer direct causality between coral reef health and condition with the shoreline positioning, which has important implications for coastal and ecosystem management in protected coastlines.

A link between reef degradation and shoreline position has significant implications for the future of reef shorelines and their management. Since the equilibrium planform model depends on the bathymetry and the prevailing wave climate, changes in any of

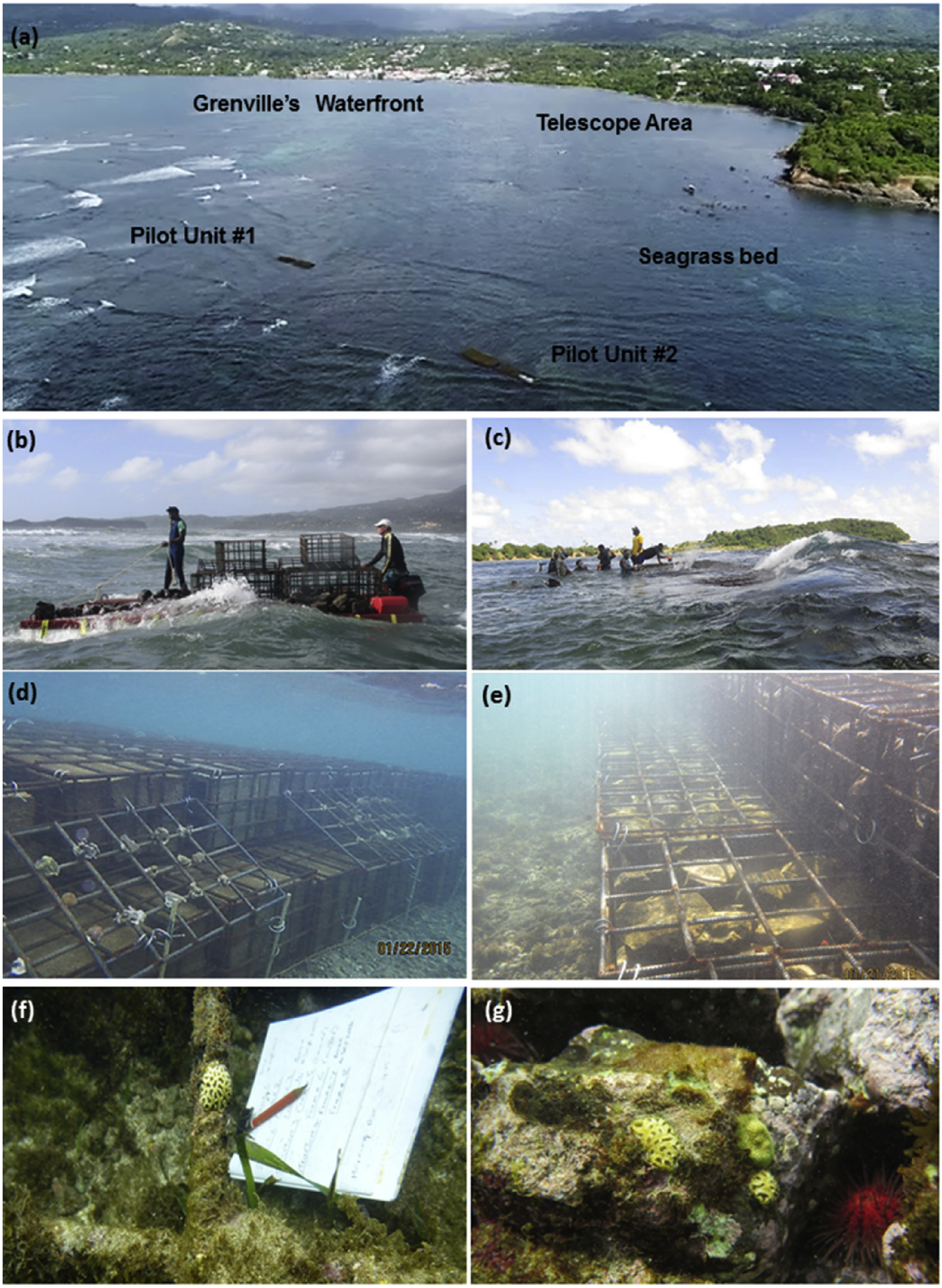

**Fig. 7.** Snapshots of pilot units. (a) General overview of pilot sites #1 and #2 with respect to the coastline. (b) Custom made barge loaded with baskets and rocks for constructing the breakwater; (c) building the reef breakwater, one stone at a time and packing the second layer of baskets at low tide with waves now breaking directly on the breakwater; (d) and (e) submerged view of the pilot units on top coral reef rubble right after installation with coral transplants evident in (d); (f) and (g) show details of coral recruitment on bars and fill materials 12 months after installation.

these two factors will modify the propagation and currents in the Bay and trigger changes in the shoreline to adapt to a new long-term equilibrium, which may have negative impacts on coastal communities. These changes can occur from natural climate variability, as seen in beach responses in the South Pacific associated to rotation of the wave energy direction by El-Niño Southern Oscillation (e.g. Ranasinghe et al., 2004), but also driven by reef degradation and restoration, or other human interventions. This is a very important lesson for management of these coasts, since it allows disclosing direct connections between environmental changes, human interventions and coastal responses.

