environments

MDPI

Article

Assessment of the Role of Nearshore Marine Ecosystems to Mitigate Beach Erosion: The Case of Negril (Jamaica)

Pascal Peduzzi [1,2,3,*], Adonis Velegrakis [4], Bruno Chatenoux [2], Marisol Estrella [5] and Theofanis Karambas [6]

1 United Nations Environment Programme, UNEP/GRID-Geneva, 1219 Geneva, Switzerland
2 Institute for Environmental Sciences, University of Geneva, 1211 Geneva, Switzerland; bruno.chatenoux@unepgrid.ch
3 Department F.A. Forel for Environmental and Aquatic Sciences, Faculty of Sciences, University of Geneva, 1211 Geneva, Switzerland
4 Department of Marine Sciences, University of the Aegean, 81100 Mytilene, Greece; afv@aegean.gr
5 United Nations Environment Programme, Post-Conflict and Disaster Management Branch, 1219 Geneva, Switzerland; marisol.estrella@un.org
6 School of Civil Engineering, Aristotelian University of Thessaloniki, 54124 Thessaloniki, Greece; karambas@civil.auth.gr
* Correspondence: pascal.peduzzi@unige.ch

Abstract: Coastal and marine ecosystems are supplying a wide range of services. With accelerated Sea Level Rise, intensification of waves and storm surge severity and increasing anthropogenic pressures, these areas are under multiple threats and society may not receive the same level of ecosystems services. This study aims at measuring the trend of beach erosion and at identifying and quantifying the role of some coastal and marine ecosystems in mitigating beach erosion in the region of Negril (Jamaica). In this location, the tourism industry provides the main source of economic revenue. Even at the national level, the two beaches are important assets linked with 5% of the national revenue as 25% of the hotel rooms are located around Negril. In Jamaica, the tourism industry is a significant component of national GDP. 25% of hotel rooms are located around the two beaches of Negril, which have lost an average of 23.4 m of width since 1968. Given the importance of Negril's beaches to their economy, the Government of Jamaica asked UNEP to conduct a study to identify causes of beach erosion in Negril and potential solutions to address trends of beach erosion, in the context of future sea level rise scenarios induced by climate change. This paper addresses the current beach erosion status and future trends under different climate scenarios. We explain how, by using remote sensing, GIS, wave modelling and multiple regressions analysis associated with national, local and community consultations, we were able to identify and quantify the role of ecosystems for mitigating beach erosion. We show that larger widths of coral and seagrass meadows reduce beach erosion.

Keywords: ecosystems services; beach erosion; climate change adaptation; disaster risk reduction; environment; GIS; remote sensing; models

Citation: Peduzzi, P.; Velegrakis, A.; Chatenoux, B.; Estrella, M.; Karambas, T. Assessment of the Role of Nearshore Marine Ecosystems to Mitigate Beach Erosion: The Case of Negril (Jamaica). *Environments* **2022**, *9*, 62. https://doi.org/10.3390/environments9050062

Academic Editor: Sílvia C. Gonçalves

Received: 14 April 2022
Accepted: 3 May 2022
Published: 16 May 2022

1. Introduction

In recent years there has been a better understanding of the role of nearshore ecosystems (e.g., coral reefs, seagrass meadows and mangroves) in the resilience of the coastal zone [1,2]. They are now recognised as crucial constituents of the adaptation response to various coastal natural hazards such as tsunamis [3], extreme hydrodynamic events and climatic changes due to their role in the dissipation of incoming wave energy [4–6].

Nearshore ecosystems such as coral reefs and seagrasses are threatened ecosystems. Coral reefs have already been in retreat [7,8] due to a variety of impacts from Climate Variability and Change (CV & C) including those from (a) the increasing mean sea levels [9,10], (b) increasing variability and mean rise in sea water temperatures [11,12], and (c) extreme events such as tropical cyclones and high energy storms [13,14]. Nearshore seagrass meadows also appear to be in decline in many coastal areas due to unfavourable physicochemical changes [15] increasing nearshore sediment transport and deposition [16] and impacts from human from development [17–19].

Wave dissipation by nearshore ecosystems is particularly important for the low-lying sedimentary coasts i.e., the beaches which constitute dynamic functional links between terrestrial and marine ecosystems. Beaches are critical components of the coastal system. They constitute a substantial fraction of the global coastline [20], are by themselves important habitats [21], provide protection against the marine flooding of the coastal ecosystems and assets they front [22,23], and have a high hedonic value and economic potential. Tourism, a most important economic activity, has been increasingly associated with vacationing wholly, or partially, at coastal locations and beach recreational activities according to the 'Sun, Sea and Sand-3S' tourism model [24]. For many of the world's islands as, for example, in the Caribbean region, 3S tourism accounts for more than 23% of the GDP of most Island States [25]. Beach aesthetics, carrying capacity and related infrastructure are crucial for the tourism sector and the economy [26,27].

At the same time, global beaches are under increasing erosion [28,29], which can be differentiated into: (a) irreversible retreat of the shoreline, due to mean sea level rise (MSLR) and/or negative coastal sedimentary budgets that force either beach landward migration or drowning [30]; and (b) short-term erosion, caused by storm waves/surges, which may, or may not, result in permanent shoreline retreats but can be, nevertheless, devastating [31–33].

Erosion is particularly alarming for island beaches due to: (i) their (generally) limited dimensions and diminishing sediment supply [34]; (ii) the deterioration of the nearshore ecosystems that provide protection from marine erosion [35,36]; and (iii) their crucial role in the island economies and the increasing backshore development that has increased asset exposure [37]. The projected relative mean sea level rise, combined with potential increases in the intensity/frequency of energetic events will exacerbate beach erosion [38] with severe impacts on coastal ecosystems, infrastructure/assets and the beach hedonic value and carrying capacity for recreation/tourism [34,39,40]. Potential increases in extreme events in e.g., the North Atlantic [41] will exacerbate beach erosion With increasing coastal populations, infrastructure and activities, higher losses are projected from e.g., extreme hydrodynamic events (storm waves and surges), especially in developing countries where vulnerability is already high [42].

This contribution presents the results of a study on the role of nearshore marine ecosystems (coral reefs and segrasses) for the physical resilience of two adjacent Caribbean pocket beaches (Long and Bloody Bays, Negril, Jamaica) which are both protected areas (Negril Marine Park) and important tourism destinations; these beaches host about 25% of the hotel rooms in the country and contribute to about 5% in the national Gross Domestic Product-GDP [43–45]. Beach erosion was assessed through the collation and analysis of historical information on beach shoreline positions (1968–2008), whereas the influence of the nearshore ecosystems on the beach resilience was examined through the comparison of beach erosion trends along the beaches with the distribution of the fronting shallow coral reefs and seagrass meadows as well as by wave modelling. The study formed part of a wider study by the United Nations Environment Programme [43]), which was aiming to develop an integrated risk and vulnerability assessment methodology (RiVAMP) in order to build resilience against the adverse impacts of natural hazards.

2. Study Area

The Caribbean region and, Jamaica in particular, is a 'hot spot' of nearshore ecosystem degradation [46]. Negril is located at the western Jamaican coast and comprises two pocket, sand barrier beaches: the 7 km long Long Bay in the south and the 2 km long Bloody Bay at the north. The barrier beaches are bordered by Eocene/Miocene limestone promontories (Figure 1), have low beach ridges (rarely >2 m in height) but no developed backshore dunes and are characterised by increasing coastal development [43,44]. They front Great Morass, a large, low-lying back-barrier system (elevations of 0–3 m), bounded to the east by the Fish River (Springfield) Hills and underlain for its most part by peats of varying thickness [47,48]. Previous studies have suggested that both beaches have been under spatio-temporally variable erosion since the 1960's (average rates estimated between 0.25 and 1 m/yr, see [49,50] and that this erosion is a relatively recent phenomenon coinciding in time with increasing SLR trends, alterations to the Great Morass drainage and the development of a high density tourist industry [48]. There have been plans to construct a series of offshore breakwaters at the southern section of Long Bay [51,52], which however there were shelved in July 2016 due to strong resistance by the local community [53].

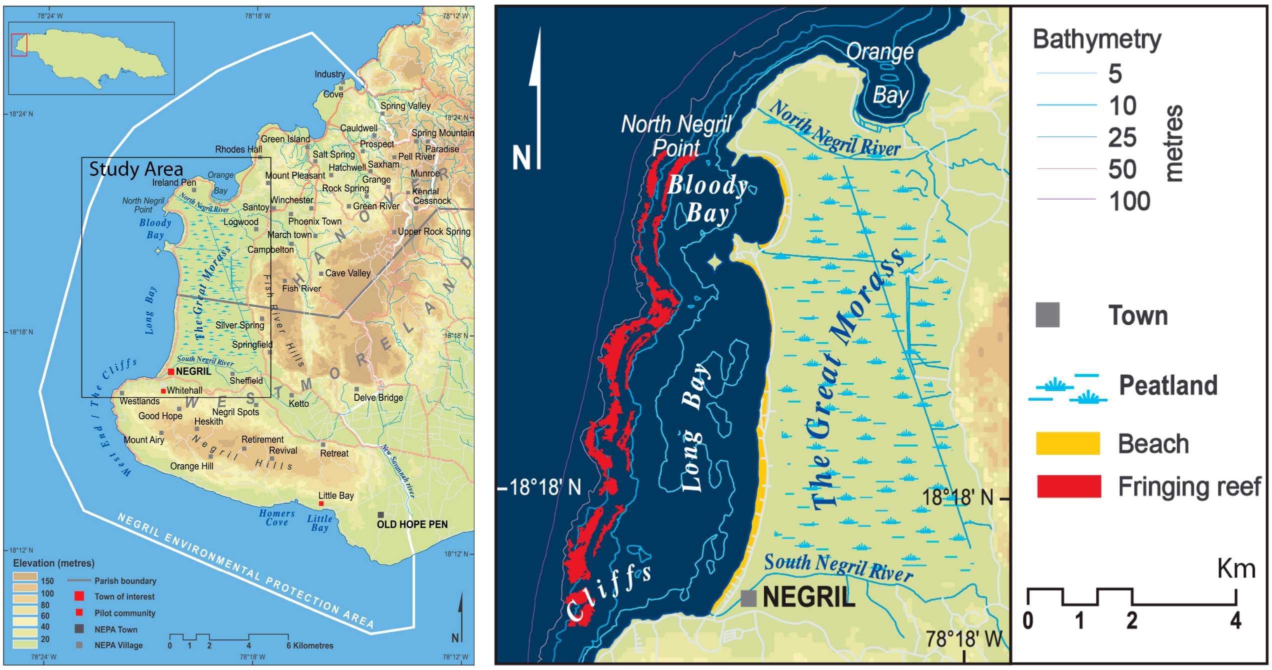

Figure 1. Location map of the study area.

