Predicting the Impact of Sea-Level Rise on Caribbean Sea Turtle Nesting Habitat

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Abstract: *The projected rise in sea level is likely to increase the vulnerability of coastal zones in the Caribbean, which are already under pressure from a combination of anthropogenic activities and natural processes. One of the major effects will be a loss of beach habitat, which provides nesting sites for endangered sea turtles. To assess the potential impacts of sea-level rise on sea turtle nesting habitat, we used beach profile measurements of turtle nesting beaches on Bonaire, Netherlands Antilles, to develop elevation models of individual beaches in a geographic information system. These models were then used to quantify areas of beach vulnerable to three different scenarios of a rise in sea level. Physical characteristics of the beaches were also recorded and related to beach vulnerability, flooding, and nesting frequency. Beaches varied in physical characteristics and therefore in their vulnerability to flooding. Up to 32% of the total current beach area could be lost with a 0.5-m rise in sea level, with lower, narrower beaches being the most vulnerable. Vulnerability varied with land use adjacent to the beach. These predictions about loss of nesting habitat have important implications for turtle populations in the region.*

Key Words: climate change, geographic information system (GIS), habitat loss, turtle nesting beaches

Predicción del Impacto del Incremento del Nivel del Mar Sobre el Hábitat de Anidación de Tortugas Marinas del Caribe

Resumen: *Es probable que el incremento proyectado en el nivel del mar aumente la vulnerabilidad de zonas costeras en el Caribe, que ya están bajo presión de una combinación de actividades antropogénicas y procesos naturales. Uno de los mayores efectos será la pérdida de hábitat de playa, que proporciona sitios de anidación a tortugas en peligro. Para evaluar los impactos potenciales del aumento en el nivel del mar sobre el hábitat de anidación de tortugas marinas, usamos medidas del perfil de playa en playas de anidación de tortugas en Bonaire, Antillas Holandesas, para desarrollar modelos de elevación de playas individuales en un sistema de información geográfica. Estos modelos posteriormente fueron utilizados para cuantificar áreas de playa vulnerables a tres escenarios diferentes de incremento de nivel del mar. También se registraron características físicas de las playas y fueron relacionadas con vulnerabilidad e inundación de la playa y con frecuencia de anidación. Las playas variaron en características físicas y por lo tanto en su vulnerabilidad a la inundación. Con un incremento de 0.5 m en el nivel del mar, se perdería hasta 32% del total de la superficie actual de playa, las playas más angostas son las más vulnerables. La vulnerabilidad varió con el uso de suelo adyacente a la playa. Estas predicciones sobre la pérdida de hábitat de anidación tienen implicaciones importantes para las poblaciones de tortugas en la región.*

Palabras Clave: cambio climático, pérdida de hábitat, playas de anidación de tortugas marinas, SIG

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Introduction

Coastal zones are among the most dynamic and productive areas on Earth and, as such, have attracted considerable population settlement and economic investment (Clark 1997). Many of these areas are particularly susceptible to coastal hazards such as storm surges and coastal erosion and, with the projected rise in sea level resulting from anthropogenic global warming, threats to coastal areas are increasing (Huang 1997).

Small island states such as those in the Pacific and the Caribbean are particularly vulnerable to sea-level rise because of their small physical size, high population density, and reliance on coastal resources (IPCC [Intergovernmental Panel on Climate Change] 2001*a*). In many cases, the majority of settlements, economic activity, infrastructure, and services are located at or near the coast, and local economies are often reliant on just a few sectors, such as tourism or agriculture (Nicholls 1998). Sea-level rise will have a range of physical impacts on small islands, including increased likelihood of coastal flooding, salinization of coastal wetlands and aquifers, and increased beach erosion and coastal land loss (Klein & Nicholls 1999).

Loss of beach habitat has both economic and environmental consequences in the Caribbean. Tourism is the main source of revenue for many Caribbean islands and the loss of beaches threatens this sector both indirectly, by loss of revenue, and directly, through loss of buildings (Potter 1996). Beaches also provide valuable ecological services in the form of natural protection for adjacent habitats such as lagoons and wetlands, and essential nesting habitat for endangered species such as marine turtles (Hendry 1993).

Six species of sea turtles nest on the mainland and island beaches of the Caribbean: the hawksbill (*Eretmochelys imbricata)*, loggerhead (*Caretta caretta),* green (*Chelonia mydas*), leatherback (*Dermochelys coriacea),* Kemp's ridley (*Lepidochelys kempii),* and olive ridley (*Lepidochelys olivacea).* Populations of all these species are declining throughout the region because of overexploitation, disease, incidental capture by fishers, and destruction of critical nesting habitat (Eckert 1995; Herbst & Jacobson 1995; Witham 1995; Pandav et al. 1997; Hall et al. 2000; Mortimer et al. 2000).

Turtles have evolved with continuous habitat alteration through natural coastal processes such as seasonal erosion and accretion and high-tide flooding. The extensive coastal development seen in the last 30 years on many Caribbean islands, however, has occurred within the time required by some turtle species to reach maturity, and the impacts of rapid habitat modification are only now starting to emerge. Aside from direct loss of nesting habitat, other factors associated with development, including artificial lighting, beach compaction, beach nourishment, noise and activity, pollution, and coastal defenses such as sea walls (Witherington 1992; Crain et al. 1995; Bouchard et al. 1998; Katselidis & Dimopoulos 1998) influence nesting success. This combination of factors compounds the threat of projected sea-level rise to nesting turtle populations.

Turtles nest on a variety of beach types, which may be affected in different ways by sea-level rise. The mechanisms by which nesting females choose a beach or site on a beach are poorly understood (Mortimer 1995). Turtle species share broad nesting requirements. They nest on exposed marine beaches in deep, relatively loose sand above high-tide level (Hendrickson 1995). There is, however, a great deal of inter- and intraspecific variation in preference in terms of more specific beach characteristics. These include a number of physical features, such as beach length, width, height, slope, orientation, and vegetation (Horrocks & Scott 1991; Mortimer 1995; Salmon et al. 1995; Kikukawa et al. 1999). All these features are likely to be affected by beach-front development and sea-level rise.