### 5.2. *A reef-based adaptation solution in Grenville bay*

In Grenville, coastal impacts have been severe and led to a present dire situation. Villagers have built makeshift breakwater of tires and driftwood to try to slow erosion, which have been largely unsuccessful. The remnants of these 'defenses' can be seen in Fig. 3-c (as in 2015). Fishing families are now considering moving to higher ground (AP 2013).

This paper presents one of the few existing examples available to date of a reef restoration project designed and engineered to deliver risk reduction benefits (for a review, see Ferrario et al., 2014). The approach was guided by a holistic understanding of the past, present and after-project situations (Table 1). It required combining historical data, local knowledge, modeling, field testing and monitoring. Since reef colonization requires a stable substrate, the stability of the structure had to be assessed carefully using local settings, structural analysis and the surveying the geotechnical capacity of the seabed. This technically-focused approach was not only necessary for an effective design but also helped with local stakeholder engagement and ownership, both critical for the long-term project sustainability.

The community-based focus was another central piece of this project. This approach promoted a sense of local stewardship, and required keeping the financial benefits of the project within the community. This involved balancing construction considerations, developing a flexible design, and using locally sourced materials and labor. This aligns well with the challenges that construction in small island states present, where availability of materials and equipment is limited and local stewardship is critical.

As with other restoration projects, the aim of the Grenville artificial reef was to enhance the habitat and ecological functions of the natural reef. These considerations were also a central piece of the design. The materials used and the basket design creates a high porosity stable structure that can enhance coral growth. The hypothesis for the future is that the biological community (particularly the crustose coralline algae and corals) could also improve the stability of the structure by cementing the structural canvas. This, as well as other potential services provided by the structures, like fish usage and production, will be the subject of further investigation and observation as monitoring of the artificial reef continues. Techniques to accelerate biological recruitment on the artificial structures could also be beneficial and will be explored. In this regard, the use of coral reef nurseries for active restoration of the reef community and enhancing growth could be potentially useful, as has been shown in other sites (Cabaitan et al., 2008; Rinkevich, 2015, 2008; Shaish et al., 2008).

Benthic algae and corals compete for space on coral reefs. Algae abundance can actively overgrow live corals or passively take over space after corals have died. Extensive areas of the Bay are currently dominated by algae and stressors that damage live coral while fostering algae development, such as overfishing and eutrophication, likely played a role in the past in reducing the areas covered by corals. All of these stressors will also impact the trajectory for restoration of biological benefits from the reef. However, at the same time the development of restoration projects can first increase coral habitat and second enable efforts to address other reef stressors including multiple strategies for reducing algal growth on reefs.

### 5.3. *Implications of the study for reef restoration*

Despite the fact that coral reefs currently offer coastal protection to coastal communities, reefs are not managed as infrastructure and their damage and degradation continues (Bridge et al., 2013). Recognizing refs as natural infrastructure (Elliff and Silva, 2017; Van Zanten et al., 2014) could represent an incentive for their protection against stressors such as overfishing and impaired water quality (Bellwood et al., 2004). An emphasis in coastal protection could also create further funding and technical opportunities to restore coral reefs (Chavanich et al., 2015; Elliff and Silva, 2017; Silva et al., 2016; Støttrup et al., 2017), for example climate adaptation funds.

Modeling shows that the designed offshore reef extends a 'sheltering' effect from waves well beyond its structural footprint, similarly to natural reefs. This could have important management-relevant implications when comparing and planning offshore versus onshore restoration options: protection along the shoreline (e.g. revetments) has local effects and can have consequences upstream and/or downstream; meanwhile, offshore interventions (e.g. coral reef restoration) could offer more widespread protection, although their design can result more challenging. In Grenville, the implementation of the project should be extended to the full array (as modeled) to directly test and measure large-scale restoration coastal protection benefits.

In conclusion, these findings and the overall approach could help coastal communities to (i) better assess the coastal protection offered by coral reefs and their role on shoreline stability, (ii) identify how degradation can result in severe coastal impacts, and (iii) advance ecosystem-based engineering as an effective option for coastal protection and climate adaptation. While there is no one-size-fits-all solution, the findings in this article are particularly important for tropical nations and Small Island States, which are on the front lines of climate change and have the most to gain from protecting and managing coral reefs as coastal infrastructure.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.01.024.

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