Negril beaches are fronted by a narrow shelf (submerged coastal platform), with water depths reaching 500 and 100 m at distances less than about 6 and 3.5 km, respectively; drowned cliffs and a fringing coral reef are found 2–3 km from the coastline at water depths of about 20–40 m (Figure 1). Isolated shallow coral reef patches are found inshore, together with patchy seagrass meadows dominated by *Thalassia testidium* and interspersed with patches of *Syringodium filiforme and Halimeda opuntia* [54]. Beach sediments consist almost entirely of moderately/poorly sorted, biogenic sands, with onshore ('dry' beach) sediments being generally coarser (median grain sizes-D50s of 0.26–1.06 mm) than the shallow nearshore material (D50s of 0.25–0.81 mm) [43]. Sands are dominated by amorphous/recrystallized grains (about 65% of the total), with the remaining consisting almost entirely of recent bioclasts, mostly *Halimeda*, red algae, echinoderm, foram, bivalve and gastropod fragments; coral reef derived material is scarce. Bioclast composition suggests that the seagrass meadows are the main sources of the recent beach sediments [50].

The area is characterized by a relatively moderate hydrodynamic regime [49]. Tidal ranges are small along the Negril coast (up to 0.3 m above MSL on springs) and tidal currents have a NE-SW orientation and magnitudes of up to 0.2 m/s. Wind and swell waves impinging onto the beaches come mainly from the NW and W. Wave and sediment transport observations and modelling indicate that swell waves mostly induce beach erosion through offshore sediment transport, whereas wind waves may promote beach recovery [51]. Negril lies in the North Atlantic hurricane belt. Analysis of historical information has shown that it has been an increase in the frequency of hurricanes since 1995 (particularly of the Category 4 and 5 hurricanes) as well as in the mean rainfall and peak wind intensities UNCTAD 2018). Negril beaches are affected by the energetic waves and storm surges associated with tropical storms [55]; it has been estimated that the 10-year event can generate offshore wave heights (Hs) of 6.4 m and periods of 10.7 s and storm surges of 0.2–0.3 m, whereas the 50-year event may induce storm waves with offshore heights and periods of 9.2 m and about 13 s, respectively, and storm surges of up to 1.5 m [49].

Jamaica's coral reefs are mostly degraded, although some areas have been identified as relatively healthy [7]. Generally, there is a dearth in integrated information concerning changes in the distribution of nearshore ecosystems at the island scale [43].

3. Data and Methods

Interactions between the Negril nearshore ecosystems and beach morphodynamics were studied using two approaches. First, multiple regression analysis was used to assess the effects of the coral reefs and seagrass meadows on the observed patterns of beach erosion. Secondly, hydrodynamic modelling was employed to study the impacts of the nearshore ecosystems on beach dynamics. All available relevant environmental information on the Negril has been collated (Table 1) and a high resolution Quickbird satellite image was analysed to fill information gaps, particularly with regard to the spatial distribution of nearshore coral reefs and seagrasses.

Table 1. Geospatial data used.

Data	Notes
Quickbird satellite image	0.6 m resolution, four bands (blue, green, red and near infra-red), Acquisition date: 16 January 2008
Digital Elevation Model	6 m resolution
Offshore bathymetry	2 m resolution, original data from SWI (2007)
Shorelines 1968, 1980, 1991, 2003 and 2006	Collation of previous information based on aerial photos or field measurements (SWI, 2007; UNEP, 2010)
74 beach profiles (November 2006)	Profiles of the 'dry' and 'wet' beach (to water depths of 1–1.5 m) perpendicular to the shoreline (SWI, 2007)

3.1. Seagrass and Coral Distribution and Beach Erosion Trends

The distribution of the shallow water ecosystems in Negril (i.e., the distribution of seagrasses and coral reefs) was studied through the analysis of a high-resolution satellite image (multispectral—0.6 m resolution, Quickbird sensor) using *eCognition Definiens* to broadly classify ecosystems. Pixels were grouped using segmentation procedures, i.e., image sub-division into separate regions. We used an object-oriented approach, based on segmentation process, i.e., grouping pixels in objects using multiple criteria such as their spectral radiance (computed from reflectance), morphology, texture [56].

Using GIS techniques, environmental features and seabed depths were extracted along the marine extensions of 74 beach profiles of Bloody and Long Bays (see Figure 2) collected during a previous study [49]. The image classification of sandy beach was used to extract the 2008 Negril shoreline. It was then compared against ancillary records of shorelines from 1968, 1980, 1991, 2003 and 2006 to assess rate of beach erosion for each profile.

Although the available remote-sensed information can provide valuable information on the historical changes of the Negril beaches, there are also some limitations. First, shoreline extraction from remote-sensed information may give rise to errors without calibration by synchronous ground-truthing, even in the case of high-resolution images [57,58]. Secondly, and most importantly, remote-sensed information represents instantaneous shoreline positions (snapshots) as is commonly collected in different seasons, and without control for tidal effects or for seasonal and random beach erosion/accretion patterns [59], thus it may not represent long-term average conditions for the period of data collection.

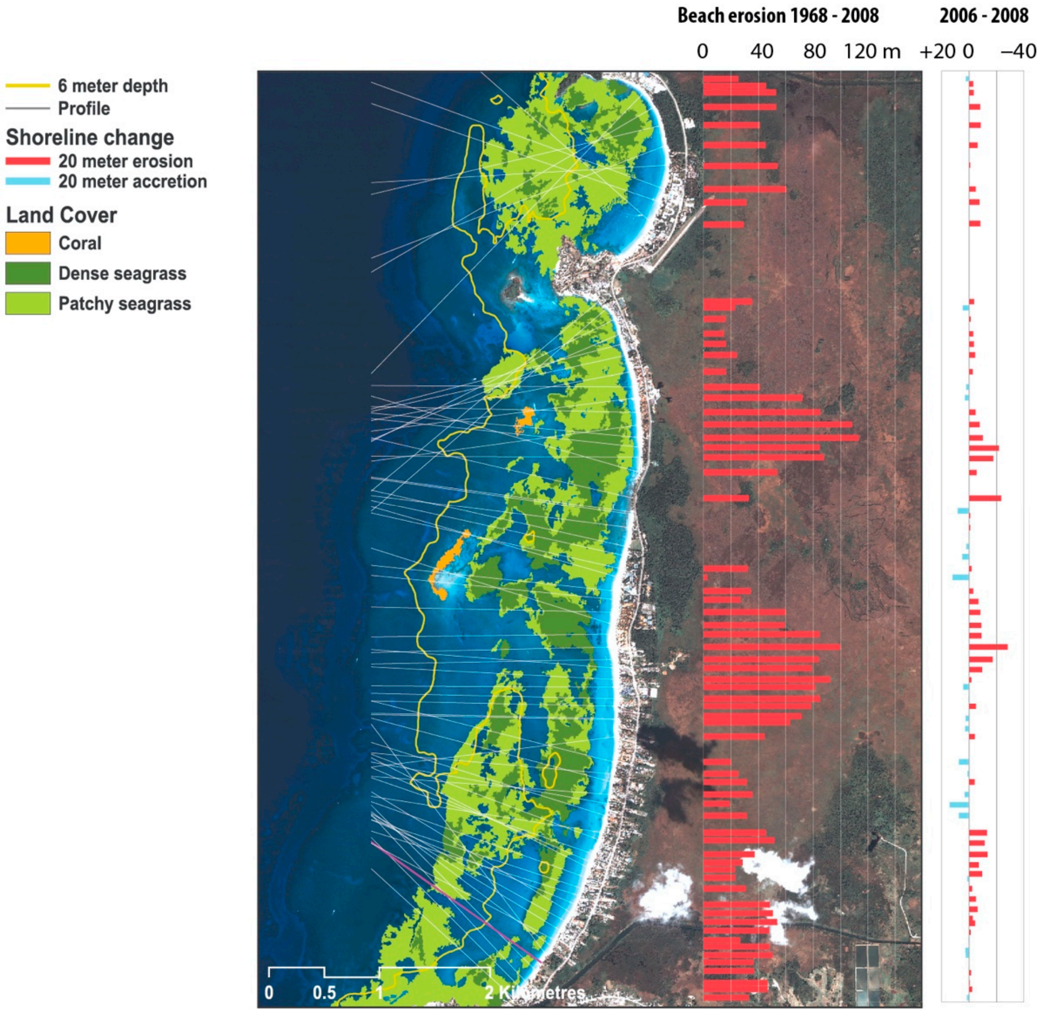

Figure 2. Over Quitckbird image (60 cm resolution taken 16 January 2008), distribution of nearshore ecosystems, location of the beach and seabed profiles considered, and rates of beach erosion. Location of the profile modelled and perpendicular lines are shown (in white). Long-term trends (in red) for 1968–2006 and short-term (2006–2008) in blue for accretion and red for erosion.

In order to estimate beach erosion rates, shoreline positions were adjusted for tidal effects. Digitised information concerning the historical shorelines was adjusted using the horizontal shoreline displacements due to tidal excursion for the 2006 and 2008 information (when image acquiring times were available), estimated on the basis of the local tidal curves and the 2006 beach profiles. For the remainder of the data (1968, 1980, 1991 and 2003), digitised shorelines were displaced landward, using the horizontal landward excursion induced by a 0.3 m tidal level rise; this ensures that, at least, tidal effects do not influence positively estimations of beach erosion.

3.2. Multiple Regression Analysis

The influence of different beach attributes (e.g., beach slope, the presence of offshore patches of coral reefs and seagrass meadows) on beach erosion rates was studied through multiple regression analysis, an efficient tool for identifying and modelling the role of ecosystems in conjunction with other contextual parameters [3,60]. In this case, the analysis was performed using beach (cross-shore) erosion (in m) as the dependant variable, whereas the set of independent variables included: nearshore bathymetry (e.g., the distance to a given depth or the water depth at a given distance); cross-shore distributions of the shallow water ecosystems (e.g., the width of a seagrass or coral patches along a cross-shore profile); the Iribarren number (which represents the relationship between the beach slope and the wave characteristics and provides an indication of beach vulnerability to the wave energy [61]; and various other spatial parameters (Table 2). These values were extracted along a 3 km extension of the beach profiles using GIS techniques.

Table 2. Variables extracted for each of the 74 profiles.