It is important to identify where and how known nesting areas might be affected by sea-level rise so that management can be effectively targeted. In this context a geographic information system (GIS) is a useful tool with which to map habitats in detail and assess the areas threatened by inundation.

We examined the nesting distribution of turtles on Bonaire, Netherlands Antilles, and determined the possible extent of beach habitat under threat as a result of various scenarios of sea-level rise. Four species of sea turtles—hawksbill and leatherback, both listed as critically endangered on the World Conservation Union (IUCN) Red List (IUCN 2003), and green and loggerhead, listed as endangered—nest on Bonaire, and suitable beach habitat is critical for their reproductive success. The identification of areas under threat can be used to guide coastal-management decisions.

Methods

Study Site and Turtle Nesting Population

The Caribbean island of Bonaire (12°12′N, 68°17′W), Netherlands Antilles, lies approximately 80 km north of Venezuela. Bonaire consists of the main island (288 km^2) and the smaller satellite island of Klein Bonaire (6 km^2). The coastal zone of the main island is characterized by rough rocky shores with small pocket beaches on the north and east coasts and less exposed west and south coasts. Klein Bonaire has Bonaire's longest stretch of sandy beach on its north and east shores, and higher energy shores are interspersed with smaller pockets of sand on the west coast. Fringing reefs and sea-grass beds around the islands support small populations of juvenile green and hawksbill turtles (Sybesma 1992).

Adult females of four turtle species nest on Bonaire and Klein Bonaire, with the majority of nesting attempts attributable to hawksbill and loggerhead turtles in a ratio of approximately 2:1. Occasional attempts by green and leatherbacks have been noted (Sybesma 1992).

Surveys of potential turtle nesting beaches have been conducted since 1993 by the Sea Turtle Club Bonaire (STCB), and we used these data to derive a relative measure of nesting activity on each beach. Surveys were conducted from March to December each year, with the majority of nesting recorded from June to August. Because surveys were only carried out during the day, the identification of actual nest locations was difficult and a distinction between false crawls and actual nests was not possible. Signs of attempted nesting include body pits that females dig into the sand before they dig the nest chamber for the eggs, along with the distinctive tracks left as the female moves across the beach. To control for annual variation in survey extent and frequency, we took the nesting level on each beach as the mean number of recorded nesting attempts per survey from 1993 to 2000. The STCB has divided the continuous stretch of beach on Klein Bonaire into eight sectors (Fig. 1) for survey and data analysis purposes, and we used the same sectors in our study. The mainland and Klein Bonaire support small turtle nesting populations, approximately 7–8 and 14 individual females, respectively.

Measurement of Beach Characteristics

Because no preexisting data on beach profiles were available, we collected profile measurements and used a GIS (ArcView v.3.2, ESRI, Redlands, California) to develop elevation models of 13 of the nesting beaches on the mainland and on Klein Bonaire. Fieldwork was carried out in April and May 2002, when we measured the profile of each beach relative to the high-water mark at 50-m intervals, using a 60-m measuring tape and standard surveying techniques (Cambers 1998). We assessed the accuracy of the surveying technique in a blind trial and all measurements were within 0.5° ($n = 16$), which is within rounding error. Additional data recorded for each profile included compass bearings and identification of offshore substratum. For georeferencing purposes, x and y (UTM/UPS WGS 84) coordinates were taken at the start and end of each beach using a handheld global positioning system (Garmin GPS III Plus, Garmin International, Olathe, Kansas; estimated error 2.5 to 3.0 m). We used GPS readings solely to georeference the start point of each beach. All subsequent points that we used in the model were measured manually relative to the start point.

We used slope and ground distances to calculate the horizontal distance and elevation (to 0.1 m) of each point along the profiles. We then used these measurements, along with the initial GPS coordinates, to derive x, y, and z UTM coordinates for each point. Using these coordinates, we constructed triangulated irregular network (TIN) models for each beach and subsequently converted these models to 1-m horizontal and 0.1-m vertical resolution digital elevation models (DEMs) for analysis.

Beach Area under Threat

We used three scenarios of sea-level rise (0.2, 0.5, and 0.9 m) in our analysis. We based these scenarios on the full range of current predictions of potential sea-level rise in the next 100 years (IPCC 2001*b*). We reclassified the beach grids to identify areas of beach below these elevations and the area of beach susceptible to flooding. Because of the lack of available data (Pilkey & Cooper 2004), it was not possible to model the evolution of beach morphology with sea-level rise. Our calculations therefore represent the current nesting habitat under threat from sea-level rise and the potential for a shift in the nesting range, based on the assumption of maintenance of the current beach profile.

We examined associations among physical attributes of the beaches, vulnerability to sea-level rise, and level of nesting activity. We used six physical variables—length, width, slope, elevation, aspect, and land use behind the beach. Categories of aspect were north, northwest, west, southwest, east, and northeast, and land use behind the beach was categorized as shrub, road, hotel, or salt lake. We took the proportion of beach area under threat from a 0.5-m rise in sea level, an intermediate value, as a measure of vulnerability. We used correlation analyses to test for associations between continuous variables and Kruskal-Wallis tests to examine the effects of categorical variables on vulnerability to sea-level rise.

Nesting Habitat under Threat

Female sea turtles prefer to nest within specific elevational ranges above mean sea level, and this may affect nest success (Horrocks & Scott 1991; Maktav et al. 2000). In the absence of specific data on nest location for Bonaire, we identified an elevational range of 0.3 to 1.8 m above the mean high-water mark in the individual beach models, encompassing the range thought to be preferentially used by hawksbills (Horrocks & Scott 1991) and loggerheads (Maktav et al. 2000). We measured the impact of the three different scenarios of a rise in sea level, assuming no change in beach morphology, on beach area within the nesting range to assess the proportion of nesting habitat under threat of flooding.

