A National Coastal Hazard and Social Vulnerability Analysis for The Bahamas

I. Introduction

Rising sea levels and increases in the intensity and frequency of storms have decision-makers and planners around the world looking for strategies to adapt to climate change and to enhance community resilience to coastal hazards. Traditional reliance on hardened shorelines (i.e. seawalls, groins, etc.) is proving unsustainable given the expense to build and maintain these structures, and their unintended consequences for shoreline erosion and habitat loss (Defeo et al. 2009, Peterson and Lowe 2009, Dugan et al. 2011, Toft et al. 2013, Arkema et al. 2015, Temmerman and Kirwan 2015, Gittman et al. 2016). As an alternative, managers are increasingly turning to coastal ecosystems – coral reef, oyster reef, seagrass beds, dunes, marsh, mangrove, and other types of coastal forests – for their ability to attenuate waves and reduce storm surge (e.g. Arkema et al. 2013, Ferrario et al. 2013, Narayan et al. 2016, Bradley and Houser 2009, Koch et al. 2009). Planners, waterfront residents, NGOs and other stakeholders are asking where and under what circumstances will conservation or restoration of natural habitats reduce the risk of coastal flooding and erosion for vulnerable communities in lieu of (or in concert with) hardened shorelines?

Mitigating the impacts of coastal hazards and adapting to climate change is particularly relevant for The Bahamas, a low-lying coastal nation. Hurricane Joaquin in 2015 was followed by Hurricane Matthew almost one year later to the day. Both hurricanes caused significant damage to different parts of The Bahamas, with Matthew being the first major hurricane to hit New Providence since 1929. Two category 4 hurricanes in quick succession has given a new sense of urgency to prepare for what may be a stormy future. Fortunately, The Bahamas has an incredible wealth of pristine habitat, with extensive coral reef, seagrass beds, coastal coppice and mangrove forests. The potential for leveraging these ecosystems to provide coastal protection and other co-benefits (e.g., habitat for fisheries and to support tourism activities) is high, but requires tools and science to help planners evaluate where they should allocate resources to conserve or restore these habitats.

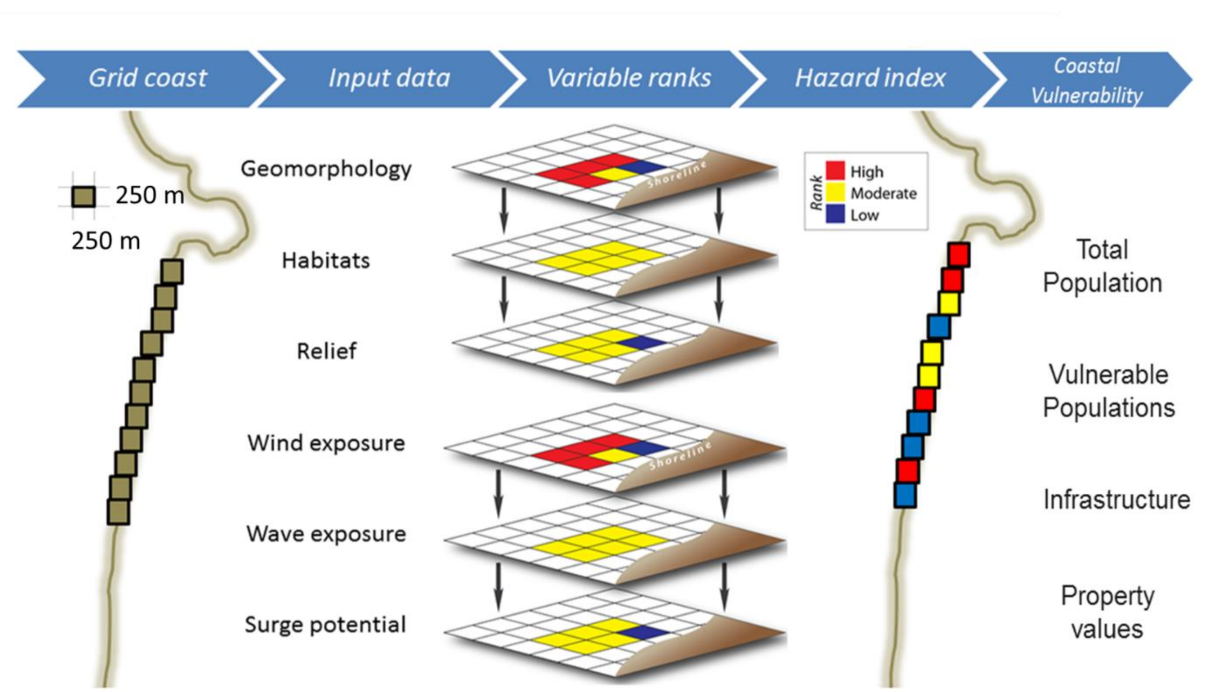
To understand where coastal ecosystems in The Bahamas play a critical role in reducing the risk of flooding and erosion for vulnerable communities, we conducted a national coastal hazard and social vulnerability analysis. The impetus for this analysis grew out of work conducted in 2015-17 to use an ecosystem-services approach to inform the design of a sustainable development plan for Andros Island. This work was a collaboration between the Office of the Prime Minister of The Bahamas (OPM), University of The Bahamas, Natural Capital Project (NatCap), The Nature Conservancy (TNC), and SEV Consulting Group supported by the Biodiversity and Ecosystem Services Program at the Inter-American Development Bank. We combined stakeholder engagement, scenarios analysis, and ecosystem-services modeling to inform development planning for Andros (Arkema and Ruckelshaus *in press*). A core component of this project was to map and value the contribution of coastal habitats on Andros to fisheries, recreation and tourism, and coastal protection under several different development scenarios designed by stakeholders. Quantifying coastal protection included a vulnerability analysis to identify where people and property along the shoreline were vulnerable to coastal hazards now and in the future, and where nature habitats might be providing protection from these hazards (Arkema et al. *in press*). Building on the work in Andros, we used a similar approach to quantify and map coastal protection provided by coral reefs, mangroves, seagrass, coastal coppice and pine forest for the country of The Bahamas.