Data Analysed	Derived Variables	Type of Variables
Beach erosion 1968–2008	Length [m]	Beach retreat or accretion (1968–2008 and 2006–2008)
Field topographic profiles (2006)	Beach profile	Iribarren number ($\xi = \beta/(H_o/L_o)^{1/2}$, where β the beach slope and H_o and L_o the offshore wave heights and lengths, respectively)
Bathymetry	Wave run-up	Wave run-up
Morphology	Distance [m]	Distance from the shoreline computed for several depths (4, 5, 6, 7, 8, 9, 10, 12, 15, 20 m)
Morphology	Depth [m]	Depths computed for fixed distances from the shoreline (500, 1000, 1500, 2000, 2500 and 3000 m)
Seagrass meadows	Width [m]	Cross-shore widths of dense, patchy and total seagrass meadows (patchy + dense)
Seagrass meadows	Distance [m]	Minimum distance from shoreline to dense, patchy and total seagrass
Coral reef	Width [m]	Cross-shore widths of shallow and deep coral reefs
Coral reef	Distance [m]	Minimum distance from shoreline to shallow and deep reefs

A correlation matrix was used to identify groups of non-correlated independent variables, each one corresponding to a specific hypothesis. These were tested by running multiple regression analysis in specialized software (*Statistica 9*). The selection of the most relevant hypothesis was based on relevance (p-value < 0.05) and maximisation of percentage of variance explained (R^2) as well as visual interpretation of predicted values against observed values. This process allows for identification of combinations of parameters that best explain beach erosion and thus confirms or rejects the hypothesis on the potential role of the different environmental and geomorphological features.

3.3. Wave Modelling

In order to investigate further the effects of nearshore ecosystems on the Negril beaches, two different modelling approaches were used. First, the hydrodynamic regime was assessed through a 2-D wave model (model ALS, for full details, see [62] that can simulate coastal hydrodynamics along coasts up to 20–30 km long and to water depths of about 40–50 m with relatively low computational costs. The model is based on wave energy balance considerations in shallow waters [63]. Diffraction effects are incorporated, and the solution is based on an implicit backward finite difference scheme [64]. In nearshore waters a module, based on hyperbolic type, mild-slope equations, is incorporated to deal with compound wave fields under shoaling, refraction, diffraction, reflection (total and partial) and breaking, and the 2-D continuity and momentum equations are used (depth- and short wave-averaged) to simulate wave-induced currents. Experiments were run using observed in the area offshore wind and swell wave conditions.

Cross-shore distribution of the wave and bed shear stress fields has been simulated using an advanced 1-D cross-shore model involving high-order *Boussinesq* equations-*Boussinesq* model (for details see [34,59,65,66]. In order to investigate the role of seagrasses, a canopy flow module is incorporated that assesses wave dissipation due to flow above and within the seagrasses (details in [67]. The model was run in stationary mode for particular profiles containing coral reefs and seagrasses (for locations see Figure 2) to simulate wave dissipation (a) under the observed conditions, (b) in the case of the absence of these ecosystems and (c) under moderate increases of the sea level.

4. Results and Discussion

4.1. Distribution of Nearshore Ecosystems and Beach Erosion

Analysis of the 2008 satellite imagery (16.3 km^2) showed limited coverage (11.9%) by dense seagrasses; patchy seagrass coverage was higher (24.8%). Shallow coral reefs were found to be scarce (0.4% of the area), mostly concentrated offshore of the central section of Long Bay (Figure 2). However, it should be noted that the seabed relief in some areas shows evidence of relict coral reefs, i.e., bathymetric manifestations of now redundant (and eroding) coral reefs [68]. Seagrass meadows were generally observed at depths shallower than about 10 m but their long-term distribution trends could not be assessed from the historical information, due to lack of baseline data and the low resolution of the historical imagery.

With regard to long-term morphodynamics (Figure 2), historical shorelines digitized from aerial and satellite imagery and field surveys (Table 1) were compared. The results, anchored on 74 beach profiles (Table 1 and Figure 2) show that Negril beaches have been under severe erosion in recent decades, with erosion being spatio-temporally variable. Bloody Bay shows lower erosion rates than Long Bay [49], where high spatial variability is observed; the highest rates of erosion are recorded at the beach to the north and south of the 'shadow' of the shallow coral reef and at the southern margin of the beach where seagrass coverage is lesser (Figure 2). Average 'dry' beach erosion between 1968 and 2008 was estimated as about 23.4 m i.e., 0.59 m/yr, with some locations experiencing shoreline retreats of more than 55 m i.e., 1.37 m/yr. (see also [69]). Comparison between the most recent information analysed suggests similar patterns in erosion trends for the period 2006–2008. Such erosion rates are *in par* with those of other Caribbean beaches [70] and very worrying if the small remaining widths of the Nergil beaches are considered (Figure 2). To assess the contribution of MSLR, a MSLR rate of 3.4 mm/yr [71] was used in the absence of more accurate local information; this amounts to a MSLR of about 0.14 m for the period of consideration (1968–2008). Using an ensemble of cross-shore morphodynamic models [34], consisting of the models from Bruun, Edelman and Dean [72–74] models, and 74 beach profiles (Table 1 and Figure 2), maximum shoreline retreat due to MSLR was estimated as about 6 m. Thus, MSLR cannot explain by itself the observed high beach losses.

Coastal development over the recent decades must have contributed to the observed beach loss. Sand barrier beaches tend to "roll over" or self-adjust (by e.g., migrating inland) under rising mean sea levels and storm surges [75]. The extensive coastal development which took place in Negril during the recent decades [44] may have inhibited such adjustment, 'locking' the beaches at certain positions and resulting in vertical downcutting/scouring, offshore sediment losses and, ultimately, beach drowning [50,76].

Storm intensification and sequencing could certainly control beach erosion [77] provided that there is no adequate supply of new material to replace mounting offshore losses [78,79]. This may have been the case in Negril, where biogenic sand production in the seagrass meadows and coral reefs has been found to be diminished [50]; nevertheless, more detailed research is required to accurately assess overall sediment volumes and budgets. Finally, beach erosion may have been facilitated by the diminishing wave dissipation afforded by the declining Negril nearshore ecosystems.

4.2. Multiple Regression Analysis

To assess the role of coral reefs and seagrasses in wave dissipation, it was necessary to distinguish two models: a model referring to the protection afforded by the shallow coral reefs to the beach sections they front (9 cases) and a model referring to all other sections; this was due to the small number of profiles associated with coral reef shadows. The dependent variable to be explained was total erosion (ErTot, in m) between 1968 and 2008.

The model for sites behind coral reefs (Table 3 and Figure 3a) is robust, the *p*-values are highly significant (much smaller than 0.05) and the variation explained is very high (adjusted R^2 = 0.77). It is based on only two variables: the width of shallow coral reef (SwRfW) and the water depth at 1000 m (Dpt1000), a proxy for the seabed slope. Results show that wider coral reefs and steep slopes have a protective effect on beaches (i.e., reducing erosion or increasing accretion). The correlation matrix shows no autocorrelation between the two independent variables (r = −0.35, R = 0.91, R^2 = 0.83 and Adjusted R^2 = 0.77).

Table 3. Results from statistical regression, cases behind coral protection, with SwRfW as the width of shallow coral reef in meter, and Dpt1000 as the water depth (in meter) at 1000 m from the shoreline.

Variables	Beta	% Expl.	B	*p*-Level
Intercept			77.85	0.00051
SwRfW	−0.91	66.9	−0.47	0.00238
Dpt1000	−0.64	33.1	−7.95	0.01248

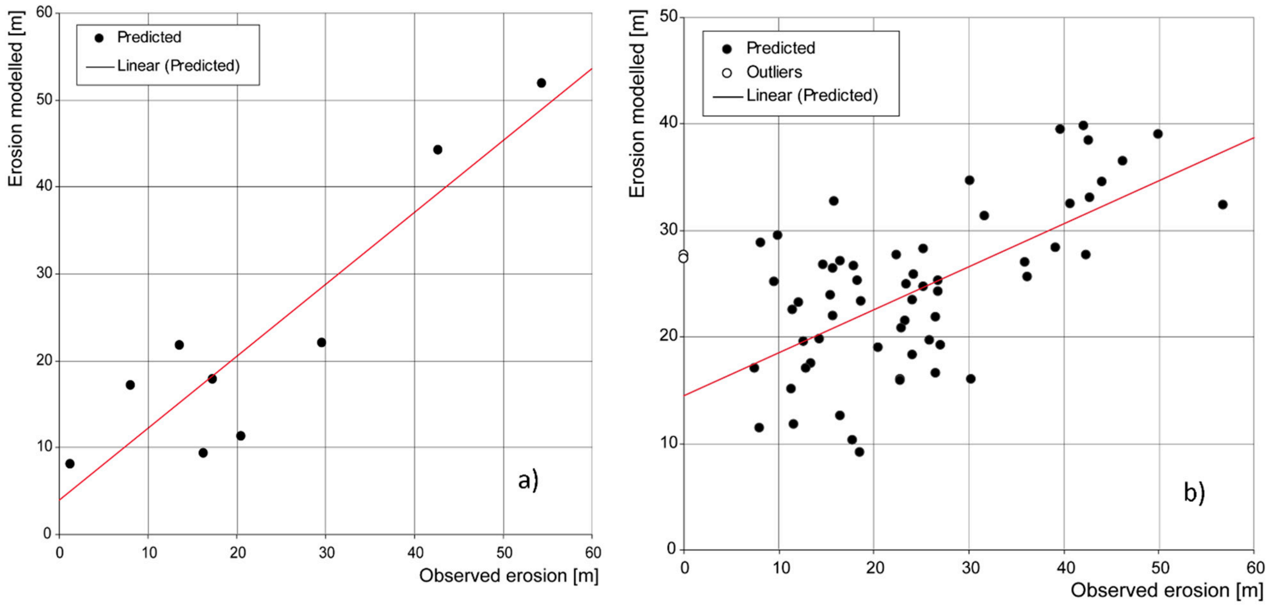

Figure 3. Modelled versus observed erosion for (**a**) areas behind coral reefs and protection and (**b**) areas behind seagrasses (and with coral reef protection).

In the above table, the coefficients "Beta" and "B" provide information on the relative contribution of each susceptibility factor to influence beach erosion. Beta is the coefficient applied on a rectified sampled (i.e., values minus the mean, divided by standard deviation), whereas B is the coefficient which can be applied on original data as a weighting coefficient in the model. A negative coefficient means that the specific variables tend to be negatively correlated with beach erosion. In this table, a wider coral reef associated a deeper the depth at 1000 m (meaning a steeper proximal slope) is correlated with smaller beach erosion.

