Construction setback regulations and sea-level rise: Mitigating sea turtle nesting beach loss

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Abstract

Global sea-level rise of up to 0.6 m is predicted in the next 100 years. In areas where coastal structures prevent landward migration of beaches, a major impact of sea-level rise will be a loss of beach habitat, with repercussions for beach-dependent organisms such as sea turtles. Setback regulations, which prohibit construction within a set distance from the sea, have the potential to mitigate loss of beach area by providing a buffer zone which allows for the natural movement of beaches in response to perturbation. The potential impact of a rise in sea level on 11 important sea turtle nesting beaches in Barbados under a range of setback regulations was determined. Three sea-level rise scenarios were modelled under five different setback regulations (10, 30, 50, 70 and 90 m). Beach area was lost from all beaches under all sea-level rise scenarios with a 10 and 30 m setback, from some beaches with a 50 m setback and from one beach with a 70 m setback. No beach area was lost with a 90 m setback distance. Sea turtles nest within a range of beach elevations and there was an overall loss of beach habitat within the preferred nesting elevation range with both a 10 and 30 m setback under all sea-level rise scenarios. Considerable variation in the extent of beach and nesting area loss was observed. The implementation and enforcement of adequate setback regulations have the potential to maintain the ecological and economic function of beaches in the face of extensive coastal development and sea-level rise.
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1. Introduction

One of the impacts of the changing climate is a projected rise in sea level of between 18 and 59 cm by the year 2090–2099 [1]. The consequences of a rise in sea level are likely to include more extensive coastal flooding, inundation of low-lying coastal areas and heightened coastal erosion [2,3]. The extent to which individual coastlines will be affected by sea-level rise is strongly determined by local physical, biological and socio-economic conditions [4],

but under natural conditions, beaches are expected to shift landward in response to rising seas [5]. The scope for this migration to occur will depend, however, on the land-use behind the beach and whether the inland retreat of habitat is restricted [6,7]. Where buildings or other hard structures constrain landward beach recession, erosion can occur [8]. This enhanced erosion will often occur against a background of already altered natural seasonal cycles of erosion and accretion, for example as a result of the interruption of littoral transport by groynes and jetties, reduction of sediment input, or increased wave energy as a result of reef damage [9]. Loss of beaches as a result of sea-level rise is therefore of particular concern in areas where the coastal zone has been extensively modified by humans. This is the case in many small island nations, where most of the limited flat land on which to build lies near the coast.

Management responses to beach recession and erosion can be divided into three broad categories: protect, accommodate, or retreat [4]. The traditional response to localised erosion has been the construction of sea walls or equivalent 'hard' structures designed to protect buildings, with little consideration of their impact on ecosystem processes [10,11]. While some structures can promote sand accretion in small areas, local currents and sand transportation patterns are often altered over much larger distances, causing erosion at points further along the coast [12]. The realisation that these reactive solutions can actually increase erosion has resulted in a shift towards 'soft' methods [13], such as beach nourishment, dune building and artificial reefs, which simulate natural structures. An alternative option, accommodation, involves the continued use of vulnerable areas and acceptance of the risk to property and beach area. As more sustainable approaches to coastal management have evolved, retreat is increasingly being considered as a realistic option. The method of retreat depends largely on the extent of current coastal development. Setback regulations, which prohibit construction within a certain distance from the sea, are a pre-emptive retreat strategy. In locations that are already extensively developed, coastal realignment may be necessary. In this case, buildings are moved back a certain distance from the sea.

The method implemented in any particular locale is largely determined by local factors [4], but setbacks or coastal realignments have several advantages over traditional beach protection structures. Most notably they provide a buffer area which can simultaneously accommodate the naturally dynamic nature of beaches [14] and provide protection for coastal property [15]. The latter is realised simply because beachfront property is located further away from the immediate impacts of storm waves. In addition, buildings set back from the beach provide privacy for property owners and better access for beach users.

Maintaining beach area yields clear ecological and economic benefits. Beaches have obvious economic importance, specifically for many tropical islands in their capacity as a major tourism resource [16]. In this paper, however, the focus is largely on the ecological function of beaches, in particular as sea turtle nesting habitat; sea turtles depend on sandy beach habitat for nesting. As nesting populations increase owing to successful conservation efforts [17−19], there is a growing need to maintain the habitat on which these species depend for reproduction. In many areas, the quality of nesting beaches has already been compromised by beachside construction, exposing sea turtles to lights, activity, noise and altered physical characteristics, all of which can affect nesting success [20]. As sea levels rise and beaches are squeezed between development and an advancing sea, females are forced to nest in a relatively narrower band, exposing them not only to the impacts of development but also to a greater risk of nest overlap and saltwater inundation of their nests.

Incorporating ecological requirements of wildlife into coastal planning is an essential part of integrated coastal management. On the Caribbean island of Barbados, conservation efforts have resulted in an increase in hawksbill turtle nesting to a current level of approximately 2000 nests annually (J.A. Horrocks, unpublished data). Many of the beaches used for nesting, however, lie on two of the most developed stretches of coastline in the Caribbean. The aim of this study was to examine the impacts of projected sea-level rise scenarios on sea turtle nesting beaches in Barbados and determine the potential for existing setback regulations to mitigate loss of sea turtle nesting area. Using a Geographic Information System (GIS) to produce beach models of the main Barbadian nesting beaches, beach area loss was examined under a range of sea-level rise and setback regulation scenarios.