To communicate these results and share them with key stakeholders and decision-makers, we developed a viewer accessible at http://marineapps.naturalcapitalproject.org/bahamas/. We used this viewer in a workshop and training in December 2016 in Nassau, The Bahamas to build the capacity of staff in relevant ministries, departments, NGOs, and consulting firms to employ ecosystem-services data and tools to inform coastal resilience and development planning. The viewer shows where people are vulnerable to coastal hazards now and under a future sea-level rise scenario, and where coastal and marine habitats are playing an important role in providing coastal protection for the entire coastline of The Bahamas.

II. Approach

a. Introduction to the coastal hazard and social vulnerability analysis

The national coastal hazard and social vulnerability analysis was completed using the InVEST Coastal Vulnerability model and census data from the Department of Statistics of The Bahamas. The Coastal Vulnerability model is an index based approach that computes the relative exposure of the shoreline to coastal hazards based on characteristics such as the presence of habitat, elevation, wind and waves, shoreline type, and surge potential (Arkema et al. 2013, Langridge et al. 2014) (Figure 1). The hazard index is typically coupled with social and economic data on people, property and infrastructure to highlight where human settlements and critical infrastructure are most vulnerable to storm waves and surge. In the case of The Bahamas demographic data collected during the 2010 census at the supervisory district level was aggregated using the National Oceanographic and Atmospheric Administration (NOAA)'s globally available Nighttime Lights Time Series.



$$EI = (R_{Geomorphology} R_{Relief} R_{Habitats} R_{SLR} R_{WindExposure} R_{WaveExposure} R_{Surge})^{1/7}$$

Figure 1. *The InVEST Coastal Vulnerability model uses an index based approach to calculate the relative vulnerability of a region to coastal hazards. The index combines shoreline attributes such as wave exposure and geomorphology to calculate a hazard index for each shoreline segment, which is coupled with demographic and economic information about people and other important assets along the coast.*

We used the InVEST Coastal Vulnerability model to calculate exposure and social vulnerability to hazards in 250 meter segments along the coast of The Bahamas. Model inputs included information on shoreline geomorphology created using satellite imagery, relief from a globally available topographic dataset, the presence of coastal and nearshore habitats including coastal coppice, pine and mangrove forests, coral reef, and seagrass beds, sea-level change, wave exposure extracted from a globally available dataset of wave statistics, and potential for storm surge calculated as the distance between land the continental shelf edge. Each of these inputs was ranked for each shoreline segment based on a combination of absolute and relative rankings to produce a qualitative assessment of vulnerability where '1' is the least vulnerable and '5' the most vulnerable. Details on the data inputs and methodology used in the national analysis can be found in the Appendix (below) and in Arkema et al. 2013 and Langridge et al. 2014.

The resultant hazard index was calculated by taking the geometric mean of the ranked input datasets (Figure 1). The distribution of values produced by the hazard index for the current situation and all future scenarios was classified into quantiles with the lowest quantile (bottom 20% of the distribution) representing those shoreline segments with the lowest relative risk of exposure to coastal hazards, and the upper quantile (top 20% of the distribution) showing those shoreline segments with the greatest relative risk.