The percentage of explanation of each variable can be computed using the ration between the square of each Beta value on the sum of these square, in the case of width of coral reef:

$$\frac{(-0.91)^2}{(-0.91)^2 + (-0.64)^2} = 0.669$$

In the model, the width of coral reef and the slope are the main factors identified explaining 66.9% and 33.1% of the model respectively.

The *p*-level provide a good insight on the probability that the link is due to a coincidence.

The *p*-level indicates the probability that the variable was selected by coincidence. For example a *p*-level of 0.05 indicates that there is 5% of chance that the selected variable is a "fluke". This level is customarily treated as a "border-line acceptable" error level. So the lowest the *p*-level the highest the confidence in the selection. In this study the range of *p*-level are between 0 and 0.01248, meaning the all the selected variables have between 0 and 1.2% of being selected by coincidence, meaning the model is solid.

The model explains 83% of the erosion with a 91% correlation. Coral reef widths and slopes were selected as significant parameters in the model. Widths play the main role (66.9%) followed by seabed slopes (33.1%). These correlations values appear high (especially for linear regressions) should, however, be viewed with caution, given the small number (9) of cases (Figure 3a).

With regard to seagrasses, the model is also robust (Table 4 and Figure 3b) with the *p*-values highly significant (much smaller than 0.05). The percentage of variation explained is less than the previous model (41%), but still within acceptable limit (adjusted R^2 = 0.37). It is based on 59 records and 3 variables, namely: (i) the total width of seagrass meadows (TotSgW, in m), (ii) the minimum distance (in m) where 6 m water depth is recorded (Depth6) and (iii) the Iribarren number calculated for a 10 years return period (Irbn10y). It shows that wider seagrass meadows are associated with less erosion along the beach they front (Figure 3b)). The correlation matrix shows no autocorrelation between the three variables (maximum absolute value of r = 0.32). Two outliers had to be suppressed as they had no observed erosion (0 m) between 1968 and 2000, while the model predicted more than 27 m of retreat (see Figure 3b). These two cases are located next to each other and in front of the coastal facilities of large hotels. Ground verification revealed that significant beach re-arrangement/replenishment had taken place in these two locations. R = 0.64 R^2 = 0.41 Adjusted R^2 = 0.37 (adjusted R2, is the variance value, taking in consideration the number of variables versus size of the sample).

Table 4. Results from statistical regression, cases without coral protection, with TotSgW as the total width of seagrass meadows in meter, Depth6 as the minimum distance where a six meters water depth is recorded and Irbn10y as the Iribarren number (Komar, 1998) calculated for a 10 year return period.

N = 59	Beta	%Expl	Std. Error	B	Std. Error	t(55)	*p*-Level
Intercept				32.89	6.40	5.14	0.00000
TotSgW	−0.58	47.3	0.11	−0.02	0.00	−5.21	0.00000
Depth6	0.39	32.0	0.11	0.01	0.00	3.42	0.00119
Irbn10y	−0.25	20.7	0.11	−21.54	9.46	−2.28	0.02666

The model explains 41% of the erosion (correlation r = 0.64). Seagrass and bed slopes (of the seabed and the 'dry' beach) were selected as parameters in the model. Seagrass was found to play the main role (47.3%) followed by seabed slope (32%) and the Irbn10y (20.7%).

4.3. Wave Modelling

Several experiments were carried out using different offshore wave regimes, such as wind and swell waves and extreme storm conditions. In all cases, the results show considerable effects of the shallow coral reefs on the nearshore wave propagation patterns as well as the wave-induced flow fields (Figure 4).

In terms of the effects of coral reefs on cross-shore wave energy distribution, cross-shore wave modelling confirms the results of both the statistical analysis and the 2-D modelling. The shallow reef appears to function as a natural breakwater [59], with wave heights decreasing very significantly at its lee (Figure 5). Wave height attenuation due to the reef and back-reef grasses was found to be in some areas up to about 93%. Most of this attenuation was due to the shallow coral reef itself with the effect of the back-reef seagrasses being minimal (Figure 5a).

Generally, wave attenuation was found to be higher under more energetic waves and less under increased sea levels (assuming that there will not be corresponding coral reef growth). Our results also show that, at least for the SLR and wave conditions tested, there will be an offshore migration of the wave breaking zone offshore allowing for significant wave dissipation in deeper waters (Figure 5a,b). Regarding the ratio of wave attenuation under the future and present sea level scenarios examined, this is lower in the nearshore waters, up to a distance of about 50 m from the coastline where the trend appears to reverse (Figure 5c); the results show that the ratio between the wave height attenuation under increased (+0.45 m) and the present mean sea levels increases above unity closer to the coastline. *Nevertheless*, as increased sea levels will also influence many other beach processes, such the wave set up, the size/quantity of resuspended sediments and the filtering of the wave energy frequencies by the coral reef [80], SLR may decrease the coastal protection afforded by the shallow coral reefs [81] and intensify beach erosion at Negril [68].

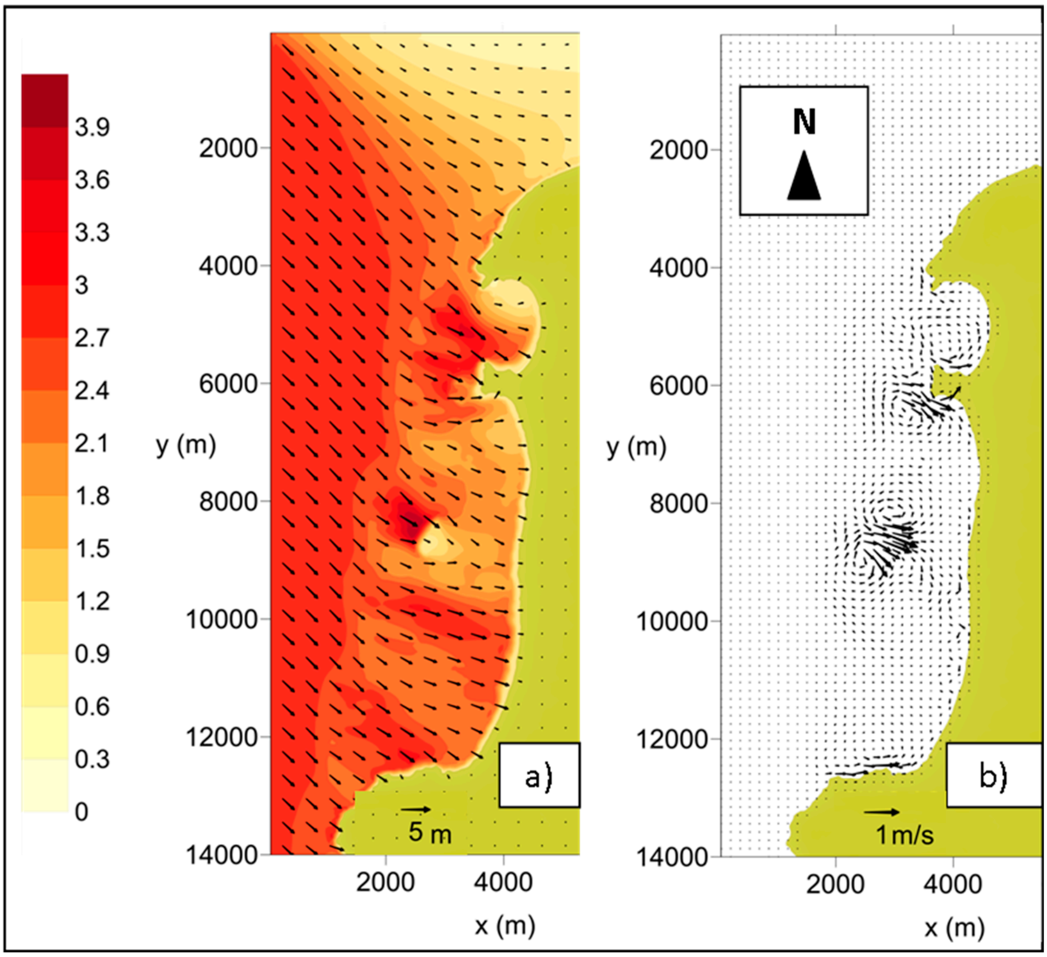

Figure 4. Example of model results for wave heights (**a**) and wave-induced currents (**b**) at the Negril coastal area. Conditions: Offshore wave height (Hrms) of 2.8 m, and period (Tp) of 8.7 s. Waves approach from the NW.

In the absence of reefs, seagrass meadows exert significant control on the cross-shore wave energy distribution (Figure 6). Wave height attenuation of up to 28% was found for the conditions tested (Figure 6a), suggesting that the Negril seagrasses are important agents of wave dissipation and supporting the results of multiple regression analysis. It should be noted that nearshore wave attenuation due to seagrasses depends on many parameters such as meadow and wave characteristics [82–84]. With regard to SLR impacts, the results show that, assuming that the seagrass extent and elevation remain the same, wave attenuation will be only slightly reduced (Figure 6b,c), under the moderate SLRs tested.