In cases where landward beach movement in response to sea-level rise is constrained, inundation of currently preferred nesting areas could result in female turtles shifting their nest sites up the beach. We predicted the potential nesting area for beaches by measuring current nesting area and assuming a landward shift of this area in accordance with the increase in sea level. For example, under a scenario of a 0.2-m rise in sea level, areas currently in

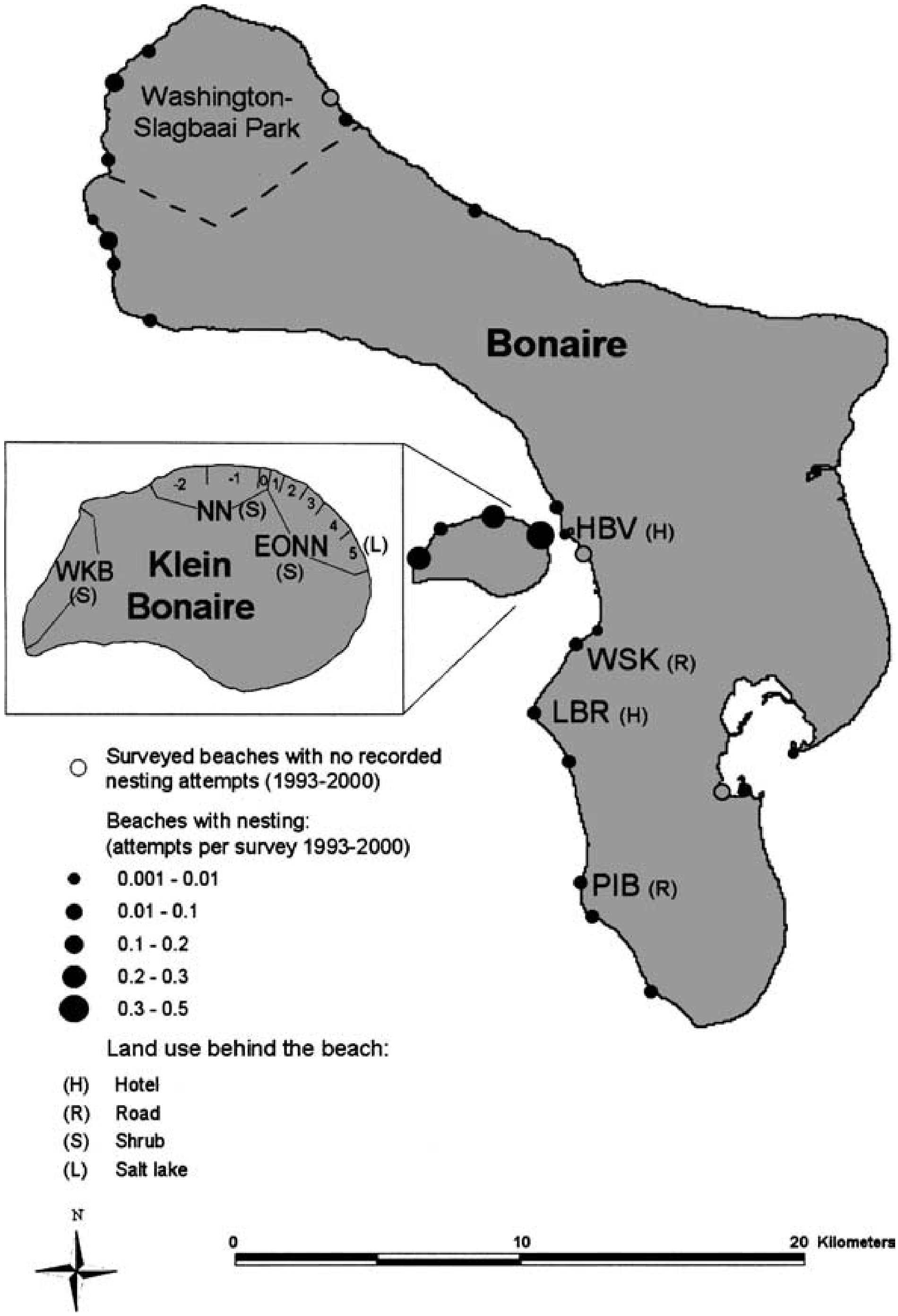

Figure 1. Locations of Bonaire beaches with differing levels of nesting activity recorded from 1993 to 2000. The inset is the satellite island of Klein Bonaire with the surveying sections indicated. The letters and numbers represent the 13 beaches used in the geographic information system analysis. Abbreviations: East of No Name, EONN; No Name, NN; Harbour Village, HBV; Lighthouse Beach Resort, LBR; Pink Beach, PIB; West Klein Bonaire, WKB; Windsock, WSK.

the range 0.5 to 2.0 m would fall within the preferred range, again assuming no change in beach morphology. We repeated this analysis for each of the scenarios and recorded the beach area that is in the potential nesting elevation range.

We examined the potential for beaches with different land uses behind them to accommodate shifts in nesting range using a Kruskal-Wallis test. As an indicator of adaptability, we used the proportion of beach area in the potential nesting range after a 0.5-m shift as a proportion of the current range. In the absence of data that would allow us to account for possible changes in beach morphology, this at least provided some indication of the potential for adaptation through a shift in nest distribution.