b. Introduction to the online viewer

Results from this analysis are presented in an online viewer (http://marineapps.naturalcapitalproject.org/bahamas/) (Figure 2). The user can explore several different outputs from the Coastal Vulnerability model in the viewer. The first output is coastal exposure, which categorizes shoreline segments from low to high exposure based on their underlying characteristics (geomorphology, wave exposure, etc. as explained above). The viewer shows the results of the coastal hazard index for a 'current' scenario (2015) and a 'future' scenario (2040). The future scenario includes sea-level rise, which was incorporated into the model using a simple additive approach (see methods in Appendix) to highlight how relative vulnerability may change as sea levels rise. The second output shows the distribution of people (total population/500m^2), elderly (>65) and young (<15) people. By overlaying the hazard index with demographic information, users can see where particularly vulnerable communities, such as elderly or children, are most exposed to coastal hazards. The third output indicates where habitat may be playing a role in reducing risk to coastal communities (i.e., 'habitat role'). Habitat role was computed by taking the change in coastal exposure between a run of the model 'with' and a run of the model 'without' habitats included. The 'without' habitat scenario assumes that all habitat is degraded or lost from a given shoreline segment, and the resultant changes in exposure to coastal hazards indicate the relative importance of habitat at providing protection in that area.

We assessed coastal exposure at a national scale and for three sub-regions: Northern, Central and Southern Island groups. Since the hazard index produces relative results for exposure from coastal hazards, changing the geographic scope over which the model is run may change the relative rankings along the shoreline. Thus the scale at which the analysis is done needs to align with the scale of decision-making. For instance, the national scale analysis can inform the country's Integrated Coastal Zone Management process or decisions related to national climate adaptation. The regional scale may be most informative for post-disaster reconstruction (which tends to be for a subset of the islands after a hurricane hits) and coastal resilience planning for future storms. Island scale runs were outside the scope of this analysis, but requested by representatives of the key ministries, departments, NGOs and consulting firms at the December 2016 training as many of their decisions are made at an island scale (i.e., master planning).

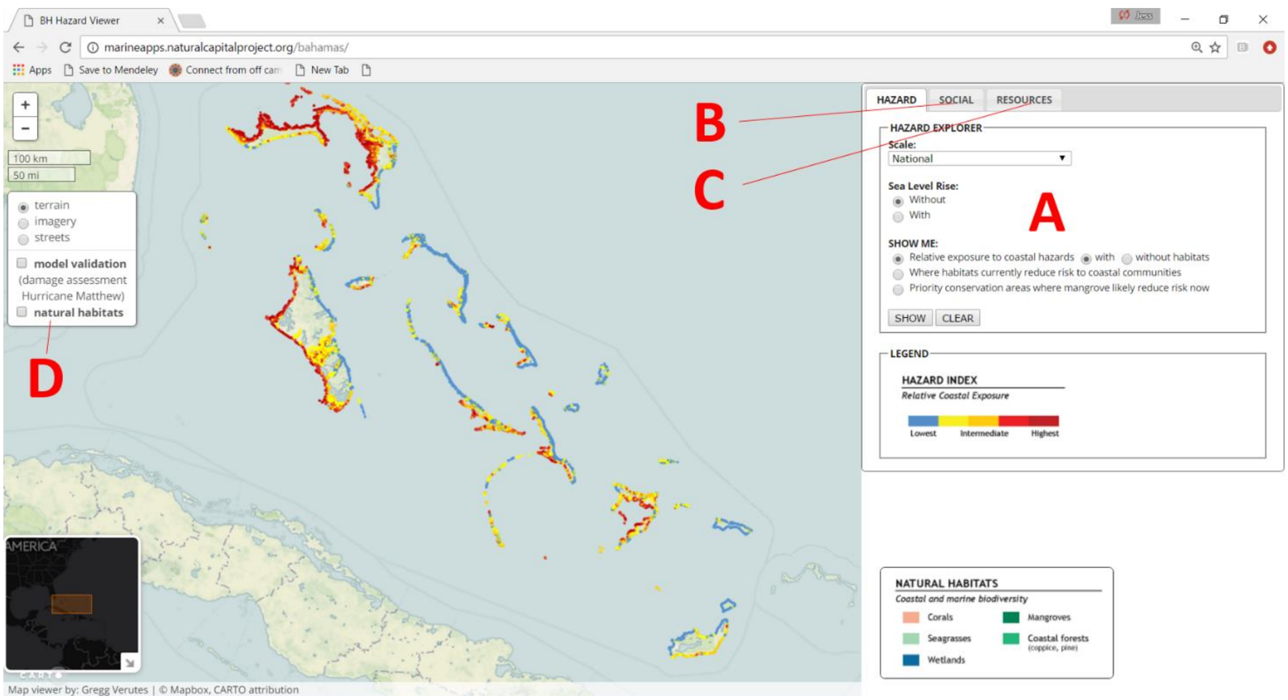


Figure 2. *The online viewer allows users to explore results from the coastal hazard and social vulnerability analysis for The Bahamas including the coastal hazard index and associated metrics (A). Several different overlays are included: demographic information (on the SOCIAL tab) (B), a map of existing natural habitats (D), and information about recent damages on New Providence during Hurricane Matthew (D). Resources and methodology are also included on the RESOURCES tab (C).*

III. Results

Here we describe some results from the analysis using a series of questions designed to help the user navigate the viewer and understand how information generated from this analysis can be used to inform a suite of management questions.

a. What areas are at highest risk from coastal hazards?