2. Study area

Barbados (59°35′W, 13°10′N) is the easternmost island of the West Indies. The island has an area of 430 km^2 and is relatively flat, rising gently to the central highland region. Due to its low elevation and low-lying coastal plain, Barbados is classified as vulnerable to sea-level rise [3]. Beaches have considerable economic and environmental importance in Barbados. Beach-based tourism is crucial to the economy of the island and accounts for more than half (56%)

of export earnings, with annual visitor numbers exceeding the resident population by approximately two to one [21]. Use of Barbados' beaches has been valued at $24 million annually [22]. The beaches also provide nesting habitat for one of the Caribbean region's largest hawksbill (*Eretmochelys imbricata*) turtle nesting populations [19]. Nesting activity has been monitored using standardised effort on high-density nesting beaches since 1997, and the numbers show an upward trend [19]. Currently, approximately 2000 nests per year are laid, mostly on the south-west and west coasts of the island. The highest nesting density occurs at Needham's Point on the south-west coast, where one of the study sites, Drill Hall, was located.

Beaches on the west and south coasts of Barbados are fairly uninterrupted and are composed of coralline particles derived from the reef offshore. Beach characteristics around the island vary seasonally, depending on the prevailing wind and sea conditions. Easterly or north-easterly winds exist over the Caribbean Sea in winter, shifting to predominantly easterly or south-easterly winds in summer [23]. The more exposed windward beaches in Barbados are therefore located on the northern and eastern coastline, with the lowest wave energy being found on the west coast [24]. Most of the leeward beaches have been modified from their natural state, primarily by development for tourism, and there are consequently very few undeveloped beachfront areas along the west and south coasts [25].

3. Methods

3.1. Data collection and processing

The setback regulations currently in place for islands in the Caribbean were found from recent literature ($<$ 2 years old), or through contact with the appropriate government agency responsible for building regulations. Using a method similar to that of Fish et al. [6], beach profile measurements were used to create digital models of 11 beaches on the west and south-west coasts (Fig. 1). The beach models were then used to simulate a number of different sea-level rise (SLR) scenarios, under a range of setback regulations. Beach profile measurements were taken at the 11 beaches in late May 2002, immediately prior to the June–September period of peak hawksbill nesting activity in Barbados [19]. The profile of each beach was measured relative to the high water mark at changes in profile or direction, using a 60-m measuring tape and standard surveying techniques [26,27]. For georeferencing purposes, *x* and *y* (UTM/UPS WGS 84) coordinates were taken at the landward end of each profile using a hand-held global positioning system unit (Garmin GPS III® Plus, Garmin International Inc., Olathe) with an estimated error of 2.5–3.0 m. The bearing of each profile was also recorded and the coordinates of each point along the profile relative to the initial GPS point were then calculated using this bearing and measurements of horizontal distances between points.

Distance and slope measurements for each profile were used to calculate the elevation of each profile point, which were added to the coordinate points. GIS software (ESRI ArcGIS 8.3) was used to develop triangulated irregular network (TIN) models from the derived *x*, *y* and *z* UTM coordinates for each point, and these models were converted to 1 m^2 horizontal resolution Digital Elevation Models (DEMs) in the form of raster grids for each beach. Elevation was recorded in centimetres. For each beach model, the average slope, width, elevation and maximum elevation were found.

The IPCC Third Assessment Report projected that global mean sea levels may be expected to rise between 0.09 and 0.88 m between the years 1990 and 2100 [27]. The Fourth Assessment Report projected rises of between 0.18 and 0.59 by 2090–2099, although the upper ranges could increase by 0.1–0.2 m if recently observed increases in ice flow from Greenland and Antarctica were to increase linearly with the global mean temperature change [1]. On the basis of these projections, three scenarios of a 0.1, 0.5 and 0.9 m rise in sea level were used in the analyses.

The response of sandy beaches to a rise in sea level is generally assumed to be a landward and upward shift of the beach [5,28] and the rate of predicted global sea-level rise should allow most beaches to move in response. Although unlikely, it is also possible that beach movement could be constrained such that the current beach area is flooded. For the purpose of comparison, both these situations were examined, firstly assuming no beach movement and therefore inundation of the current beach area and secondly assuming beach movement in response to sea-level rise.