Results

Distribution and Correlates of Nesting Activity

Twenty-eight beaches were surveyed at various times between 1993 and 2000, of which 25 had nesting activity

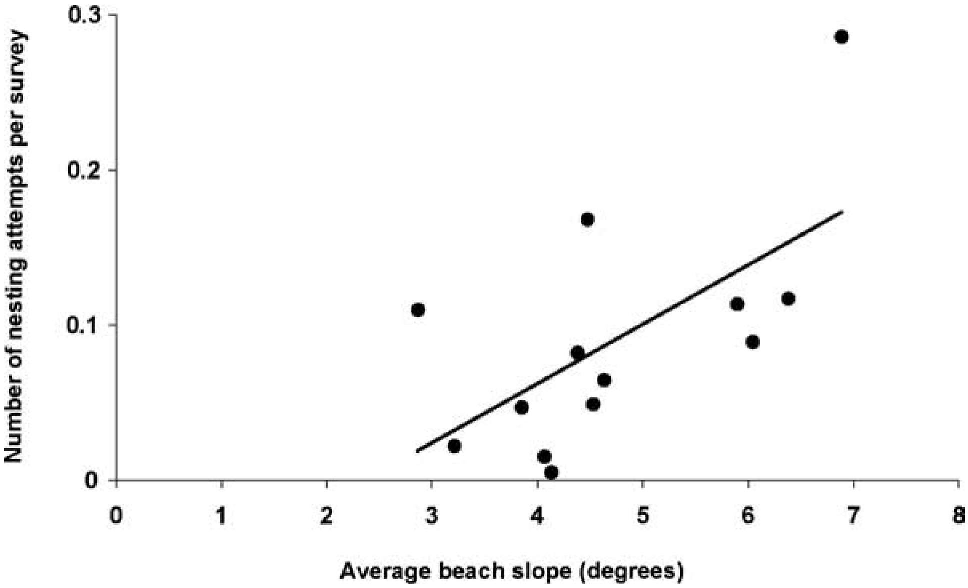

Figure 2. Relationship between level of turtle nesting activity on beaches on Bonaire and the average slope of the beach.

(Fig. 1). Nesting beaches were distributed around the coastline of the mainland and Klein Bonaire, with the majority (76%) of recorded nesting activity occurring on Klein Bonaire. Levels of nesting varied around the island, with the Washington-Slagbaai area, the north coast, and the southwestern coast showing moderate numbers (44, 31, and 91 attempts, respectively) of nesting attempts relative to the rest of the island. Little nesting activity was observed on the west and east coasts during the survey period. Nesting activity was significantly correlated only with beach slope ($r = 0.61$, $n = 13$, $p < 0.02$), with higher nesting frequency on beaches with steeper slopes (Fig. 2).

Beach Area under Threat

The 13 beaches surveyed represented an area of 88,298 m^2. Inundation of the total current beach area was 14% under the most conservative scenario of sea-level rise (0.2 m). This increased to 31% and 50% under a 0.5-m or 0.9-m rise in sea level, respectively. On average, the area of any individual beach under threat with a 0.5-m rise in sea level was 38% of the current beach area (±24% SD) but ranged widely among beaches (Table 1). The most vulnerable beach, taking vulnerability as the proportion of the beach that would be inundated under the scenario of a 0.5-m rise in sea level, was Lighthouse Beach Resort (LBR), of which 83% could be lost.

Vulnerability to sea-level rise was significantly and negatively correlated with mean elevation ($r = -0.85$, $n = 13$, $p < 0.001$), maximum elevation ($r = -0.59$, $n = 13$, $p = 0.03$), and beach width ($r = -0.59$, $n = 13$, $p = 0.04$); thus, lower, narrower beaches were more susceptible to sea-level rise. Vulnerability also differed significantly with land use behind the beach (Kruskal-Wallis test, $\chi^2 = 8.50$, $p = 0.04$, $n = 3$; Fig. 3a). Beaches most vulnerable to land loss were those backing onto salt lakes and hotels, and these were also the lowest and narrowest beaches (Table 2 & Fig. 1).

There was no relationship between beach vulnerability and nesting activity ($r = -0.26$, $n = 13$, $p = 0.39$). Moreover, although a visual trend was apparent, nesting frequency did not differ significantly with land use (Kruskal-Wallis test, $\chi^2 = 4.26$, df = 3, $p = 0.24$; Fig. 3b).

Table 1. The potential area of 13 beaches on Bonaire that would be lost to inundation under three possible scenarios of rise in sea level: 0.2, 0.5, and 0.9 m.

	Beach area inundated, m^2 (proportion of total area)		
*Beach**	*0.2 m*	*0.5 m*	*0.9 m*
EONN1	406 (0.14)	902 (0.30)	1 683 (0.56)
EONN2	302 (0.10)	688 (0.24)	1 311 (0.45)
EONN3	454 (0.14)	990 (0.30)	1 867 (0.57)
EONN4	493 (0.06)	1 259 (0.15)	3 520 (0.42)
EONN5	1 136 (0.27)	3 413 (0.82)	3 958 (0.95)
NN0	400 (0.12)	947 (0.28)	1 541 (0.46)
NN-1	1 381 (0.11)	2 208 (0.11)	4 430 (0.97)
NN-2	494 (0.05)	1 252 (0.12)	2 200 (0.21)
HBV	382 (0.21)	856 (0.47)	1 387 (0.76)
LBR	737 (0.43)	1 446 (0.83)	1 654 (0.95)
PIB	1 766 (0.32)	3 510 (0.63)	4 634 (0.84)
WKB	3 259 (0.13)	7 688 (0.32)	12 670 (0.52)
WSK	1 059 (0.15)	2 203 (0.32)	3 717 (0.54)
Total	12 269 (0.14)	27 362 (0.31)	44 572 (0.50)

**Abbreviations: East of No Name, EONN; No Name, NN; Harbour Village, HBV; Lighthouse Beach Resort, LBR; Pink Beach, PIB; West Klein Bonaire, WKB; Windsock, WSK.*