At a national scale the islands with the greatest proportion of high risk shoreline include Grand Bahama, Abaco, Crooked Island, The Exumas and Long Island. Also notable is the west coast of Andros Island. These results reflect the importance of storm surge potential as a strong driver of risk to coastal hazards in The Bahamas. The analysis incorporates exposure from storm surge based on a proxy of the distance from land to the edge of the continental shelf. A large distance between the shoreline and the continental shelf allows for the water from the surge to build up and the coastline to be more likely to flood. The highly vulnerable areas on these islands are predominantly those areas that sit on the shallow bank, exposing them to particularly high storm surge potential. Look at the 'Relative exposure to coastal hazards' 'with habitats' layer overlaid onto satellite imagery (accessed in the panel on the left side of the screen). This provides a clear picture of the distribution of the coastal hazard index across the country, and the relationship between exposure and storm surge potential (Figure 3).

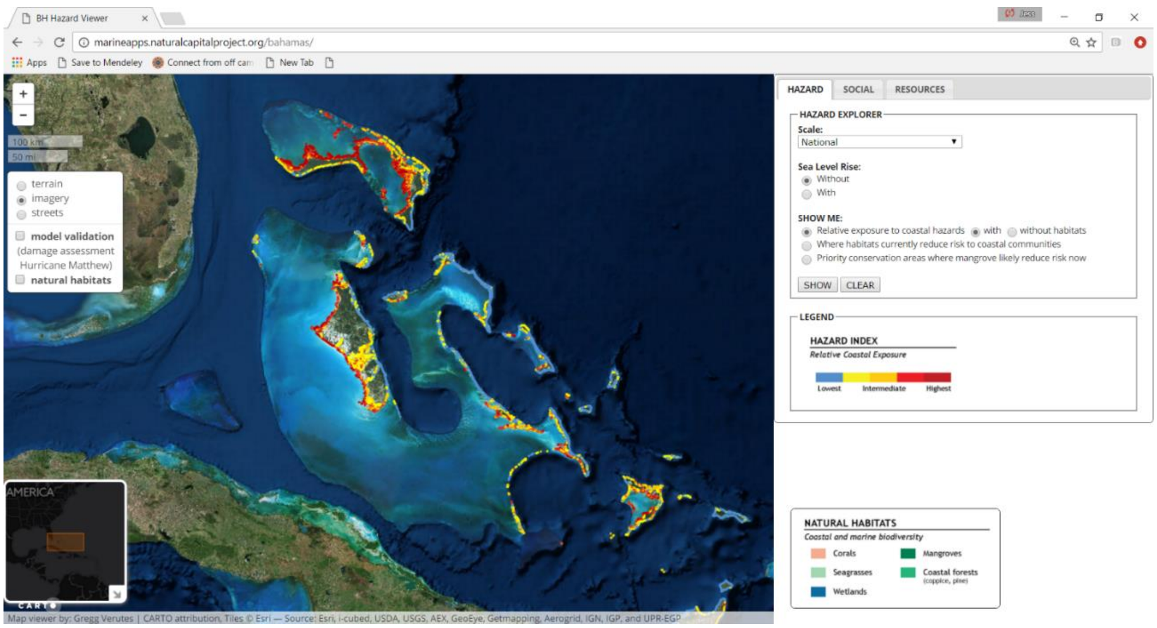


Figure 3. *Overlaying the coastal hazard exposure index for The Bahamas onto satellite imagery shows a general pattern in the region where risk of exposure to coastal hazards is highest along those coastlines that border shallow banks. This reflects the importance of storm surge potential as a driver of risk in The Bahamas.*

b. Where are people at risk?

Many of the areas that have high relative coastal exposure in The Bahamas are not places people are currently living, for example the west coast of Andros and Abaco, or the north side of Grand Bahama. Understanding social vulnerability to coastal hazards requires information about people, homes and infrastructure, as well as exposure to storms and sea-level rise. On the viewer look at the 'SOCIAL' tab and select 'Total Population'. This shows where people are living in relation to those places at high risk to coastal hazards (keep the hazard index selected, the demographic information will be overlaid). Some examples include (but are not limited to) Spring Point Settlement on Acklins, Freeport and the West end of Grand Bahama, Lowe Sound on Andros, Farmer's Hill on Exuma, South Beach on New Providence (and much of the Southern side of the island).