3.2. Beach and nesting area loss assuming no beach retreat

For the first part of the analyses, beach movement was assumed to be fully constrained such that no landward shift could occur and therefore rising sea levels would result in flooding of the current beach area. The surface area of each
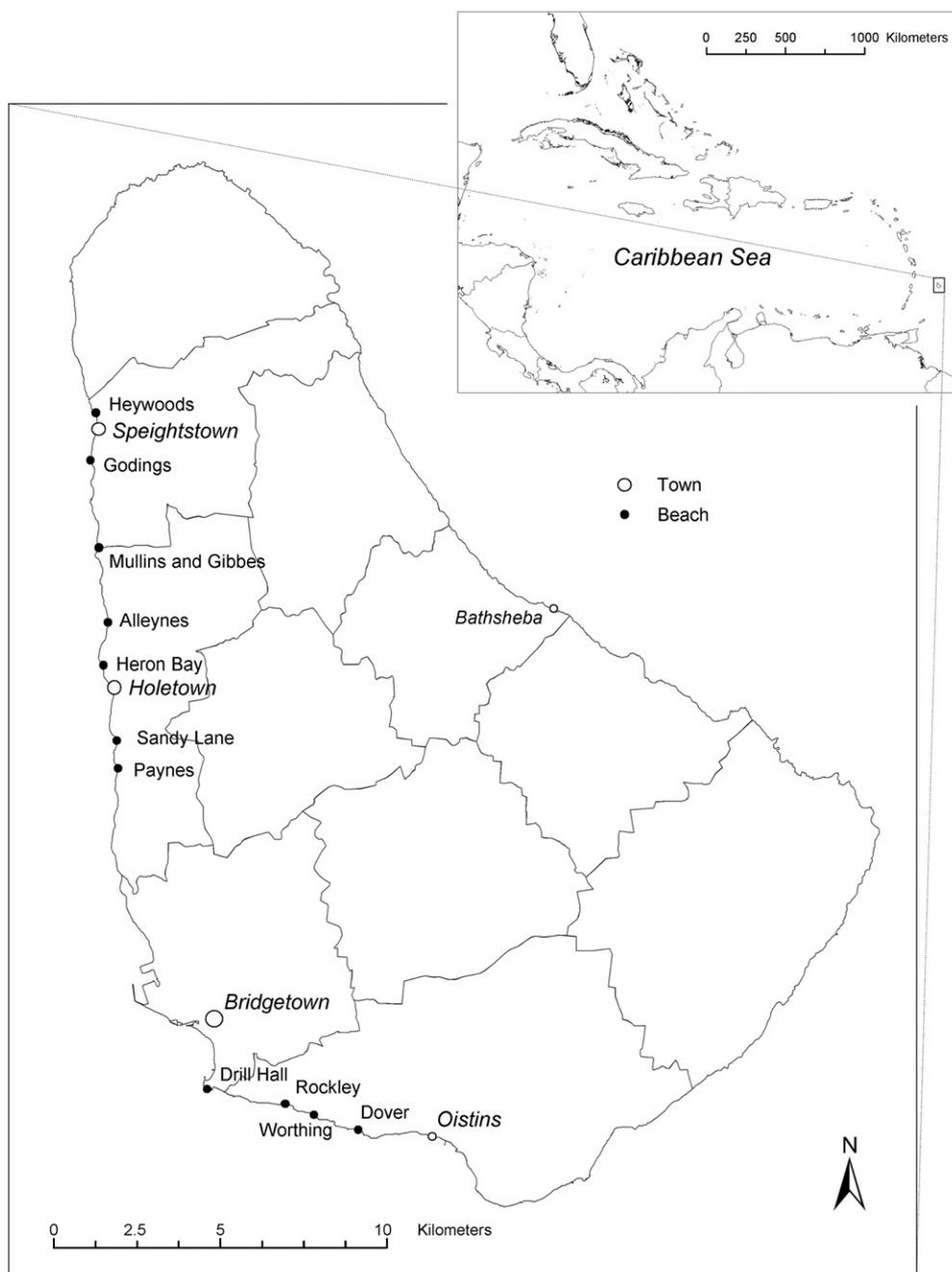
Fig. 1. Location of the study beaches around the island of Barbados.

beach grid below each of the elevations (0.1, 0.5 and 0.9 m) was found in order to identify the present area of beach that would be lost to inundation under each scenario.

Hawksbill nests occur at elevations between 0.3 and 1.8 m (mean 1.11 m) above mean sea level in Barbados [24]. These values were used to identify the area of beach currently lying within this elevation range and therefore the current nesting area. The nesting surface area inundated under each of the three sea-level rise scenarios was obtained, both in absolute and in relative (percentage) terms.

3.3. Beach and nesting area loss assuming beach retreat

A more likely scenario is that beaches can shift landward in response to sea-level rise. Models predict that as the sea level rises, wave energy will redistribute sand and move the beach landwards whilst maintaining the current beach profile; the extent to which the beach moves back depends on the slope of the shoreface. To estimate the extent of beach recession (R, in metres), the basic Bruun model [28] was used, which was reduced to:

$$R = \frac{1}{\tan\theta}S$$

where θ is the shoreface slope and S is the sea-level rise (in metres). Recession rate calculations were based on the current shoreface slope and assumed that no increase in beach area above the current level would occur (i.e. there would be no net increase in the available sediment in the future to widen beaches beyond their current size which, given the deterioration of reefs as providers of beach substrate, is not an unreasonable assumption).

New beach models, which accounted for a horizontal shift in beach position, were constructed for each combination of sea-level rise and setback distance. A building construction setback regulation of 30 m from the high water mark is currently in place for Barbados, while a survey of setback distances on the other Caribbean islands showed that they range from 10 to 81 m from the high water mark (HWM) (Fig. 2). To encompass this range, five different setback distances: 10, 30, 50, 70 and 90 m from the current HWM, were used in the models.

For each setback distance it was assumed that an immovable structure was located at that distance from the high water mark. As the beach retreats, beach area is maintained until the 'structure' is reached, beyond which the beach is lost. For example, if a 30 m setback is in place on a 25-m wide beach and the beach is predicted to shift horizontally by 10 m (as estimated by Bruun's rule), then 5 m of the shifted back-beach area will be lost. Following the method outlined above, new beach DEMs were constructed for each sea-level rise scenario and setback distance. Total beach surface area and the area within the preferred sea turtle nesting elevation range were then measured, and the percentage area lost from the original beach calculated.

Associations between physical features of the beach (total area, beach length, mean and maximum elevation, mean width and mean and maximum slope), sea turtle nesting area and the level of beach vulnerability were assessed using Pearson correlation tests. Beach vulnerability was measured as the proportion of the total area of each beach lost after
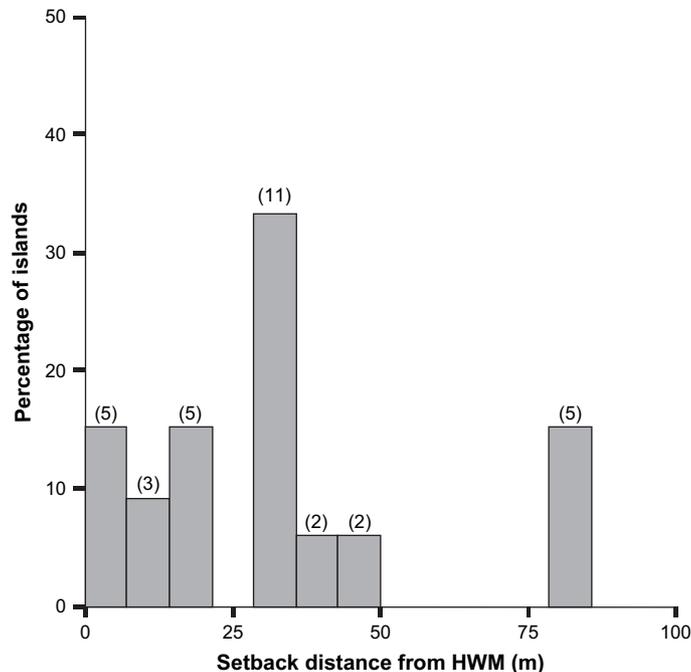

Fig. 2. Setback distances set out in regulations for 33 islands in the Caribbean region.

an intermediate (0.5 m) scenario of sea-level rise and a 10 m setback. Differences in vulnerability between the coastlines were tested using Mann−Whitney U tests.