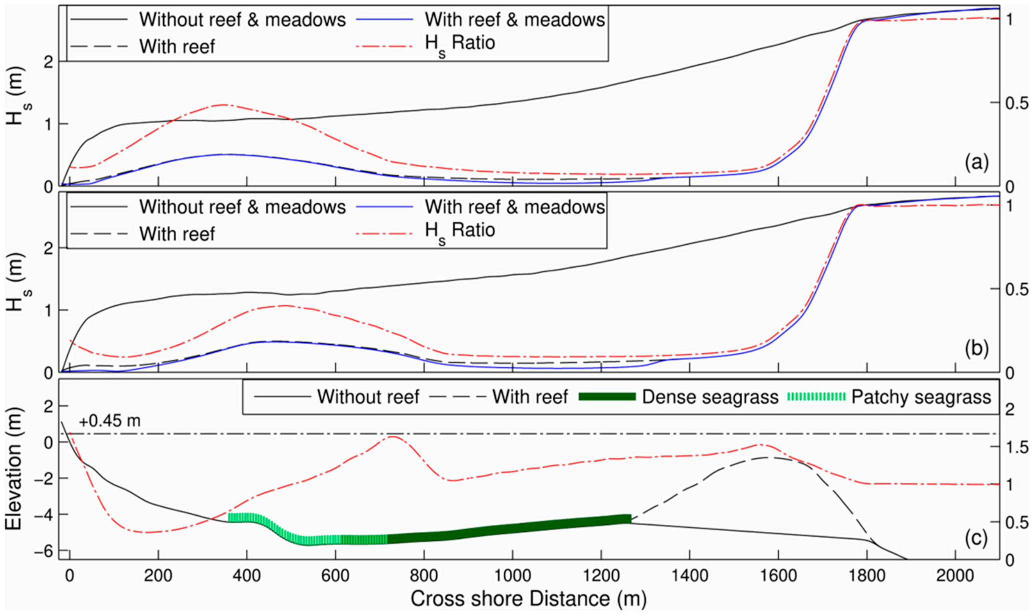

Figure 5. Effects of the shallow coral reef and of the combined reef and back-reef seagrasses on the present and future cross-shore distribution of wave height along a cross-shore profile (for profile location see Figure 2). (**a**) Cross-shore wave height and wave attenuation ratio (Hs ratio, scale at the right axis) due to observed ecosystems under the present mean sea level. (**b**) Cross-shore distribution of wave height and attenuation ratio under a 0.15 m MSLR coupled with spring tides (+0.3 m). (**c**) Bed profile and cross-shore distribution of the ratio of wave attenuation under an increased sea level (+0.45 m) and the present mean sea level (stippled line, Hs ratio$_{(+0.4)5}$/Hs ratio$_{(0.0)}$, scale at the right axis). Offshore wave height and period modelled, Hrms = 2.8 m and Tp = 8.7 s, respectively. Median sediment size (D50), 0.28 mm. Dense seagrass characteristics as shoot density of 400/m^2, canopy height of 0.20 m and grass diameter of 0.01 m; patchy seagrass characteristics as 200/m^2, 0.20 m and 0.01 m, respectively (example from profile 40).

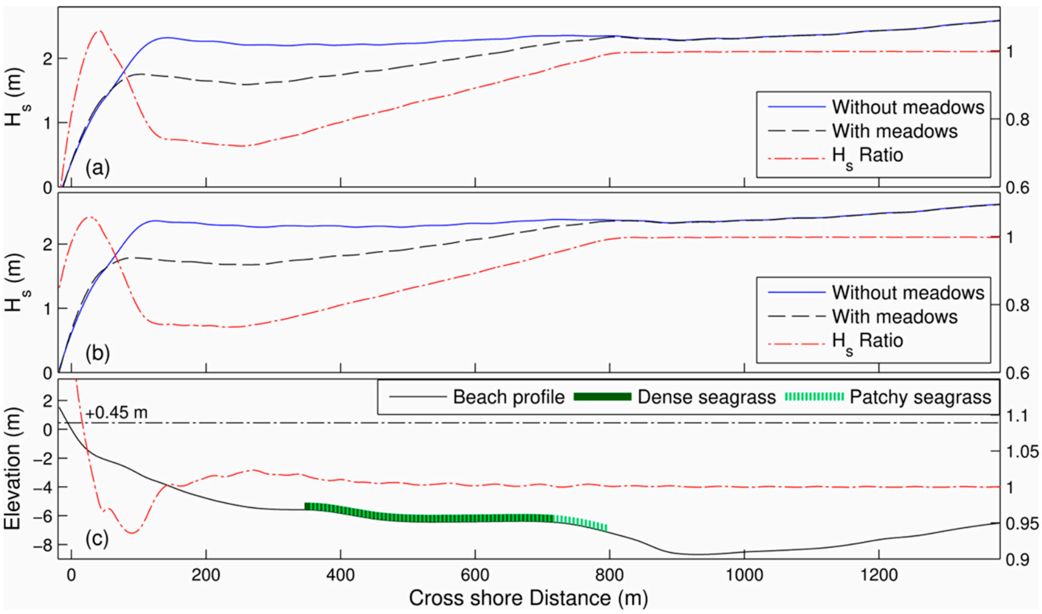

Figure 6. Effects of the shallow seagrass meadows on the wave energy (height). (**a**) Cross-shore wave height and attenuation ratio (Hs ratio, scale at the right axis) due to seagrasses under the present mean sea level. (**b**) Cross-shore distribution of wave height and attenuation ratio under a 0.15 m MSLR coupled with spring tides (+0.3 m). (**c**) Bed profile and cross-shore distribution of the

ratio of wave attenuation under an increased sea level (+0.45 m) and the present mean sea level (stippled line, Hs $ratio_{(+0.4)5}$/Hs $ratio_{(0.0)}$, scale at the right axis). Offshore wave height and period modelled, Hrms = 2.8 m and Tp = 8.7 s, respectively. Median sediment size (D50), 0.28 mm. Dense seagrass characteristics as shoot density of 400/m^2, canopy height of 0.20 m and grass diameter of 0.01 m; patchy seagrass characteristics as 200/m^2, 0.20 m and 0.01 m, respectively (example on profile 21).

4.4. Discussion

Analysis of the available geo-spatial information suggests that both Negril beaches (Bloody and Long Bays) have been under severe erosion in the period 1968–2008 with rates of up to 1.3 m/yr in some beach sections. Erosion has been spatio-temporally variable but, as erosion is dominant along most of the shoreline, offshore sediment loss appears to be more significant for the morphodynamics of the Negril pocket beaches than beach rotation [85].

Generally, all approaches used in the study show that the nearshore ecosystems (i.e., coral reefs and seagrass meadows) exert significant control the Negril beach morphodynamics, as they: (a) protect the beaches from the impinging wave energy; and (b) supply the beach with much needed biogenic sand. However, these results do not preclude that anthropogenic decline of other ecosystems might have also contributed to the observed high rates of beach erosion; there has been a progressive removal of trees along the Negril beaches to facilitate beach recreational activities since the 1980s [43,44]. It should be also noted that although our statistical results are robust, these are based on comparisons between the 2008 distribution of nearshore ecosystems and the cumulative effects of 40 years of erosion. Nevertheless, as these results are supported by the wave modelling as well as by results from previous studies [43,68], they convey a strong message for a need to protect and if, possible, rehabilitate the Negril nearshore ecosystems. Local and national consultations revealed that the Negril coral reefs are under multiple threats, including impacts from storms, climate-driven coral bleaching and acidification, the decline of black urchin population and invasive species (e.g., lion fish), as well as nearshore water and sediment pollution [43].

Beach erosion is not expected to be abated in the short, or medium, term. Our modelling results project that the effectiveness of the present nearshore ecosystems to mitigate beach erosion is likely to diminish under MSLR, if it is not accompanied by ecosystem expansion/growth. At the same time, if the projected MSLR is taken into consideration, beach erosion is likely to intensify. In order to assess potential SLR effects on the Negril beaches, a modelling exercise was undertaken. Three cross-shore (1-D) morphodynamic models, the SBEACH, Larson and Kraus, Leon'yev and Xbeach models [86–88], set up using recorded Negril beach profiles that did not include coral reef and seagrasses and found to be hot spots of erosion, were run under different SLR scenarios and wave conditions (for details of the models/approach, see [34]. The models gave different projections, with the Xbeach showing always higher shoreline retreats (Figure 7), which justifies their use in an ensemble form. Under the present MSL, the current 10-year storm event (surge of about 0.2 m and offshore (at 20 m depth) wave height and period of 4 m and 9 s, respectively [49], coupled with spring tides is projected by the model ensemble to force a shoreline retreat of about 7.7 m. In comparison, if a moderate MSLR (0.15 m) is assumed for 2060, such an event is projected to force a shoreline retreat of about 8.8 m. These projections are comparable to those estimated previously [69] and are particularly worrying for the already eroding Negril beaches (Figure 2), especially if the relatively moderate forcing used (i.e., the current 10-year event) is considered.

The above results demonstrate the risk posed to the Negril beaches by CV & C. Beach erosion is projected to advance, placing coastal human populations, assets and activities and the important back-barrier ecosystem of Great Morass under considerable erosion and flood risk. Therefore, adaptation measures are clearly needed to protect the Negril population and assets as well as the beach carrying capacity for recreation/tourism [39]. As a 'business as usual' approach appears not to be any longer an option given the economic importance of the Negril beaches, long-term policies and integrated approaches should be considered.

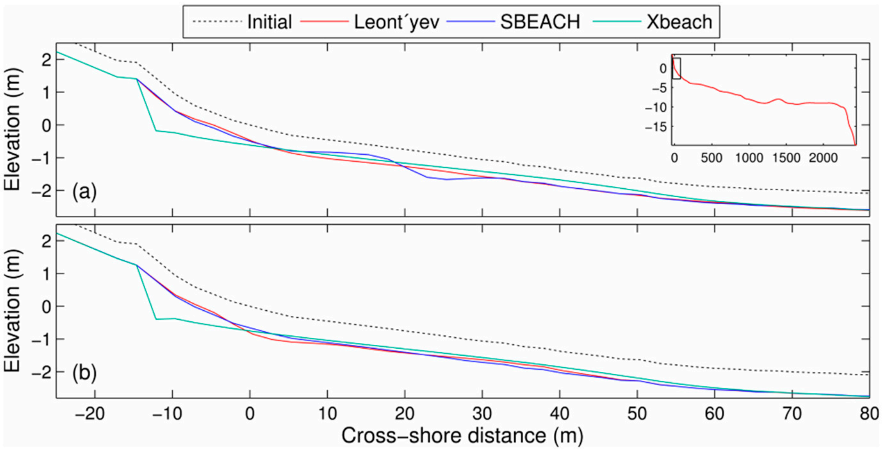

Figure 7. Cross-shore morphodynamic evolution of Negril beach at a representative beach profile (for location, see Figure 2). (**a**) cross-shore beach retreat under a storm surge of 0.2 m (the current 10-year event) coupled with a spring tide (+0.3 m above MSL); an offshore wave height (Hs) of 4 m and period of 9 s (at 20 m water depth) and a seabed sediment size (d50) of 0.73 mm are used. (**b**) cross-shore beach retreat under a storm surge of 0.2 m (the current 10-year event), coupled with a MSLR of 0.15 m (in 2060 assuming linear sea level rise of 3 mm/yr and a spring tide (+0.3 m above MSL); offshore wave height (Hs) of 4 m and period of 9 s (at 20 m water depth and seabed sediment size (d50) of 0.73 mm are used. Simulation times 3 h.

Our results point that in addition to effective policies aiming for sustainable coastal development [89], a combination of 'green' and 'grey' engineering adaptation options may be required [90], including three main technical actions to address beach erosion: (i) conservation and, if possible, enhancement of the present nearshore coral reefs and seagrass meadows; (ii) construction of offshore structures (e.g., submerged breakwaters) to protect beach 'hot spots' of erosion against excessive wave action; and (iii) beach nourishment, i.e., beach replenishment with suitable fill material, preferably biogenic marine sands of suitable grading and composition.