A map of damage information collected on New Providence after Hurricane Matthew by the Pacific Disaster Center shows good general agreement between those areas suggested by the model to be at high relative risk to coastal hazards and those areas which sustained Hurricane damage (Figure 4) (this is available as an overlay in the viewer in the 'model validation' option on the left hand toolbar) (Pacific Disaster Center 2016). Overlaying information about the population distribution on New Providence, shows that the stretch of highly vulnerable shoreline on the island is also disproportionally highly populated. This underscores the importance of incorporating demographic information into a risk analysis.

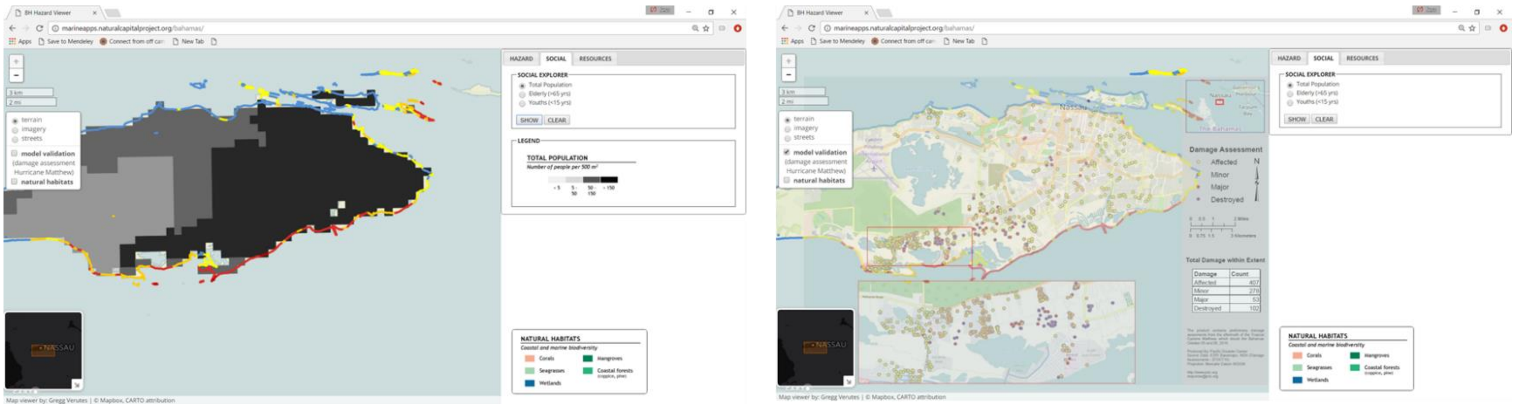


Figure 4. *The southern coastline of New Providence is one of the areas of The Bahamas that is at high risk of exposure to coastal hazards. This stretch of coastline is also one of the most densely populated parts of the island, and saw damage during Hurricane Matthew.*

Taking this one step further, looking at the demographics of the population reveals that the family islands are disproportionately comprised of old and young people. On the viewer, explore the 'Elderly' and 'Youths' maps on the 'SOCIAL' tab. It is important to look at the demographics of the settlements because not all populations are equal with regard to their resilience in the face of disasters. Research from the social science literature has shown that age (both elderly and young) is one of the strongest drivers of social vulnerability to coastal hazards (Cutter et al. 2003, Peacock et al. 2012, Arkema et al. *in press*). On Andros, for example, elderly and young people make up ~20% and >50% of the population respectively, making it – along with most of the other family islands which share similar bimodal distributions – particularly vulnerable.

c. Where is habitat playing an important role in providing protection?

Habitats like coral reef, seagrass beds, coastal coppice, pine and mangrove forests can mitigate the risk of people and property from exposure to coastal hazards. The Bahamas is replete with areas of pristine natural habitat, and there are many areas where people are benefiting from the multiple lines of defense that these habitats provide. For example, Arthur's Town at the Northern end of Cat Island, the Northern end of Long Island, Rolleville and Jolly Hall on Exuma, the West end of Grand Bahama, the East Coast of Abaco are all areas where multiple habitats including coral reef, seagrass beds, coastal coppice and mangrove forests co-occur along the coast and in the nearshore region of populated areas. From a risk management perspective, these may be areas where habitat matters the most in providing crucial coastal protection services to towns and infrastructure.

On the 'Hazard Explorer' tab of the viewer, select the option to 'SHOW ME: Where habitat currently reduces risk to coastal communities'. This will map the habitat role metric, which quantifies the increase in risk resulting from a 'without habitat' scenario that assumes the loss of all current habitat and the protective services it provides. Areas with a high habitat role are places where the model suggests that habitat is providing coastal protection. The West end of Grand Bahama, for example, has long stretches of populated shoreline that are currently at relatively low to intermediate risk of exposure to coastal hazards (bottom three quantiles of the Hazard Index). As evidenced by a high habitat role, these areas are likely benefitting from protection provided by extensive fringing reef, coastal coppice and mangrove forest and seagrass beds (Figure 5). If these habitats are lost, reflected by the 'without' habitat scenario, risk increase significantly along the shoreline (shoreline segments generally increase by one to three quantiles, now largely falling in the upper two quantiles of the Hazard Index).