4. Results

4.1. Beaches and physical characteristics

The 11 beaches studied represented a total of 8.6 km of the coastline and an area of 168 410 m^2. Of the beaches surveyed, only two were wider than 30 m from the high water mark to the widest point of the beach. Beach characteristics often vary with aspect, and beaches on the two coasts differed in their physical characteristics (Table 1), which could affect the vulnerability to sea-level rise (SLR). West coast beaches were significantly narrower (Mann−Whitney $U = 0$, $n = 11$, $p = 0.008$) and steeper (Mann−Whitney $U = 1.0$, $n = 11$, $p = 0.014$) and had a higher maximum elevation (Mann−Whitney $U = 1.0$, $n = 11$, $p = 0.014$) than the south coast beaches. Although the mean elevation was on average higher on west coast beaches, the difference was not significant (Mann−Whitney $U = 7$, $n = 11$, $p = 0.19$).

4.2. Vulnerability of beach and nesting areas to loss assuming no beach retreat

Under an intermediate rise in sea level (0.5 m), 26% of the total beach area (all beaches combined) would be lost, with the total losses ranging from 4% to 51% after a rise of 0.1 and 0.9 m, respectively. The average proportion of area potentially lost from any individual beach under a 0.5 m rise was 29% (±12% S.D.; range: 13%−46%). Using the proportion of total area lost under a mid-range scenario (0.5 m), Drill Hall beach was identified as the least vulnerable beach and Heron Bay beach as the most vulnerable.

Eighty percent (133 909 m^2) of the total beach area surveyed was in the preferred nesting elevation range (i.e. 0.3−1.8 m). For individual beaches, on average, 78% (±11% S.D.; range: 54%−94%) of the beach lay within this elevation range. This proportion did not differ significantly between the two coasts (south: 86.0 ± 8.16%, west: 72.8 ± 10.4%; Mann−Whitney $U = 4$, $n = 11$, $p = 0.06$).

4.3. Vulnerability of beach and nesting areas assuming beach retreat and variable setback distances

The most common setback distance in a survey of 33 Caribbean islands was 30 m, the same as in Barbados (Fig. 2). A third of the islands surveyed had a setback of 30 or 30.5 m, 15% had no setback regulation currently in place and 15% had a distance of 81 m.

Landward shift of beaches with a rise in sea level was constrained by 10, 30, 50 and 70 m setback distances, but not by a 90 m setback distance (Fig. 3). All the beaches lost some area with 10 and 30 m setbacks; five beaches were also affected by a 50 m setback and one, Drill Hall, was affected by a 70 m setback. Fig. 3 shows the average proportion of beach habitat lost under each of the setback regulations for each sea-level rise scenario. As expected, a greater proportion of beach area was lost with larger changes in sea level. With a 10 m building setback in place, an average of 41% (±17% S.D.) of the current beach area was lost with a 0.1 m SLR, increasing to an average of 93% (±13% S.D.) with a 0.9 m SLR. Six beaches (Alleynes, Godings, Heron, Heywoods, Mullins and Sandy Lane Bay beaches)

Table 1

Minimum, maximum and mean values ± 1 S.D. of physical beach characteristics and vulnerability scores for beaches on the west and south coasts of Barbados

Physical variable	Min.	Max.	West coast (mean ± 1 S.D.)	South coast (mean ± 1 S.D.)	U	p
Beach length (m)	363	1152	833 ± 327	681 ± 270	10	0.450
Beach mean elevation (cm)	0.5	1.3	0.94 ± 0.27	0.76 ± 0.24	7	0.186
Beach maximum elevation (cm)	1.25	3.09	2.20 ± 0.50	1.47 ± 0.15	1	0.014
Beach slope (°)	1.8	5.8	4.67 ± 0.89	2.46 ± 0.56	1	0.014
Beach width (m)	11	45	16.45 ± 3.56	29.0 ± 11.56	0	0.008
Vulnerability to SLR	0.53	0.90	0.75 ± 0.10	0.64 ± 0.15	6	0.131

Vulnerability to sea-level rise (SLR) was measured as the proportion of the total area of each beach lost after a 0.5 m SLR in the presence of a 10 m setback regulation. West coast beaches, $n = 7$; South coast beaches, $n = 4$. Mann−Whitney U and p values are given.
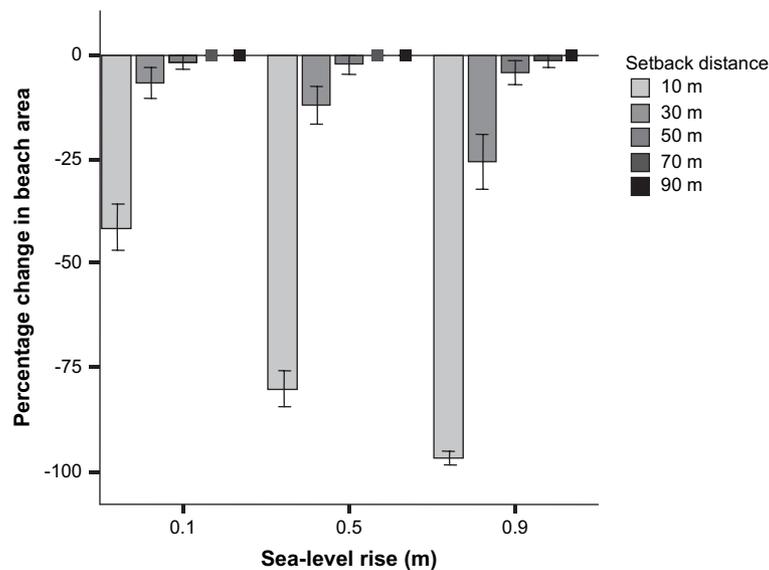
Fig. 3. Proportion of beach area lost in Barbados under each of the three sea-level rise scenarios with 10, 30, 50, 70 and 90 m setback regulations. Means are shown ± 1 S.E. $N = 11$ beaches in all cases.