Efforts to arrest beach erosion should maximize relevant functionalities of the present coastal ecosystems; their protection and rehabilitation/restoration could yield both short- and long-term benefits. Coral reef and seagrass meadows restoration, together with appropriately designed coastal protection schemes could increase beach resilience. A long-term management approach is also required at the catchment scale to ensure the good coastal water quality [43]. Beach replenishment schemes would require significant financial investment, whereas 'hard' engineering works would also need to be carefully designed and followed by detailed environmental impact studies under a variable and changing climate. It should be noted that the significance of Negril beaches as economic resources and the low effectiveness of offshore 'hard' engineering works (e.g., breakwaters) to protect beaches from the MSLR [91,92] suggest that beach nourishment schemes may be necessary if the carrying capacity of the beach as an environment of leisure is to be maintained. Marine aggregates constitute a most suitable, but often scarce material for beach nourishment [93]. Finding suitable offshore resources to supply the large quantities of material needed [49] will not be an easy exercise and not exempt of adverse environmental impacts [93].

Figure 8 provides historical level of beach as observed by aerial photo in 1968 (left) as compared with possible coastal retreat, should all the ecosystems be removed (according to model). We see that the infrastructures would be at threat and the beach would be mostly lost in this location.

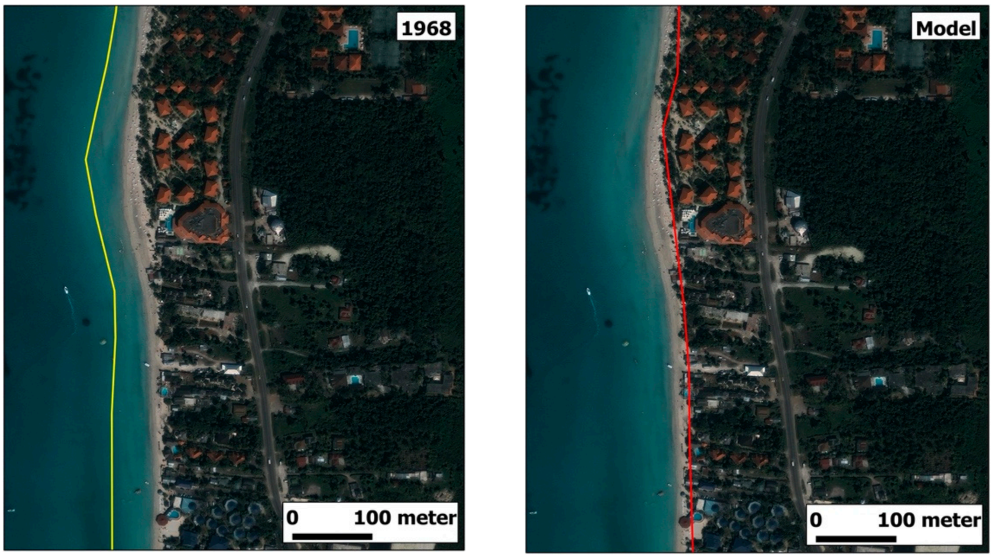

Figure 8. (**Left**): the yellow line shows where the beach was in 1968. (**Right**): the red line shows where the beach would be if all the ecosystems are removed (using our model and artificially replacing width of shallow coral and width of total sea grass by 0).

Finally, the results of this study have wider implications. The socio-economic importance of Caribbean (and not only) beaches is increasing, as they are premier 3 s tourism destinations. Therefore, as beaches form vital components of the sustainable development for many Small Island Developing States (SIDS), particular efforts should be made to increase beach resilience and adaptive capacity under CV & C. Adaptation options should certainly include monitoring, conservation and, if possible, rehabilitation of the nearshore ecosystems. Given the large costs of technical engineering options, nearshore ecosystems could be critical in controlling coastal exposure and vulnerability [94,95].

5. Conclusions

This short contribution presents the results of a study of the influence exerted by the nearshore marine ecosystems (coral reefs and seagrasses) on the resilience of two adjacent Caribbean pocket beaches (Long and Bloody Bays, Negril, Jamaica) that are very important beach tourism destinations. Analysis of historical information on beach shoreline positions (1968–2008) has shown that Negril beaches have been under severe and spatio-temporally variable erosion. The highest rates of erosion were observed at Long Bay beach, to the north and south of the 'shadow' of the shallow coral reef, where also seagrass coverage was found to be reduced. Average 'dry' beach erosion between 1968 and 2008 amounted to about 23.4 m (i.e., 0.59 m/yr), with some locations experiencing shoreline retreats of more than 55 m (i.e., 1.37 m/yr), Such erosion rates are worrying, if the small (remaining) widths of the Nergil beaches are considered.

The Negril beaches are already under very considerable erosional pressures, which will most likely intensify in the future. Possible drivers of the current beach erosion are

(a) the MSLR, which in itself cannot, however, explain the observed rates of erosion;
(b) intensification or changes in the regional storm wave and surge regime, which may have increased offshore beach sediment losses and
(c) reductions in the coastal ecosystem (shallow coral reef and seagrass meadows) areal coverage that has diminished both the natural beach protection and the (biogenic) sediment supply.

Assessment of the influence of the nearshore ecosystems on the beach physical resilience on the basis of a comparison of beach erosion trends along the beaches with the distribution of the fronting shallow coral reefs and seagrass meadows and nearshore wave modelling has shown that the shallow coral reefs have a very significant effect on nearshore wave energy distribution and play a significant role in protecting beaches from erosion; the shallow, patch reefs appear to function as natural breakwaters. The nearshore seagrass meadows were also found to exert significant control on the (cross-shore) wave energy distribution, with wave height attenuation of up to 28% found for the tested conditions tested; this suggests that the Negril seagrasses are important agents of wave dissipation

The mean sea level rise will have various impacts. Wave energy distribution will change due to the expected widening of the surf zone and changing inshore wave dissipation. There will be also changes in the wave set up magnitude and distribution, the size/quantity of resuspended sediments and the filtering of the wave energy frequencies which might result in overall reductions in the coastal protection afforded by the shallow coral reefs.

Our results demonstrate the critical services that nearshore ecosystems provide to Negril beaches (in terms of coastal protection and sediment supply). The nearshore ecosystems of Negril play a crucial role in providing beach material and dissipating the nearshore wave energy, especially during energetic wave conditions. However, the Negril coral reefs and seagrasses have been under multiple pressures by both coastal human development and pollution. Field observations, as well as local consultations, had revealed degraded corals, due to increased nearshore pollution [43].

Therefore, there should be efforts to mitigate water pollution. Based on our recommendations a wastewater treatment facility was built, this will reduce the pollution and amount of nutriments in the water. We presented our results to the hotels' owners. Previously they were removing the sea grass as the tourists do not like swimming in it. We recommended to create some areas free of sea grass, but to replant the sea grass behind. These recommendations were followed by the hotels owners who understood that they were self-inducing the beach erosion via removing sea grass. For coal reef, the issue is more complex as it would take time to regrow, and climate change is likely to pose further threat to this ecosystem. A submarine breakwater can be built (grey engineering) but it is sensitive as it can have implications on the ecosystems, as well as on aesthetics value. If such solution was chosen, it should be built parallel to the shoreline at the right distance, such infrastructure should be carefully designed and computed to disrupt the energy of waves and should be made of lime stones with natural shape, so that the coral may regrow on top of it.

Coral reefs and nearshore seagrasses are environmental assets that should be considered in all climate change adaptation and disaster risk management strategies, as well as in development planning. Even if 'grey' engineering solutions would be finally chosen, "hybrid" solutions that also consider ecosystem-based solutions should be also certainly introduced. It is also noteworthy that these ecosystems offer additional services that cannot be provided by 'grey engineering' measures, such as carbon storage, biodiversity support, and touristic attractions (landscape, diving).

Finally, further erosion of Negril beaches is likely, if no adaptation action is taken. The Negril beaches form pillars of the 3S tourism industry in Jamaica. Investing in restoring the quality of the ecosystems will bring many benefits to people's livelihoods at both local and national scales.

Author Contributions: Conceptualization, P.P., A.V.; methodology, P.P., A.V., B.C., T.K.; formal analysis, P.P., B.C., A.V., T.K.; investigation, P.P., B.C., A.V., M.E.; resources, P.P., M.E.; data curation, P.P., A.V., B.C., T.K.; writing—original draft preparation, P.P., A.V., M.E.; writing—review and editing, P.P., A.V., M.E.; visualization, P.P., B.C., A.V., T.K.; supervision, P.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the United Nations Environment Programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: http://2012-2018.unepgrid.ch/RIVAMP/Data/ (accessed on 13 April 2022).