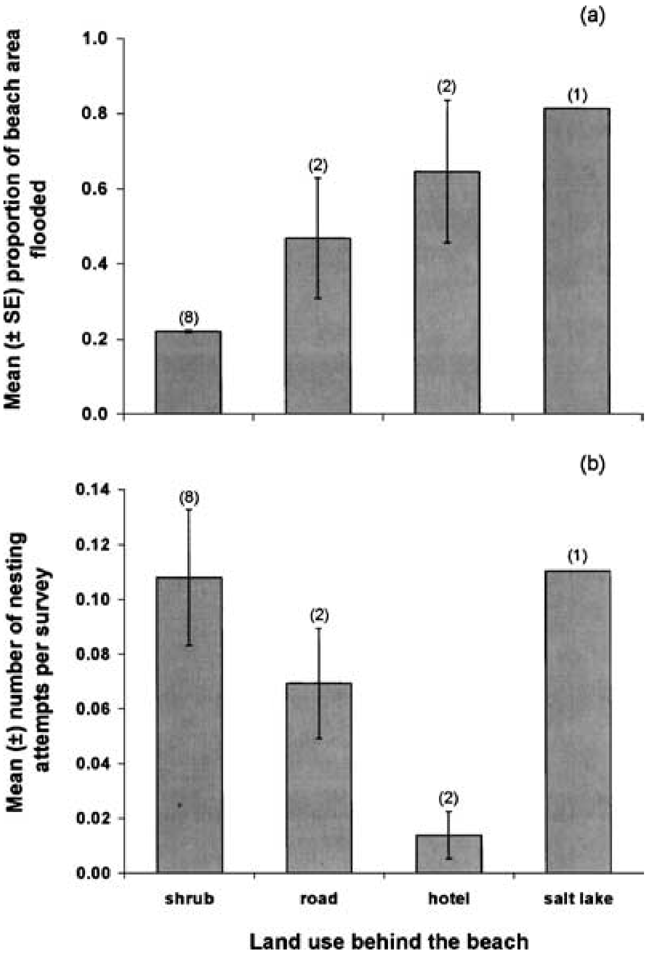

Figure 3. (a) Proportion of beach area lost under the scenario of a 0.5-m rise in sea level and (b) number of turtle nesting attempts per survey, with different types of land use behind the beach. Sample sizes are given in parentheses.

Current Nesting Habitat under Threat

An area of 47,123 m^2 lies in the suggested optimal elevation range for hawksbill and loggerhead nesting (i.e., 0.3–1.8 m above current sea level), representing 53% of the total surveyed beach area. With a 0.5-m rise in sea level, 23% of the current nesting area was under threat of flooding, and with a 0.9-m rise this increased to 52%. Individual beaches varied in profile and thus in the extent to which the nesting area within them was threatened (Table 2). Sixty-four percent (±23% SD) of an individual beach, on average, was in the optimal nesting range. Without taking into account the possibility that females may shift their nest location in response to sea-level rise (see the next section), a 0.2-m rise in sea level resulted in an 11% decrease in nesting area. The beach area within the nesting range was further reduced to 41% (±23% SD) and 21% (±19% SD) of the total beach area with 0.5- and 0.9-m rise in sea level, respectively. No significant correlation

Table 2. Area of optimal nesting remaining on Bonaire after three possible scenarios of rise in sea level: 0.2, 0.5 and 0.9 m.

	Optimal nesting area remaining, m^2 (proportion of total beach area)		
Beach[a]	*0.2 m*	*0.5 m*	*0.9 m*
EONN1	2 093 (0.70)	1 516 (0.51)	681 (0.23)
EONN2	2 198 (0.76)	1 758 (0.61)	751 (0.26)
EONN3	2 277 (0.70)	1 617 (0.50)	593 (0.18)
EONN4	7 046 (0.85)	5 549 (0.67)	1 847 (0.22)
EONN5[b]	755 (0.18)	317 (0.08)	0 (0.00)
HBV[b]	975 (0.53)	577 (0.32)	52 (0.03)
LBR[b]	286 (0.17)	120 (0.07)	6 (0.003)
NN0	2 417 (0.72)	1 998 (0.59)	1 340 (0.40)
NN-1	8 205 (0.64)	6 437 (0.50)	3 867 (0.30)
NN-2	5 519 (0.54)	7 305 (0.71)	7 234 (0.70)
PIB	2 029 (0.37)	1 118 (0.20)	412 (0.07)
WKB	3 104 (0.13)	2 459 (0.10)	1 693 (0.07)
WSK	4 473 (0.65)	3 476 (0.51)	1 989 (0.29)

[a]*Abbreviations: East of No Name, EONN; No Name, NN; Harbour Village, HBV; Lighthouse Beach Resort, LBR; Pink Beach, PIB; West Klein Bonaire, WKB; Windsock, WSK.*
[b]*One of the three lowest and narrowest beaches.*

was found between nesting activity and the area of the beach currently lying within the nesting range ($r = 0.07$, $n = 12, p = 0.84$) or the proportion of beach lying within this area ($r = -0.14$, $n = 12$, $p = 0.66$).

Potential for a Shift in Nesting Range

Beaches varied with respect to the area currently available to accommodate shifts in preferred turtle nesting range. In all but one case the total amount of potential nesting area after a shift in response to sea-level rise decreased under each scenario (Fig. 4). Inevitably beaches with a smaller area, such as LBR and EONN5 (for full names of beach descriptors, see Fig. 1), lost potential habitat faster than those with larger areas, such as NN-1. Beach NN-2 gained in nesting area because of the large proportion of beach area presently above the elevation of the current nesting range (which would be available to accommodate a shift in nest distribution), and because of the shallower slope of the beach above the original range. The potential for beaches to accommodate shifts in nest distribution varied significantly with land use behind the beach ($\chi^2 = 7.84$, df $= 3$, $p = 0.049$). Beaches with hotels and salt lakes behind them were the least able to accommodate shifts following a 0.5-m rise in sea level (Fig. 5). Potential nesting area on these beaches was reduced to 33% and 14% of the original nesting area, respectively.