disappeared completely under the most extreme sea-level rise scenario with a 10 m setback. A similar pattern was seen with 30 and 50 m setbacks, although less beach area was lost (Fig. 3). The proportion of beach lost decreased significantly as setback distance increased ($r = -0.86$, $n = 11$, $p < 0.001$) and varied considerably between beaches. With a 10 m setback and a 0.5 m SLR, the loss ranged from 53% (Rockley) to 90% (Sandy Lane) of the original beach area. With a 30 m setback the range was 0% (Dover) to 50% (Drill Hall). Only one beach, Drill Hall, exhibited any loss with setback distances greater than 50 m. With a 70 m setback, this beach lost 17% of its area under a 0.9 m SLR.

Vulnerability, taken as the proportion of beach lost under a 0.5 m SLR with a 10 m setback, was on average 75% for the west coast and 64% for the south-west coast (Mann–Whitney $U = 6$, $n = 11$, $p = 0.13$). Beach vulnerability was not significantly related to any of the measured beach physical characteristics: total area, beach length, mean and maximum elevation, mean width and mean and maximum slope (all $r < 0.56$, $p > 0.07$).

The amount of hawksbill nesting area remaining after beach movement varied with both setback distance and sea-level rise level (Fig. 4). With 10 and 30 m setbacks, there was an overall decrease in nesting area with rising sea level, although the loss was significantly less severe with a 30 m than a 10 m setback for all sea-level rise scenarios (Wilcoxon signed rank tests: 0.1 m SLR: $T = 0$, $n = 11$, $p = 0.004$; 0.5 m SLR: $T = 0$, $p = 0.003$; 0.9 m SLR: $T = 0$, $p = 0.003$). Beaches varied in the extent of nesting habitat loss. Under a 10 m setback and a 0.5 m SLR all beaches lost nesting area, and the percentage of the original nesting area lost ranged from 62% to 100%. With a 30 m setback, the loss ranged from 0.5% to 50% of the original nesting area.

5. Discussion

The variable implementation of setback regulations on many Caribbean islands motivated this study of the potential effects of these restrictions on beach area, and specifically on sea turtle nesting habitat, in the face of rising sea level. The majority of islands examined, including Barbados, currently have a 30–30.5 m setback distance. If beaches did not shift at all in response to sea-level changes, an average 26% of the beach area would be lost under an intermediate sea-level rise scenario. Based on the more realistic assumption that beaches will retreat in response to a rise in sea level, the 10, 30, 50 and 70 m setbacks all resulted in some loss of beach habitat on Barbados under various sea-level rise scenarios. As would be expected, the beach area lost increased with increasing sea-level rise, and loss of area was significantly higher with a 10 m setback regulation than with a 30 m setback. Sea turtle nesting area would also be lost
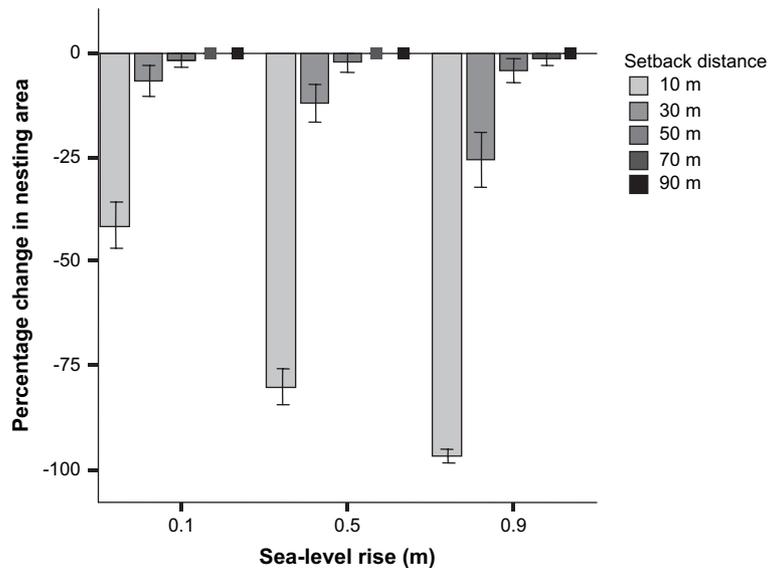
Fig. 4. Percentage change in hawksbill turtle nesting area under each of the three sea-level rise scenarios with 10, 30, 50 and 70 m setback regulations in Barbados. Negative change indicates a loss in area. Means are shown ± 1 S.E. $N = 11$ beaches in all cases.

under 10 and 30 m setback regulations, with significantly more loss with a 10 m than a 30 m setback. Considerable variation was seen between beaches in the extent of loss to inundation (i.e. if beaches do not retreat) and total loss of beach area and nesting habitat after beach retreat.