Acknowledgments: We thank the numerous people who have helped us in accessing data. We are especially grateful to our colleagues at the Planning Institute of Jamaica (Claire Bernard, Le-Anne Roper, Nadine Brown and Richard Kelly) for their efficiency and dedication to support the work in Negril as well as David Smith from Smith Warner International for making available the data and results of a comprehensive coastal engineering study for Negril. We thank Stéphane Kluser and I.M. Monioudi for their assistance in the analysis and visualization of information.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Reid, W.V.; Mooney, H.A.; Cropper, A.; Capistrano, D.; Carpenter, S.R.; Chopra, K.; Dasgupta, P.; Dietz, T.; Duraiappah, K.; Hassan, R.; et al. Millenium Ecosystem Assessment. In *Ecosystems and Human Well-Being: Synthesis*; Island Press: Washington, DC, USA, 2005; 137p.
2. Costanza, R.; De Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158. [CrossRef]
3. Chatenoux, B.; Peduzzi, P. Impacts from the 2004 Indian Ocean Tsunami: Analysing the potential protecting role of environmental features. *Nat. Hazards* **2007**, *40*, 289–304. [CrossRef]
4. Beck, M.W.; Brumbaugh, R.D.; Airoldi, L.; Carranza, A.; Coen, L.D.; Crawford, C.; Defeo, O.; Edgar, G.J.; Hancock, B.; Kay, M.C.; et al. Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. *BioScience* **2011**, *61*, 107–116. [CrossRef]
5. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* **2013**, *3*, 961–968. [CrossRef]
6. Munang, R.; Thiaw, I.; Alverson, K.; Mumba, M.; Liu, J.; Rivington, M. Climate Change and Ecosystem-Based Adaptation: A New Pragmatic Approach to Buffering Climate Change Impacts. *Curr. Opin. Environ. Sustain.* **2013**, *5*, 67–71. [CrossRef]
7. Wilkinson, C. *Status of Coral Reefs of the World: 2008*; Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre: Townsille, Australia, 2008.
8. Chen, P.-Y.; Chen, C.-C.; Chu, L.; McCarl, B. Evaluating the economic damage of climate change on global coral reefs. *Glob. Environ. Change* **2015**, *30*, 12–20. [CrossRef]
9. Woodroffe, C.D.; Webster, J.M. Coral reefs and sea-level change. *Mar. Geol.* **2014**, *352*, 248–267. [CrossRef]
10. Beetham, E.; Kench, P.S. Predicting wave overtopping thresholds on coral reef-island shorelines with future sea-level rise. *Nat. Commun.* **2018**, *9*, 3997. [CrossRef]
11. Miller, M.W.; Piniak, G.A.; Williams, D.E. Coral mass bleaching and reef temperatures at Navassa Island, 2006. *Estuar. Coast. Shelf Sci.* **2011**, *91*, 42–50. [CrossRef]
12. Williams, G.J.; Knapp, I.S.; Maragos, J.E.; Davy, S.K. Modeling Patterns of Coral Bleaching at a Remote Central Pacific Atoll. *Mar. Pollut. Bull.* **2010**, *60*, 1467–1476. [CrossRef]
13. Harris, P.T.; Heap, A.D. Cyclone-induced net sediment transport pathway on the continental shelf of tropical Australia inferred from reef talus deposits. *Cont. Shelf Res.* **2009**, *29*, 2011–2019. [CrossRef]
14. Woodroffe, C.D. Reef-Island Topography and the Vulnerability of Atolls to Sea-Level Rise. *Glob. Planet. Change* **2008**, *62*, 77–96. [CrossRef]
15. Short, F.T.; Neckles, H.A. The Effects of Global Climate Change on Seagrasses. *Aquat. Bot.* **1999**, *63*, 169–196. [CrossRef]
16. Cabaço, S.; Santos, R.; Duarte, C.M. The impact of sediment burial and erosion on seagrasses: A review. *Estuar. Coast. Shelf Sci.* **2008**, *79*, 354–366. [CrossRef]
17. Daby, D. Effects of seagrass bed removal for tourism purposes in a Mauritian bay. *Environ. Pollut.* **2003**, *125*, 313–324. [CrossRef]
18. Holon, F.; Boissery, P.; Guilbert, A.; Freschet, E.; Deter, J. The impact of 85 years of coastal development on shallow seagrass beds (*Posidonia oceanica* L. (Delile)) in South Eastern France: A slow but steady loss without recovery. *Estuar. Coast. Shelf Sci.* **2015**, *165*, 204–212. [CrossRef]
19. Manent, P.; Bañolas, G.; Alberto, F.; Curbelo, L.; Espino, F.; Tuya, F. Long-term Seagrass Degradation: Integrating Landscape, Demographic, and Genetic Responses. *Aquatic Conserv. Mar. Freshw. Ecosyst.* **2020**, *30*, 1111–1120. [CrossRef]
20. Luijendijk, A.; Hagenaars, G.; Ranasinghe, R.; Baart, F.; Donchyts, G.; Aarninkhof, S. The State of the World's Beaches. *Sci. Rep.* **2018**, *8*, 6641. [CrossRef]
21. Ackerman, R.A. The Nest Environment and the Embryonic Development of Sea Turtles. In *The Biology of Sea Turtles*; Lutz, P.L., Musick, J.A., Eds.; CRC Press: Boca Raton, FL, USA, 1996; pp. 83–106.
22. Neumann, B.; Vafeidis, A.T.; Zimmerman, J.; Nicholls, R.J. Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding—A Global Assessment. *PLoS ONE* **2015**, *10*, e0118571. [CrossRef]
23. Monioudi, I.N.; Karditsa, A.; Chatzipavlis, A.; Alexandrakis, G.; Andreadis, O.P.; Velegrakis, A.F.; Poulos, S.E.; Ghionis, G.; Petrakis, S.; Sifnioti, D.; et al. Assessment of the vulnerability of the eastern Cretan beaches (Greece) to sea level rise. *Reg. Dev. Change* **2016**, *16*, 1951–1962. [CrossRef]
24. *International Tourism Highlights*, 2019th ed.; United Nations World Tourism Organisation: Madrid, Spain, 2019.

25. *An Assessment of the Economic Impact of Climate Change on the Transportation Sector in Barbados*; Technical Report LC/CAR/L309; Economic Commission for Latin America and the Caribbean (ECLAC): Santiago, Chile, 2011; 44p.
26. Tzoraki, O.; Monioudi, I.; Velegrakis, A.; Moutafis, N.; Pavlogeorgatos, G.; Kitsiou, D. Resilience of touristic island beaches under sea level rise: A methodological framework. *Coast. Manag.* **2018**, *46*, 78–102. [CrossRef]
27. Toimil, A.; Díaz-Simal, P.; Losada, I.J.; Camus, P. Estimating the risk of loss of beach recreation value under climate change. *Tourism. Manag.* **2018**, *68*, 387–400. [CrossRef]
28. Hinkel, J.; Nicholls, R.J.; Tol, R.S.J.; Wang, Z.B.; Hamilton, J.M.; Boot, G.; Vafeidis, A.T.; McFadden, L.; Ganopolski, A.; Klein, R.J.T. A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Glob. Planet. Change* **2013**, *111*, 150–158. [CrossRef]
29. Mentaschi, L.; Vousdoukas, M.; Pekel, J.-F.; Voukouvalas, E.; Feyen, L. Global long-term observations of coastal erosion and accretion. *Sci. Rep.* **2018**, *8*, 12876. [CrossRef]
30. Nicholls, R.J.; Cazenave, A. Sea-Level Rise and Its Impact on Coastal Zones. *Science* **2010**, *328*, 1517–1520. [CrossRef]
31. Smith, A.B.; Katz, R.W. U.S. Billion-dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy and Biases. *Nat. Hazards* **2013**, *67*, 387–410. [CrossRef]
32. Ranasinghe, R. Assessing climate change impacts on open sandy coasts: A review. *Earth Sci. Rev.* **2016**, *160*, 320–332. [CrossRef]
33. Flor-Blanco, G.; Alcántara-Carrió, J.; Jackson, D.W.T.; Flor, G.; Flores-Soriano, C. Coastal erosion in NW Spain: Recent patterns under extreme storm wave events. *Geomorphology* **2021**, *387*, 107767. [CrossRef]
34. Monioudi, I.; Velegrakis, A.; Chatzipavlis, A.; Rigos, A.; Karambas, T.V.; Vousdoukas, M.; Hasiotis, T.; Koukourouvli, N.; Peduzzi, P.; Manoutsoglou, E.; et al. Assessment of island beach erosion due to sea level rise: The case of the Aegean archipelago (Eastern Mediterranean). *Nat. Hazards Earth Syst. Sci.* **2017**, *17*, 449–466. [CrossRef]
35. Peduzzi, P.; Velegrakis, A.F.; Estrella, M.; Chatenoux, B. Integrating the role of ecosystems in disaster risk and vulnerability assessments: Lessons from the Risk and Vulnerability Assessment Methodology Development Project (RiVAMP) in Negril Jamaica. In *The Role of Ecosystems in Disaster Risk Reduction*; Renaud, F.G., Ed.; United Nations University Press: Tokyo, Japan, 2013; pp. 109–139, ISBN-13: 978-9280812213.
36. Romine, B.M.; Fletcher, C.H.; Neil Frazer, L.; Anderson, T.R. Beach erosion under rising sea-level modulated by coastal geomorphology and sediment availability on carbonate reef-fringed island coasts. *Sedimentology* **2016**, *63*, 1321–1332. [CrossRef]
37. Asariotis, R. Climate change and adaptation for coastal transport infrastructure: A sustainable development challenge for SIDS in the Caribbean and beyond. In *Coastal and Marine Environments. The Handbook of Natural Resources*, 2nd ed.; Wang, Y., Ed.; CRC Press: Boca Raton, FL, USA, 2020; pp. 253–264.
38. Vousdoukas, M.I.; Ranasinghe, R.; Mentaschi LPlomaritis, T.A.; Athanasiou, P.; Luijendijk, A.; Feyen, L. Sandy coastlines under threat of erosion. *Nat. Clim. Change* **2020**, *10*, 260–263. [CrossRef]
39. McArthur, S. Why Carrying Capacity Should be a Last Resort. In *Challenges in Tourism Research*; Vir Singh, T., Ed.; Channel View Publications: Bristol, UK, 2015; pp. 288–302.
40. Andreadis, O.; Chatzipavlis, A.; Hasiotis, T.; Monioudi, I.; Manoutsoglou, E.; Velegrakis, A. Assessment of and Adaptation to Beach Erosion in Islands: An Integrated Approach. *J. Mar. Sci. Eng.* **2021**, *9*, 859. [CrossRef]
41. Knutson, T.R.; McBride, J.L.; Chan, J.; Emanuel, K.; Holland, G.; Landsea, C.; Held, I.; Kossin, J.P.; Srivastava, A.K.; Sugi, M. Tropical cyclones and climate change. *Nat. Geosci.* **2010**, *3*, 157–163. [CrossRef]
42. Peduzzi, P.; Chatenoux, B.; Dao, H.; De Bono, A.; Herold, C.; Kossin, J.; Mouton, F.; Nordbeck, O. Global trends in tropical cyclone risk. *Nat. Clim. Change* **2012**, *2*, 289–294. [CrossRef]
43. UNEP. *Risk and Vulnerability Assessment Methodology Development Project (RiVAMP): Linking Ecosystems to Risk and Vulnerability Reduction; The Case of Jamaica, Results of the Pilot Assessment*; United Nations Environment Programme: Geneva, Switzerland, 2010; 130p.
44. Rhiney, K. The Negril tourism industry: Growth, challenges and future prospects. *Caribb. J. Earth Sci.* **2012**, *43*, 25–34.
45. *Travel & Tourism: Economic Impact 2016, Jamaica*; World Travel and Tourism Council: London, UK, 2016; 30p.
46. Hughes, T. Catastrophes, Phase Shifts, and Large-Scale Degradatgion of a Caribbean Coral Reef. *Science* **1994**, *265*, 1547–1551. [CrossRef]
47. Bjork, S. *Optimurn Utilization Study of the Negril and Black River Lower Morasses, Jamaica*; Institute of Limnology: Kingston, Jamaica, 1984; 63p.
48. Robinson, E.; Hendry, M. Coastal change and evolution at Negril, Jamaica: A geological perspective. *Caribb. J. Earth Sci.* **2012**, *43*, 3–9.
49. *Beach Restoration Works at Negril: Preliminary Engineering Report*; Smith and Warner International: Kingston, Jamaica, 2007; 68p.
50. *Beach Sands Resource Assessment, Negril, Jamaica*; University of the West Indies, Department of Geology and Geography: Kingston, Jamaica, 2002; 83p.
51. Mondon, E.M.; Warner, P.S. Evaluation of a proposed solution to beach erosion at Negril. *Caribb. J. Earth Sci.* **2012**, *43*, 11–23.
52. Edwards, P. *Natural Resource Valuation Considerations for Negril Beach Stabilization Project*; National Environment and Planning Agency (NEPA): Kingston, Jamaica, 2014; 39p.
53. Barrett, L. Scrapped -Gov't Pulls Plug On Controversial $1-Billion Negril Breakwater Project. The Gleaner. 2016. Available online: http://jamaica-gleaner.com/article/lead-stories/20160713/scrapped-govt-pulls-plug-controversial-1-billion-negrilbreakwater (accessed on 3 November 2020).