Discussion

Although the potential influence of sea-level rise on sea turtle nesting habitat is difficult to establish, such information is necessary to inform management decisions. Our

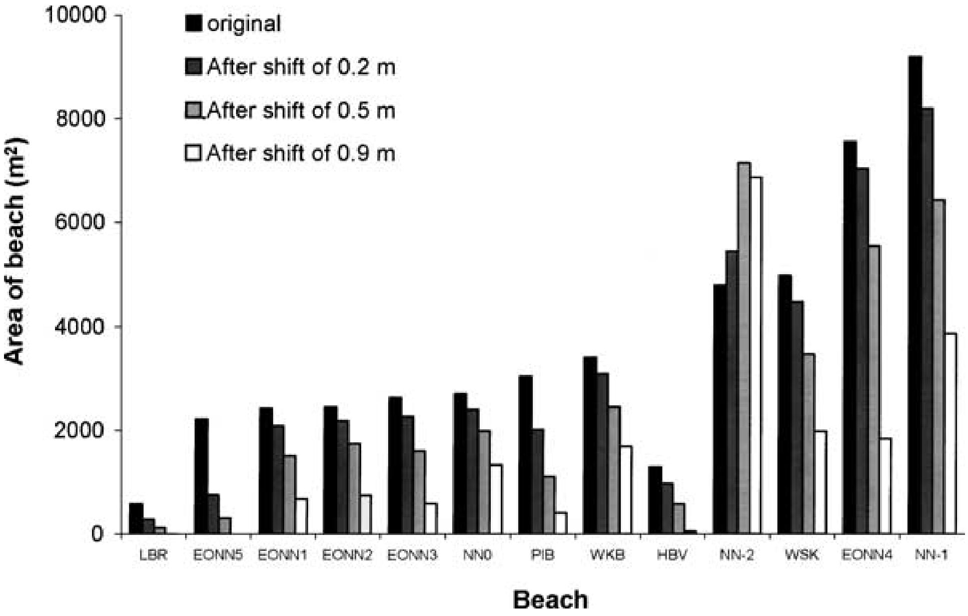

Figure 4. Area of individual beach lying within the preferred turtle nesting elevation range at present and after shifts in response to sea-level rise.

technique allowed us to explore the relative vulnerability of different beach types and therefore identify areas where nesting habitat is under threat. Such an approach may be applicable to any turtle nesting area.

Bonaire's small nesting population of hawksbill and loggerhead turtles nest on the majority of the island's available beaches. Despite this wide nesting distribution, there is considerable regional variation in the observed level of nesting, with the majority of nesting attempts focused on the small offshore island of Klein Bonaire. The observed variation in nesting level, however, does not necessarily reflect long-term historical patterns. Indeed, interviews with local fishers suggest that nesting was previously more extensive, with turtles visiting additional beaches on both the west and east coasts of the main island (Sybesma 1992). Recent changes in the distribution of nesting activity may be attributed to a number of factors, including alteration of beaches, tourism, and poaching (Sybesma 1992). Our results show, however, that current nesting beaches vary in their physical characteristics, and therefore also differ in their susceptibility to the potential impacts of sea-level rise. One-third of the current beach area used by sea turtles is under threat from an intermediate rise in sea level.

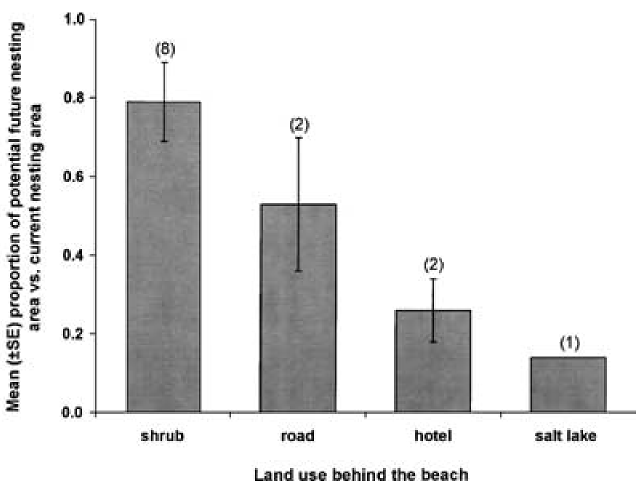

Figure 5. Proportion potential turtle nesting area after a 0.5-m rise in sea level, with different types of land use behind the beach. Sample sizes are given in parentheses.

Beach Area under Threat

The physical characteristics of beaches determined their vulnerability to sea-level rise. Narrower beaches with lower elevation were predicted, perhaps inevitably, to lose a larger proportion of their area under all scenarios of a rise in sea level. In many cases the current beach profile, in terms of slope and elevation, can be considered a result of natural processes. In others, however, the current profile may have resulted from modification of habitat behind the beach, which could explain the fact that the most vulnerable beaches included those with adjacent hotels (Fig. 1). In the case of hotels, such modification could result from altered sediment movement patterns as a consequence of the development, or from beach nourishment to improve the attractiveness of the beach to tourists. Alternatively, development may occur preferentially on flatter beaches, leading to the apparent correlation between beach vulnerability and development.

At any rate, the large proportion of beach area estimated to be under threat (up to 53% in this study) is of concern. Even the lowest estimates, of 14% with a 0.2-m rise in sea level, would mean a substantial loss of beach habitat on an island with relatively little remaining beach area and concomitant loss of protection afforded to inland habitats and coastal buildings.

Our methodology highlights the potential area of beach under threat from sea-level rise together with the threat from coastal squeeze (i.e., when landward movement of beaches is prevented by physical barriers). It does not, however, allow a full exploration of potential shoreline response. The lack of available data on coastal processes and long-term beach profile changes on Bonaire (and many other countries in tropical areas) means that it is difficult to predict more precisely the likely long-term response of the island's beaches to sea-level rise. Responses are dictated by numerous factors, such as topographic relief, substrate type, and shelter from wind and wave energy (Wells 1995), and models to effectively predict shoreline response have proven difficult to produce. The most commonly used method is the Bruun rule (Bruun 1962), which predicts increased erosion and an upward and landward migration of beaches. But this very simple model has limited application, and its ability to provide reliable predictions has been questioned even under ideal conditions (Pilkey & Cooper 2004).