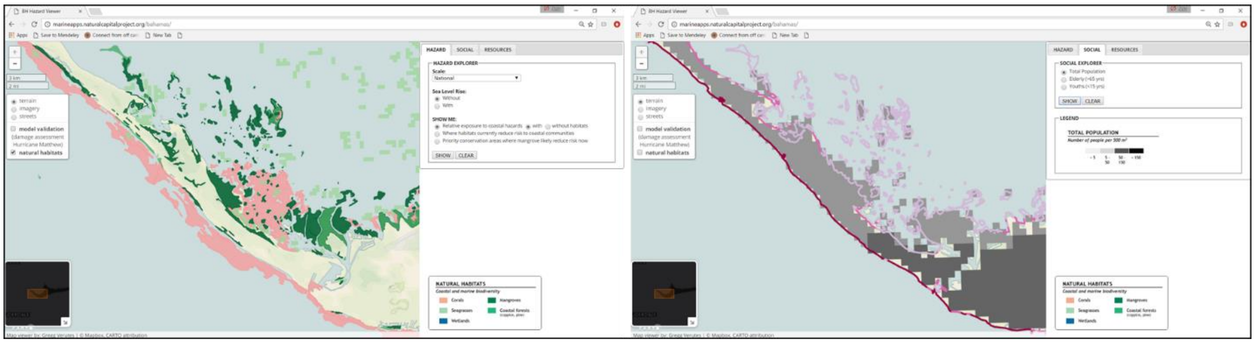


Figure 5. *The West End of Grand Bahama is a populated area that is likely benefitting from the coastal protection services of mangrove and coastal coppice forests, seagrass beds and a fringing reef. This is reflected by a high habitat role.*

Understanding where habitat is playing a critical role in providing coastal protection for people can help planners prioritize where to allocate resources for conservation and restoration. Mangrove is a particularly important habitat type in The Bahamas both because of its effectiveness at reducing flooding and coastal erosion under some circumstances, but also because mangrove is frequently cleared as part of development projects without giving thought to resultant increases in shoreline vulnerability or loss of other benefits it provides such as habitat for fisheries. For these reasons, the role of mangrove in particular is highlighted in the viewer by selecting the option 'SHOW ME: Priority conservation areas where mangrove likely reduces risk now.' This selection highlights the relative contribution of mangrove to the cumulative habitat role for that region.

d. Putting it all together. What are some lessons learned from Hurricane Matthew, and how could information from this analysis be used to mitigate risk in the future?

Understanding large scale drivers of exposure to hazards and social vulnerability in a region, and finding those locations which fit the profile of a high risk area is integral to managing risk of damages from coastal storms and sea-level rise. The results provided in the viewer are not predictive of any one particular hurricane and cannot capture the variability of unique storm tracks. They can, however, help to identify those areas of concern before a storm hits. Lowe Sound, on Andros is a good example of a region that fits a high risk profile. Navigate to Lowe Sound on the Northern end of Andros. You will see that it is at very high risk of exposure to coastal hazards, relative to the rest of The Bahamas. Lowe Sound was devastated by Hurricane Matthew, in contrast to neighboring parts of North Andros that fared much better despite being closer to the path of the hurricane (Figure 6) (CDEMA 2016). The key drivers of risk in Lowe Sound were the high storm surge potential and the low-lying elevation. However, in conversations with towns people in Lowe Sound they thought that the extremely shallow water offshore was protecting them again storm surge, when, in fact it was the opposite. The town saw an estimated 15 feet of surge during the storm. Understanding what drives risk, where those factors are present on the landscape and educating people living in high risk areas is an important component of preparedness for disasters.