The beach at Drill Hall, on the south coast of Barbados, stands out as the least vulnerable to beach loss through inundation if no beach migration occurred, but was one of the most vulnerable in terms of the proportion of area lost to development built at all setback distances. The area loss predicted for this beach, even with the longest setback distances, was due primarily to its shallow slope and exceptional width among the beaches studied. A higher proportion of beach area would therefore be lost if the beach was subsequently developed up to any of the setback distances. It is, however, unlikely that Drill Hall will be fully developed along its length up to the shortest setback distances as assumed by the model, as this would mean building directly on the beach. The width of this beach (average width = 46 m), as compared to the others on the west and south coasts, is likely a result of its more natural state. It is notable that this area is also the most intensely used hawksbill nesting habitat on the island, which is also probably an outcome of its more natural condition and stability over long periods of time.

Studies examining the impacts of sea-level rise on a similar scale to this study have found comparable levels of area loss and variability among beaches. Fish et al. [6], for example, found a similar proportion of beach loss to inundation predicted for the southern Caribbean island of Bonaire, with an average of 38% of the original beach area lost with a 0.5 m rise in sea level. The percentage loss also ranged widely, from 11% to 83%, between beaches on Bonaire. For the north-western Hawaiian islands, losses ranging from 3% to 65% of the terrestrial habitat were predicted with 0.48 m rise in sea level, with potential impacts on seabird, green sea turtle (*Chelonia mydas*) and Hawaiian monk seal (*Monachus schauinslandi*) populations which rely on the coastal habitat to breed [29]. Similar results were found by Galbraith et al. [30] for intertidal shorebird habitat in the United States where the loss ranged from 20% to 70% of the current area.

Any attempt to predict the response of beaches to sea-level rise is subject to uncertainty [31], which can arise from the uncertainty in sea-level rise predictions themselves as well as how beaches will respond to these changes in sea level. To minimise potential error arising from uncertainty in the predictions of sea-level rise, a range consistent with IPCC sea-level rise projections [1,27] was used which enabled us to simulate a wide range of possible future beach conditions [5]. Uncertainty arising from estimating how beaches will respond to sea-level rise is harder to address. As with previous studies [32,33], estimates of future beach recession were based on the Bruun model [28]. This model has been criticised [34], largely because it has been applied to situations that violate its assumption that the system is essentially 'closed' with no loss of sediment landward, offshore or alongshore. While the

conditions under which the model would perfectly estimate recession probably do not exist in nature, the Bruun model was deemed to be the most appropriate existing model for estimating future beach loss in Barbados. Sand movement landward is constrained by buildings on most beaches and offshore movement is limited by a bank reef offshore. Alongshore sediment transport does occur but at low levels; many of the beaches are separated by headlands with associated fringing reefs which limit sand transport between bays. Barbadian beaches do approach the conditions assumed by the Bruun model [35] and therefore the calculated recession rates are likely to be a reasonable representation of future beach shifts. The model assumes that long-term profiles are maintained and it is worth considering circumstances which might alter the current conditions. Loss of reef structure due to reef degradation at the ends of bays and offshore could enable more sediment to flow out of the system. In addition, construction of jetties, groynes or offshore breakwaters designed to enhance beach area will clearly disrupt current sediment transport and alter beach profiles. The model also assumes that long-term profiles are maintained irrespective of seasonal fluctuations due to storms or hurricanes. Although the frequency of severe storms is not projected to increase in the future, there is some evidence of an increase in storm intensity [36]. More intense storms produce larger storm surge and could therefore be expected to alter future beach profile. As sea levels are currently rising and ensuing consequences are imminent, it can be argued that it is not an option to defer estimates of beach loss because of a lack of a more realistic model. Instead, beach-loss estimations should be performed using existing models, acknowledging that uncertainty surrounding these forecasts exists, and therefore using an appropriate level of caution in interpreting simulation outputs [31].

6. Management considerations

The results of this study suggest that the loss of sea turtle nesting habitat that may occur with predicted sea-level rise could be exacerbated by inadequate setback regulations. Clearly, on Barbados, a 10 m setback would be insufficient if preservation of turtle nesting habitat is a consideration in coastal management, since up to 100% of the nesting area on some beaches would be lost with an intermediate rise in sea level; there would also clearly be severe implications for beach tourism. While loss with a 30 m setback was less severe, there was still an average decrease of 12%. In addition, the potential loss of 26% of the nesting habitat on the island's most important hawksbill nesting beach (Drill Hall), even with a 30 m setback, is of concern.

Loss of nesting area has implications for the reproductive success not only of the island's hawksbill nesting population, but also regionally as Barbados has one of the largest hawksbill nesting populations in the Caribbean. In addition to density-dependent effects such as nest destruction by conspecifics and elevated levels of nest disease or predation [29,37], nesting success may also be detrimentally affected by the necessity of nesting closer to the water on smaller beaches. Hawksbill nests laid closest to a mean elevation of 1.11 m above the mean water show the highest nest success on Barbados, while those laid higher or lower fare more poorly [24]. Whilst a number of management options can preserve beach area, another advantage of setbacks is that beaches remain in a natural state, maintaining vegetation, sand characteristics and morphology. The preference of hawksbills for Drill Hall, one of the few largely unmodified beaches in Barbados, highlights the importance of beach condition for turtle nesting. For islands that are devoting resources to regulating the harvest of endangered sea turtle populations and into boosting current nesting populations, there is a need to adequately protect critical habitat if long-term recovery is to be achieved. To assist in the sustainability of conservation efforts for sea turtles, the setback regulations in place must be sufficient to take into account future changes to the ecosystem.