Where inland retreat of beaches is unrestricted and natural beach profiles can be maintained, such as on Klein Bonaire, it is possible that beach loss may not be as severe as projected here. As we have demonstrated, however, it does not appear that these beaches are most at risk. The observed vulnerability of beaches backing onto hotels indicates the possible long-term impacts of development on beaches. Although beaches backed by salt lakes were also vulnerable, in this case there was no physical barrier to prevent the beach from shifting in response to a rise in sea level. To retain beaches in the face of sea-level rise, buffer areas around them must be large enough to take long-term physical changes into account, and setback regulations need to be enforced. Such regulations are only nominally in place on mainland Bonaire (M.R.F., personal observation).

Nesting Habitat under Threat

Although narrow beaches with low elevations are likely to be the most vulnerable to sea-level rise, most of the turtle nesting activity on Bonaire was on steeper beaches with higher elevations. Preference by hawksbills for steeply sloped beaches has been documented previously and may facilitate hatchling survival (Horrocks & Scott 1991). In addition, although beaches with hotels are more vulnerable to sea-level rise, these beaches do not appear to be among preferred nesting sites. It is possible that nesting activity was never high in these areas; however, anecdotal reports suggest that nesting on these beaches was more common before the advent of tourism. The level of nesting may have declined subsequently in response to human disturbance or to alteration of key beach characteristics. Because hotels were constructed before nesting surveys began, their effect on adjacent habitat remains unclear.

Despite the observed mismatch between beach vulnerability to sea-level rise and turtle nesting preferences, up to half of the potential current nesting area on Bonaire is under threat in the most extreme scenario of a rise in sea level. Given that Bonaire has a relatively small nesting population, it may be that the remaining beach area would provide sufficient habitat. But any loss of habitat has important implications for turtle populations because it reduces the range of nest sites available to females. Nest placement on the beach influences nest success, and an altered distribution of nests could result in reduced reproductive success (Horrocks & Scott 1991). Moreover, biases to temperature-dependent hatchling sex ratio could result from females being forced to nest at lower elevations, where incubation temperatures are cooler (Horrocks & Scott 1991) and where nests would be more prone to high-tide inundation. It is difficult to determine the consequences of nesting habitat loss without an understanding of which microhabitat characteristics are important for nesting females.

Although suggestions have been made as to what affects nest-site choice, the precise requirements that maximize success are still unclear. Females may spend some time digging a body pit and even an egg chamber before abandoning a site in preference for one just a few meters away. What drives this behavior and makes sites in such close proximity differ is unknown, but this emphasizes the necessity for a range of sites to be available.

In addition to nest location, choice of beach is also important for nesting females. Recent genetic studies support the suggestion that females of some turtle species return to nest on their natal beaches (Lahanas et al. 1994; Dutton et al. 1999; Hatase et al. 2002). If natal beaches and those in the surrounding area are altered so that they no longer offer suitable nesting areas, this could reduce the reproductive success, and ultimately the size, of local nesting populations. Although it is possible that other beaches in the area could be used, extensive coastal development is occurring regionally, and alternatives are likely to become increasingly scarce. Until critical habitat can be more clearly identified, it is essential from a conservation standpoint that choice of beach and nest site not be limited because reproductive success could be compromised.

We demonstrated the use of GIS to model impacts of long-term environmental change on beach habitats and to examine beach vulnerability in terms of physical attributes. We also provided a baseline database that can be updated to monitor change over time. The impacts of beach change on nesting populations could be examined in more detail at sites where more precise nest-location data have been, or can be, collected over a number of nesting seasons. In addition, distinguishing between actual nests and false crawls might allow a more detailed analysis of how beach type affects nest success and beach choice. This approach could subsequently be used to visualize and extract information about spatial patterns of nesting. Additionally, where more extensive coastline morphological data are available, more precise predictions about future change can be made at varying scales, from individual beaches to whole stretches of coast.

The potential effects of sea-level rise on nesting beaches cannot be considered in isolation from existing human threats to turtles and their habitat. Throughout the Caribbean, turtle populations have been and continue to be reduced through extensive poaching of adults for their meat and shells, despite protective legislation. Human encroachment on nesting habitat has been suggested as the primary cause of decreasing turtle activity in many areas (Shabica 1995), and loss of beach area to sea-level rise will likely exacerbate this problem. On some Caribbean islands, such as Barbados and Antigua, tourism-associated development has already compromised a significant proportion of the coastline (Potter 1996). Although Bonaire remains relatively undeveloped compared with many other areas, rapid growth of the tourism industry and subsequent coastal development are predicted. It is clear that there is an urgent need for all countries to incorporate the potential impacts of sea-level rise into coastal management plans and to enforce setback legislation. In this context, our method can provide a useful tool to generate predictions about the combined effects of development and sea-level rise on beach habitat, and nesting habitat in particular, and to ensure that the conservation requirements of sea turtles are effectively incorporated into coastal management plans.

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Literature Cited

Bouchard, S., K. Moran, M. Tiwari, D. Wood, A. Bolten, P. Eliazar, and K. Bjorndal. 1998. Effects of exposed pilings on sea turtle nesting activity at Melbourne Beach, Florida. Journal of Coastal Research **14:**1343–1347.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion. Journal of the Waterways and Harbours Division **88:**117–130.

Cambers, G. 1998. Coast and beach stability in the Caribbean Islands COSALC. St. John, U.S. Virgin Islands. Beach monitoring field manual. University of Puerto Rico, Sea Grant College Program, Mayaguez.

Clark, J. R. 1997. Coastal zone management for the new century. Ocean and Coastal Management **37:**191–216.