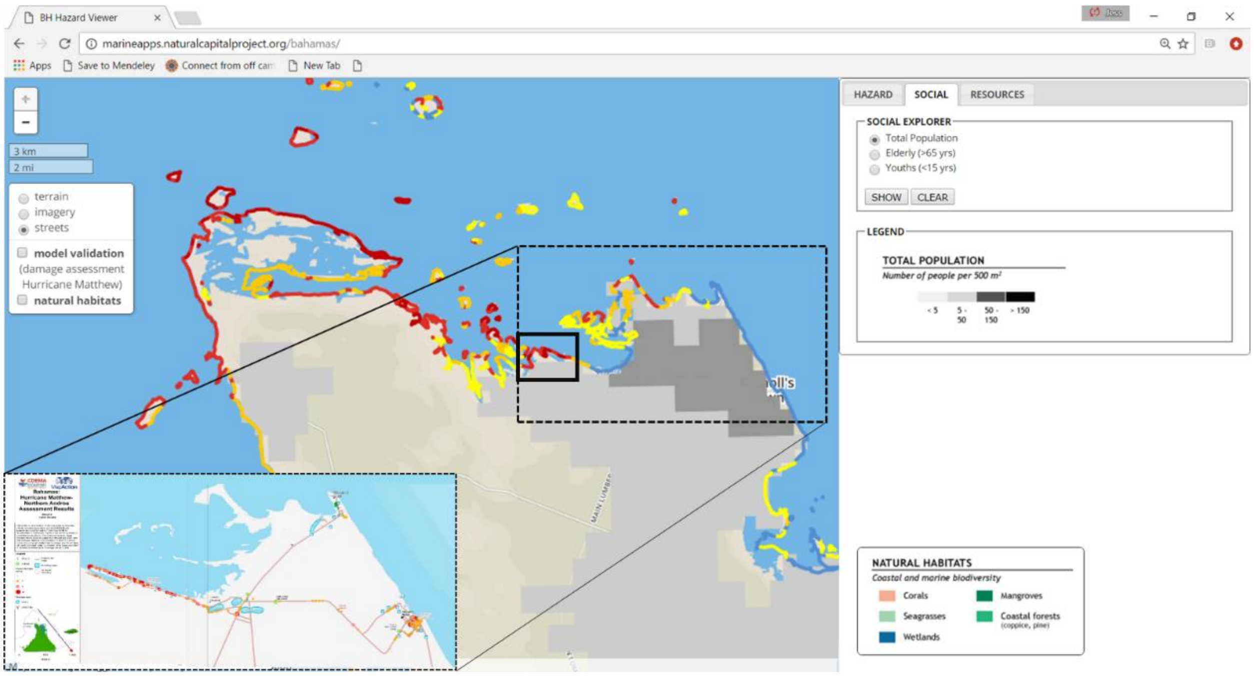


__Figure 6.__ Lowe Sound (solid black box) is an area that is at very high relative risk to coastal hazards, and was devastated during Hurricane Matthew. In contrast, neighboring settlements on North Andros (dashed box) fared better, despite being closer to the path of the hurricane.

There are multiple ways to incorporate this type of information into planning decisions. For example on Andros, like many areas across The Bahamas, residents observed that clearing mangrove along coastal roads was standard practice as roads were being built. Following the experience with Hurricane Matthew, coastal engineers wanted to know where and how much mangrove forest needed to be restored to mitigate this type of event in the future. The InVEST Coastal Vulnerability model was used to identify several locations on Andros ***where*** people were at high risk of exposure to coastal hazards and ***where*** mangrove restoration may mitigate that risk. Subsequent analysis was done at these specific sites, using a more dynamic wave modeling approach to determine ***how much*** mangrove needed to be restored. Understanding ***where and how much*** habitat is likely to be effective at providing coastal protection is a multi-step process that often requires several kinds of modeling approaches, beginning with an understanding of risk.

IV. Conclusions and Implications

The coastal hazard and social vulnerability analysis for The Bahamas presented in this report is focused on addressing several key questions related to coastal exposure, social vulnerability, and coastal protection provided by ecosystems that are fundamental to a number of different types of management decisions.

- Where is shoreline at high risk of exposure to coastal hazards in my region?
- Who is living along that shoreline, and what other valuable assets (infrastructure, homes, etc.) may be at risk?
- Where are people and property benefitting from coastal protection provided by habitats currently?
- And, what would happen if those habitats were lost?

Answering these and other similar questions are among the first steps necessary in identifying and implementing nature-based solutions to coastal protection.

The example from Lowe Sound on Andros in the previous section illustrates how this approach is being used to inform post-disaster reconstruction decisions and efforts being made to add resilience to vulnerable places in anticipation of the next disaster. The case in Lowe Sound also highlights that the Coastal Vulnerability model is a simple screening tool. It can help identify sites of interest, but additional analyses must be done in order to answer specific questions about, for example, the extent of habitat needed to provide protection from a given storm event. These additional pieces of information are needed to estimate the scope and cost of conservation and restoration activities. This type of exercise is underway now as part of The Bahamas Integrated Coastal Zone Management process (ICZM), to identify sites for shoreline stabilization projects.

There are a number of other planning contexts that may benefit from the type of information provided by the coastal hazard and social vulnerability analysis for The Bahamas. For example, these results have the potential to be useful to planners like those in the Ministry of Works who are responsible for siting important infrastructure, and would like better tools to inform the portfolio of information they might draw on when making a siting decision. At the training in Nassau in December 2016 planners from the Ministry of Works expressed a desire to have results at the island scale, since many decisions are made at an island scale. This was beyond the initial scope of this analysis, but if there is sufficient interest, the current analysis can be expanded. All attendees to the training were giving the necessary model inputs to run the model at an island scale and further guidance from the NatCap team could be provided.