54. Peduzzi, P. The Disaster Risk, Global Change, and Sustainability Nexus. *Sustainability* **2019**, *11*, 957. [CrossRef]
55. McKenzie, A. Beach Responses to Hurricane Impacts: A Case Study of Long Bay Beach, Negril, Jamaica. *Caribb. J. Earth Sci.* **2012**, *43*, 51–58.
56. Alexandris, N.; Chatenoux, B.; Lopez Torres, L.; Peduzzi, P. *Monitoring the Restoration of Mangroves Ecosystems from Space*; UNEP/GRID-Geneva: Geneva, Switzerland, 2014; 48p.
57. Rigos, A.; Tsekouras, G.E.; Vousdoukas, M.I.; Chatzipavlis, A.; Velegrakis, A.F. A Chebyshev polynomial RBF neural network for automated shoreline extraction from coastal imagery. *Integr. Comput. Aided Eng.* **2016**, *23*, 141–160. [CrossRef]
58. Schwarzer, S.; Allenbach, K.; Jaquet, J.-M. Cartographie semi-automatisée et multi-sources de la couverture du sol. 1. Périmètre de l'agglomération franco-valdo genevoise (CCSA04, moyenne résolution). *Arch. Sci.* **2009**, *62*, 107–124.
59. Velegrakis, A.F.; Trygonis, V.; Chatzipavlis, A.E.; Karambas, T.; Vousdoukas, M.I.; Ghionis, G.; Monioudi, I.N.; Hasiotis, T.; Andreadis, O.; Psarros, F. Shoreline variability of an urban beach fronted by a beachrock reef from video imagery. *Nat. Hazards* **2016**, *83*, 201–222. [CrossRef]
60. Peduzzi, P. Landslides and vegetation cover in the 2005 North Pakistan earthquake: A GIS and statistical quantitative approach. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 623–640. [CrossRef]
61. Iribarren, C.R.; Nogales, C. *Protectoin Des Ports*; PIANC: Lisbon, Portugal, 1949.
62. Karambas, T.V.; Koutandos, E.; Kampanis, N. Numerical simulation of wave-induced morphology evolution. *J. Marit. Eng.* **2013**, *166*, 13–124. [CrossRef]
63. Holthuijsen, L.H.; Herman, A.; Booij, N. Phase-decoupled refraction-diffraction for spectral wave models. *Coast. Eng.* **2003**, *49*, 291–305. [CrossRef]
64. Booij, N.; Ris, R.C.; Holthuijsen, L.H. A third-generation wave model for coastal regions: 1. Model description and validation. *J. Geophys. Res.* **1999**, *104*, 7649. [CrossRef]
65. Karambas, T.V.; Koutitas, C. Surf and swash zone morphology evolution induced by nonlinear waves. *J. Waterw. Port Coast. Ocean. Eng.* **2002**, *128*, 102–113. [CrossRef]
66. Karambas, T.V. Modeling of sea-level rise effects on cross-shore coastal erosion. *J. Mar. Environ. Eng.* **2003**, *7*, 15–24.
67. Karambas, T.; Koftis, T.; Prinos, P. Modeling of Nonlinear Wave Attenuation Due to Vegetation. *J. Coast. Res.* **2015**, *32*, 142. [CrossRef]
68. Kushner, B.; Edwards, P.; Burke, L.; Cooper, E. *Coastal Capital: Jamaica. Coral Reefs, Beach Erosion and Impacts to Tourism in Jamaica*; Working Paper; World Resources Institute: Washington, DC, USA, 2011.
69. Robinson, E.; Khan, S.; Coutou, R.; Johnson, M. Shoreline changes and sea-level rise at Long Bay, Negril, western Jamaica. *Caribb. J. Earth Sci.* **2012**, *43*, 35–49.
70. Cambers, G. Caribbean Beach Changes and Climate Change Adaptation. *Aquat. Ecosyst. Health Manag.* **2009**, *12*, 168–176. [CrossRef]
71. Rahmstorf, S. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. *Science* **2007**, *315*, 368–370. [CrossRef] [PubMed]
72. Bruun, P. The Bruun Rule of erosion by sea level rise: A discussion on large-scale two- and three-dimensional usages. *J. Coast. Res.* **1988**, *4*, 622–648.
73. Edelman, T. Dune erosion during storm conditions. In Proceedings of the 13th International Conference on Coastal Engineering (ASCE), Vancouver, BC, Canada, 10–14 July 1972; pp. 1305–1312.
74. Dean, R.G. Equilibrium beach profiles: Characteristics and applications. *J. Coast. Res.* **1991**, *7*, 53–84.
75. Komar, P.D. *Beach Processes and Sedimentation*, 2nd ed.; Prentice Hall: Hoboken, NJ, USA, 1998.
76. Nicholls, R.J.; Wong, P.P.; Burkett, V.R.; Codignotto, J.O.; Hay, J.E.; McLean, R.F.; Ragoonaden, S.; Woodroffe, C.D. Coastal Systems and Low-Lying Areas. In *Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC; Cambridge University Press: Cambridge, UK, 2007; Volume 4, pp. 315–356; ISBN 0-521-88010-6.
77. Corbella, S.; Stretch, D.D. Predicting coastal erosion trends using non-stationary statistics and process-based models. *Coast. Eng.* **2012**, *70*, 40–49. [CrossRef]
78. Duke, W.L.; Arnott, R.W.C.; Cheel, R.J. Shelf sandstones and hummocky cross-stratification: New insights on a stormy debate. *Geology* **1991**, *19*, 625. [CrossRef]
79. Webster, P.J. Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. *Science* **2005**, *309*, 1844–1846. [CrossRef]
80. Pomeroy, A.; Lowe, R.; Symonds, G.; Van Dongeren, A.; Moore, C. The dynamics of infragravity wave transformation over a fringing reef. *J. Geophys. Res.* **2012**, *117*, 11022. [CrossRef]
81. Storlazzi, C.; Elias, E.; Field, M.; Presto, M. Numerical modeling of the impact of sea-level rise on fringing coral reef hydrodynamics and sediment transport. *Coral Reefs* **2011**, *30*, 83–96. [CrossRef]
82. Bradley, K.; Houser, C. Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. *J. Geophys. Res.* **2009**, *114*, 1–13. [CrossRef]
83. Paul, M.; Amos, C.L. Spatial and seasonal variation in wave attenuation over Zostera noltii. *J. Geophys. Res.* **2011**, *116*. [CrossRef]
84. Paul, M. The protection of sandy shores—Can we afford to ignore the contribution of seagrass? *Mar. Pollut. Bull.* **2018**, *134*, 152–159. [CrossRef] [PubMed]

85. Harley, M.D.; Turner, I.L.; Short, A.D. New insights into embayed beach rotation: The importance of wave exposure and cross-shore processes. *J. Geophys. Res.* **2015**, *120*, 1470–1484. [CrossRef]
86. Larson, M.; Kraus, N. *SBEACH: Numerical Model to Simulate Storm-Induced Beach Change*; Technical Report CERC 89-9; US Army Corps of Engineers, Waterway Experiment Station: Vicksburg, MS, USA, 1989.
87. Leont'yev, I.O. Numerical modelling of beach erosion during storm event. *Coast. Eng.* **1996**, *29*, 187–200. [CrossRef]
88. Roelvink, D.; Reniers, A.; van Dongeren, A.; van Thiel de Vries, J.; Lescinski, J.; McCall, R. *Xbeach Model Description and Manual*; Unesco-IHE Institute for Water Education; Deltares; Delft University of Technology: Delft, The Netherlands, 2010; 106p.
89. Abbott, T. Shifting Shorelines and Political Winds–The Complexities of Implementing the Simple Idea of Shoreline Setbacks for Oceanfront Developments in Maui, Hawaii. *Ocean Coast Manag.* **2013**, *73*, 13–21. [CrossRef]
90. Rupp-Armstrong, S.; Nicholls, R.J. Coastal and Estuarine Retreat: A Comparison of the Application of Managed Realignment in England and Germany. *J. Coast. Res.* **2007**, *236*, 1418–1430. [CrossRef]
91. Narayan, S.; Beck, M.W.; Reguero, B.G.; Losada, I.J.; van Wesenbeeck, B.; Pontee, N.; Sanchirico, J.N.; Ingram, J.C.; Lange, J.-M.; Burks-Copes, K.A. The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences. *PLoS ONE* **2016**, *11*, e0154735. [CrossRef]
92. Bergillos, R.J.; Rodrıguez-Delgado, C.; Ortega-Sanchez, M. Advances in management tools for modeling artificial nourishments in mixed Beaches. *J. Mar. Syst.* **2017**, *172*, 1–13. [CrossRef]
93. Peduzzi, P. Sand, rarer than one thinks. *Environ. Dev.* **2014**, *11*, 208–218. [CrossRef]
94. Arkema, K.K.; Guannel, G.; Verutes, G.; Wood, S.A.; Guerry, A.; Ruckelshaus, M.; Kareiva, P.; Lacayo, M.; Silver, J.M. Coastal habitats shield people and property from sea-level rise and storms. *Nat. Clim. Change* **2013**, *3*, 913–918. [CrossRef]
95. Spalding, M.D.; Ruffo, S.; Lacambra, C.; Meliane, I.; Hale, L.Z.; Shepard, C.C.; Beck, M.W. The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean Coast. Manag.* **2014**, *90*, 50–57. [CrossRef]