The observed variation in the responses of individual beaches to sea-level rise provides support for the implementation of variable setback distances within an island. Drill Hall, for example, would benefit more from a larger setback distance than other beaches, in order to maintain its extreme width. Currently, half of the beach front is developed, while the other half is separated from an old oil refinery site and military cemetery behind by a thin, but significant, strip of land. These areas are under pressure from development and a hotel is currently being built on the oil refinery site. In this case, different setbacks could be put in place for the developed and undeveloped sections of the beach. The undeveloped land immediately adjacent would facilitate natural beach movement and would ensure that this beach continues to provide sufficient hawksbill nesting habitat in the future, as well as recreational space for the high density of tourists from adjacent hotels. Variable setbacks have been implemented on a small number of Caribbean islands, where the distances are based on the elevation normally reached by high seas [38,39] or beach slope [40]. If setbacks are to protect habitat in the long-term then it can be argued that they should take the most conservative approach which

includes all possible sources of beach recession. To address this concern, more comprehensive setback calculations have been suggested by Cambers [38] and Gibbs (1995) in [41], based on the cumulative change in coastline position predicted from historical and recent erosion data, from a major hurricane, coastal recession as a result of projected sea-level rise and dune stability. Efforts such as the 'Coast and Beach Stability in the Caribbean' program [42], which initiated the regular monitoring of beach profiles on 13 islands or island groups in the Caribbean region, can provide the data for these more comprehensive setback calculations.

While the benefits, in terms of long-term beach maintenance, to be accrued from adequate setback regulations are clear, consideration must also be given to issues which can hinder the implementation or effectiveness of setbacks. The majority of islands surveyed have setback regulations; however, most of these have been implemented fairly recently and, depending on the stage of development of the tourism industry, much of the coastline had already been developed before the regulations were put into practice [43]. The aggregation of hotels in coastal areas has been a deliberate policy adopted by many governments in the past [44] and conflict now arises between coastal managers attempting to secure the safety and structure of beaches and coastal developers wishing to take advantage of the commercial viability of beachside property. In areas that are already extensively developed, coastal realignment is an alternative, or complementary, approach to the enforcement of setbacks. Hotels have an economic life of ca. 25−30 years before they need to be extensively renovated, converted or demolished [43]. At the end of this life span there is scope for rebuilding further back from the water. This option may be more difficult on islands where there is limited flat land suitable for development. While coastal realignment is an expensive option, moving buildings back could minimise the likelihood of paying out considerable amounts in the future. For example, of the 6100 hotel rooms in Barbados, over 50% of the rooms are estimated to be at risk from a category 3 hurricane owing to their proximity to the mean sea level. Replacement costs range from US$60,000 to $100,000 per room, representing total replacement costs of US$330−550 million for damages inflicted by a single hurricane [44].

The goals of coastal management in response to sea-level rise should ideally be to ensure that development does not occur in areas vulnerable to flooding, that ecological systems can function naturally and that economic activities are protected [4]. Implementation, and enforcement, of setback regulations and coastal realignment have the potential to help fulfil these aims by preserving sufficient beach habitat to perform those ecological and economic roles. Conversely, islands without adequate setback regulations could suffer a considerable loss of beach habitat in the future. While social and economic pressures may hinder the implementation of setbacks, they represent a valuable tool for the long-term maintenance of beaches, and sea turtle nesting areas, in the Caribbean.

Acknowledgements

References

[1] IPCC. Climate change : the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

[2] Klein RJT, Nicholls RJ. Assessment of coastal vulnerability to climate change. Ambio 1999;28(2):182−7.

[3] Wong PP. Where have all the beaches gone? Coastal erosion in the tropics. Singapore Journal of Tropical Geography 2003;24(1):111−32.

[4] IPCC CZMS. Strategies for adaptation to sea level rise. Report of the coastal zone management subgroup. Response Strategies Working Group of the Intergovernmental Panel on Climate Change. Ministry of Transport, Public Works and Water Management, the Hague; 1990.

[5] Davidson-Arnott RGD. Conceptual model of the effects of sea level rise on sandy coasts. Journal of Coastal Research 2005;21(6):1166−72.

[6] Fish MR, Cote IM, Gill JA, Jones AP, Renshoff S, Watkinson AR. Predicting the impact of sea-level rise on Caribbean sea turtle nesting habitat. Conservation Biology 2005;19(2):482−91.

[7] McLean RF, Tsyban A, Burkett V, Codignotto JO, Forbes DL, Mimura N, et al. Coastal zones and marine ecosystems. In: Bijlsma L, Sanchez-Arevalo I, editors. Climate change 2001: impacts, adaptation and vulnerability. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2001. p. 343−79. Contribution of working group II to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC).

[8] Cambers G. Coping with shoreline erosion in the Caribbean. Nature and Resources 1999;35(4):43–9.

[9] Bird ECF. Sea level rise and coastline changes, Submerging coasts: the effects of a rising sea level on coastal environments. New York: John Wiley and Sons Ltd; 1993. p. 48–101.

[10] Airoldi L, Abbiati M, Beck MW, Hawkins SJ, Jonsson PR, Martin D, et al. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coastal Engineering 2005;52(10–11):1073–87.

[11] Jones A, Gladstone W, Hacking N. Sandy-beach ecosystems and climate change: potential ecological consequences and management implications. In: Proceedings coast to coast 2004: Australia's national coastal conference, Hobart; 2004. p. 6.

[12] Frihy OE. The necessity of environmental impact assessment (EIA) in implementing coastal projects: lessons learned from the Egyptian Mediterranean Coast. Ocean and Coastal Management 2001;44(7–8):489–516.

[13] Speybroeck J, Bonte D, Courtens W, Gheskiere T, Grootaert P, Maelfait JP, et al. Beach nourishment: an ecologically sound coastal defence alternative? A review. Aquatic Conservation: Marine and Freshwater Ecosystems 2006;16(4):419–35.

[14] French PW. Managed realignment – the developing story of a comparatively new approach to soft engineering. Estuarine, Coastal and Shelf Science 2006;67(3):409–23.