Crain, D. A., A. B. Bolten, and K. A. Bjorndal. 1995. Effects of beach nourishment on sea-turtles—review and research initiatives. Restoration Ecology **3:**95–104.

Dutton, P. H., B. W. Bowen, D. W. Owens, A. Barragan, and S. K. Davis. 1999. Global phylogeography of the leatherback turtle (*Dermochelys coriacea*). Journal of Zoology **248:**397–409.

Eckert, K. L. 1995. Anthropogenic threats to sea turtles. Pages 611–612 in K. A. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Hall, M. A., D. L.Alverson, and K. I. Metuzals. 2000. By-catch: problems and solutions. Marine Pollution Bulletin **41:**204–219.

Hatase, H., et al. 2002. Population structure of loggerhead turtles, *Caretta caretta,* nesting in Japan: bottlenecks on the Pacific population. Marine Biology **141:**299–305.

Hendrickson, J. R. 1995. Nesting behaviour of sea turtles with emphasis on physical and behavioural determinants of nesting success or failure. Pages 53–58 in K. A. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Hendry, M. 1993. Sea-level movements and shoreline changes in the wider Caribbean region. Pages 152–161 in G. A. Maul, editor. Climate change in the Intra-Americas sea. Edward Arnold, London.

Herbst, L. H., and E. R. Jacobson. 1995. Diseases of marine turtles. Pages 595–596 in K. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Horrocks, J. A., and N. M. Scott. 1991. Nest site location and nest success in the hawksbill turtle, *Eretmochelys imbricate,* in Barbados, West Indies. Marine Ecology-Progress Series **69:**1–8.

Huang, J. C. K. 1997. Climate change and integrated coastal management: a challenge for small island nations. Ocean & Coastal Management **37:**95–107.

IPCC (Intergovernmental Panel on Climate Change). 2001*a*. Climate change 2001: impacts, adaptation & vulnerability. Contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

IPCC (Intergovernmental Panel on Climate Change). 2001*b*. Climate change 2001: the scientific basis. Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

IUCN (World Conservation Union). 2003. 2003 IUCN red list of threatened species. IUCN/SSC, Cambridge, United Kingdom. Available from http://www.redlist.org (accessed March 2003).

Katselidis, K., and D. Dimopoulos. 1998. The impact of tourist development on loggerhead nesting activity at Daphnia Beach, Zakynthos, Greece. Pages 75–77 in F. A. Abreu-Grobois, editor. Proceedings of the eighteenth international sea turtle symposium. Technical memorandum NMFS-SEFSC-436. National Oceanic and Atmospheric Administration, Silver Springs, Maryland.

Kikukawa, A., N. Kamezaki, and H. Ota. 1999. Factors affecting nesting beach selection by loggerhead turtles (*Caretta caretta*): a multiple regression approach. Journal of Zoology **249:**447–454.

Klein, R. J. T., and R. J. Nicholls. 1999. Assessment of coastal vulnerability to climate change. Ambio **28:**182–187.

Lahanas, P. N., M. M. Miyamoto, K. A. Bjorndal, and A. B. Bolten. 1994. Molecular evolution and population genetics of greater Caribbean green turtles (*Chelonia mydas*) as inferred from mitochondrial-DNA control region sequences. Genetica **94:**57–66.

Maktav, D., F. Sunar, D. Yalin, and E. Aslan. 2000. Monitoring loggerhead sea turtle *(Caretta caretta)* nests in Turkey using GIS. Coastal Management **28:**123–132.

Mortimer, J. A. 1995. Factors influencing beach selection by nesting sea turtles. Pages 45–51 in K. A. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Mortimer, J. A., M. Donnelly, and P. T. Plotkin. 2000. Sea turtles. Pages 59–71 in C. R. C. Sheppard, editor. Seas at the millennium—an environmental evaluation—Volume 3. Pergamon, Elsevier Science, Oxford, United Kingdom.

Nicholls, R. J. 1998. Coastal vulnerability assessment for sea-level rise: evaluation and selection of methodologies for implementation. Caribbean planning for adaptation to global climate change (CPACC) Project. St. Michael, Barbados, West Indies. Available from http://www.cpacc.org/download/c6assess.pdf (accessed January 2002).

Pandav, B., B. C. Choudhury, and C. S. Kar. 1997. Mortality of olive ridley turtles *Lepidochelys olivacea* due to incidental capture in fishing nets along the Orissa coast, India. Oryx **31:**32–36.

Pilkey, O. H., and J. A. G. Cooper. 2004. Society and sea level rise. Science **303:**1781–1782.

Potter, B. 1996. Tourism and coastal resources degradation in the Wider Caribbean. Island Resources Foundation, St. Thomas, Virgin Islands. Available from http://www.irf.org/irtourdg.html (accessed June 2002).

Salmon, M., R. Reiners, C. Lavin, and J. Wyneken. 1995. Behavior of loggerhead sea turtles on an urban beach I. Correlates of nest placement. Journal of Herpetology **29:**560–567.

Shabica, S. V. 1995. Planning for protection of sea turtle habitat. Pages 513–518 in K. A. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Sybesma, J. 1992. WIDECAST sea turtle recovery action plan for the Netherlands Antilles. Page 63 in K. L. Eckert, editor. Technical report 11. U.N. Environment Program, Caribbean Environment Programme, Kingston, Jamaica.

Wells, J. T. 1995. Effects of sea level rise on coastal sedimentation and erosion. Pages 111–136 in D. Eisma, editor. Climate change: impact on coastal habitation. Lewis Publishers, Boca Raton, Florida.

Witham, R. 1995. Disruption of sea turtle habitat with emphasis on human influences. Pages 519–522 in K. A. Bjorndal, editor. Biology and conservation of sea turtles. Smithsonian Institution Press, Washington, D.C.

Witherington, B. E. 1992. Behavioral responses of nesting sea turtles to artificial lighting. Herpetologica **48:**31–39.