[15] Hayes MO. Beach erosion. In: Clark JR, editor. Coastal resources management: development case studies. Renewable Resources Information Series. Columbia, South Carolina: Research Planning Institute Inc.; 1985. p. 67–190.

[16] Dixon J, Hamilton K, Pagiola S, Segnestam L. Tourism and the environment in the Caribbean: an economic framework. Environmental economics series. Washington D.C.: Environment Department, The World Bank; 2001. 66 p.

[17] Broderick AC, Frauenstein R, Glen F, Hays GC, Jackson AL, Pelembe T, et al. Are green turtles globally endangered? Global Ecology and Biogeography 2006;15(1):21–6.

[18] Dutton DL, Dutton PH, Chaloupka M, Boulon RH. Increase of a Caribbean leatherback turtle, *Dermochelys coriacea*, nesting population linked to long-term nest protection. Biological Conservation 2005;126(2):186–94.

[19] Krueger B, Horrocks JA, Beggs J. Increase in nesting activity by hawksbill turtles (*Eretmochelys imbricata*) in Barbados. In: Seminoff JA, editor. Proceedings of the twenty-second annual symposium on sea turtle biology and conservation. NOAA Technical Memorandum NMFS-SEFSC-503; 2002. p. 149.

[20] Witherington BE. Behavioral responses of nesting sea-turtles to artificial lighting. Herpetologica 1992;48(1):31–9.

[21] McElroy JL. Tourism development in small islands across the world. Geografiska Annaler 2003;85(B):231–42.

[22] Dharmaratne GS, Braithwaite AE. Economic valuation of the coastline for tourism in Barbados. Journal of Travel Research 1998;37(2):138–44.

[23] Sheng JY, Tang LQ. A numerical study of circulation in the western Caribbean sea. Journal of Physical Oceanography 2003;33(10):2049–69.

[24] Horrocks JA, Scott NM. Nest site location and nest success in the hawksbill turtle *Eretmochelys imbricata* in Barbados, West-Indies. Marine Ecology Progress Series 1991;69(1–2):1–8.

[25] Horrocks JA, Vermeer LA. Environmental correlates of nesting and hatching seasonality of hawksbill turtles (*Eretmochelys imbricata*) in Barbados. In: Proceedings of the twelfth annual workshop on sea turtle biology and conservation. NOAA Technical Memorandum NMFS-SEFSC-361; 1992. p. 200.

[26] Cambers G. Coast and beach stability in the Caribbean islands COSALC. St John, United States Virgin Islands beach monitoring field manual. Report prepared for UNESCO-CSI and the University of Puerto Rico Sea Grant College Program. Paris: UNESCO; 1998. http://www.unesco.org/csi/act/cosalc/stjohn.htm.

[27] Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X. Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2001. 944 pp.

[28] Bruun P. Sea level rise as a cause of shore erosion. Journal of the Waterways and Harbors Division 1962;88:117–30.

[29] Baker JD, Littnan CL, Johnston DW. Potential effect of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the northwestern Hawaiian Islands. Endangered Species Research 2006;4(1):1–10.

[30] Galbraith H, Jones R, Park R, Clough J, Herrod-Julius S, Harrington B, Page G. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Waterbirds 2002;25(2):173–83.

[31] Cowell PJ, Thom BG, Jones RA, Everts CH, Simanovic D. Management of uncertainty in predicting climate-change impacts on beaches. Journal of Coastal Research 2006;22(1):232–45.

[32] Hennecke WG, Greve CA, Cowell PJ, Thom BG. GIS-based coastal behavior modeling and simulation of potential land and property loss: implications of sea-level rise at Collaroy/Narrabeen Beach, Sydney (Australia). Coastal Management 2004;32(4):449–70.

[33] Leatherman SP, Douglas BC, Crowell M. Beach erosion trends and shoreline forecasting. Journal of Coastal Research 1997;13(4):R3–4.

[34] Pilkey OH, Cooper JAG. Climate, society and sea-level rise. Science 2004;303:1781–2.

[35] Atherley K. Analysis of beach change on the Barbados coast. Coastal Conservation Project Unit, Government of Barbados; 1987.

[36] Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, et al. Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, editors. Climate change 2007: the physical science basis. Contributions of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

[37] Girondot M, Tucker AD, Rivalan P, Godfrey MH, Chevalier J. Density-dependent nest destruction and population fluctuations of Guianan leatherback turtles. Animal Conservation 2002;5:75–84.

[38] Cambers G. Planning for coastline change – guidelines for construction setbacks in the eastern Caribbean Islands. CSI info. 4. Paris: UNESCO; 1997.

[39] Wason A, Nurse L. Planning and infrastructure standards. United Nations Human Settlements Programme and United Nations Development Programme. Nairobi: United Nations Centre for Human Settlements; 1994.

[40] Norville P. Environmental management issues related to low-income housing in Saint Lucia. Caribbean disaster mitigation project. Organization of American States, Unit of Sustainable Development and Environment; 2003.

[41] Daniel EB, Abkowitz MD. Development of beach analysis tools for Caribbean small islands. Coastal Management 2003;31(3):255–75.

[42] UNESCO. Monitoring beach changes as an integral component of coastal management. Final report of the project on: institutional strengthening of beach management capabilities in the Organisation of Eastern Caribbean States and the Turks and Caicos Islands. Report CSI info. 15. Paris: UNESCO; 2003.

[43] Cambers G, Muehlig-Hofmann A, Troost D. Coastal land tenure: a small islands' perspective. Report prepared for UNESCO-CSI and the University of Puerto Rico Sea Grant College Program. Paris: UNESCO; 2003.

[44] Jackson I. Potential impacts of climate change on tourism. OAS. Mainstreaming adaptation to climate change (MACC) project; 2002.