The status quo approach to protecting people, property and infrastructure along the coastline using only hard infrastructure approaches like seawalls, groins and rockwalls is likely unsustainable moving into the future. Especially in a low-lying island nation like The Bahamas creative solutions that capitalize on the natural strengths of the region should be evaluated and leveraged to their fullest potential as part of a larger suite of adaptation strategies. Given the great abundance of natural habitat in The Bahamas, every effort should be made to value and employ these resources for the multitude of services they may be able to provide, including coastal protection. The coastal hazard and social vulnerability analysis for The Bahamas and online viewer presented here is one of many tools that may offer information to help planners as they work toward a more resilient future.

Appendix

I. Methods

a. Coastal Vulnerability Model

Below are some details about running the coastal hazard and social vulnerability analysis in The Bahamas. For general details on the InVEST Coastal Vulnerability model please refer to the user's guide: http://data.naturalcapitalproject .org/nightly-build/invest-users-guide/html/coastal_vulnerability.html and to Arkema et al. (2013). This is a ranking model, using a combination of absolute (geomorphology, habitat) and relative rankings (relief, wave exposure, surge potential), which are calculated from the entire distribution of values for 250 m shoreline segments along the coast of The Bahamas. Model inputs and rank used in The Bahamas analysis are shown in Table 1. The subsequent paragraphs give details about each input variable, and Table 2 provides details on the data sources for each model input.

The *geomorphology* input layer describes the composition of the shoreline and the relative susceptibility to erosion of different shoreline types. There was no nationwide map of shoreline geomorphology available, and one was created by the Natural Capital Project staff using satellite imagery, and was shared with attendees to the December 2016 training and workshop. In The Bahamas, sandy beaches were given the highest rank (5) in the model, followed by muddy shoreline (4), and rocky coral shoreline (3). The presence of seawalls can be accounted for in the model in two ways, either as a shoreline geomorphology type or as a separate seawall input (this latter option allows the model to reflect increased vulnerability at the edges of the seawall due to exacerbated erosion). In this analysis, some seawalls were detectable by satellite imagery and were included in the model as a rank of 2. Future updates to the model, especially in runs done at an island-wide scale might consider mapping seawalls more thoroughly.

Relief was ranked by taking the average elevation of the land within a 2,000m averaging radius, and assigning ranks of 1-5 based on the quantile distribution of all values. The averaging radius was optimized to capture major changes in elevation along the shoreline but smooth out inaccuracies in the topographic data. Two kilometers was a good radius for the large spatial scale over which the model was run and the relatively coarse globally available topographic data (see Table 2). If running this model at an island-wide scale, a user would likely want to use a smaller averaging radius.

A number of different *natural habitats* were included in this analysis including mangrove, coastal coppice and pine forests, coral reef, and seagrass beds. Data sources are listed in Table 2. Coral reef were filtered by depth, such that reef >20m deep was assumed to not be providing any coastal protection and was excluded from the analysis. The remaining 'shallow' reef was assigned a rank of 1, as was dense mangrove and coastal coppice forest. This reflects the demonstrated ability of these habitat types to function as effective wave attenuators. Pine forests, sparse mangrove and the swash swamp dwarf mangrove habitat types were giving a rank of 3. Seagrass was given a rank of 4. The individual habitat ranks were combined into one 'habitat role' value, which was incorporated into the final hazard index (see Arkema et al. 2013 supplement). In the 'without habitat' scenario, the 'habitat role' value was set to a rank of 5.

Sea-level change This analysis did not include any spatially explicit information about sea-level rise due to a lack of local tide gauge data. Instead, we looked at the relative increase in risk assuming uniform sea-level rise across the entirity of The Bahamas. To do this, a planning horizon of 2040 was assumed for this analysis. Based on the SLR curves in Parris et al. (2012) sea-level change for 2100 was set to a rank of 5 and current SLR (2014) was set to a rank of 1.Looking at the shape of the curve a rank of 2 was estimated for 2040 to reflect the relative change in SLR from current to this time step. To summarize, current SLR was represented by a rank of 1 and future SLR (in 2040) by a rank of 2.

Wave exposure was calculated based on wave power values extracted from a globally available dataset of modeled wave statistics called WAVEWATCH III. Wave exposure is calculated for oceanic and locally wind-generated waves, as sheltered coastline segments are exposed only to local waves. The final ranks are assigned based on quantile distributions of the wave power values (see Table 1 below).

Surge potential was based on the distance from each shoreline segment to the edge of the continental shelf. As discussed earlier, the distance to the shelf is a proxy for storm surge potential based on the fact that shallow approaches allow water to 'pile up' during storm events, causing the phenomena of storm surge. Initially there was some concern over how to accurately capture the complexity of storm surge in The Bahamas, and modeling storms approaching from different directions was discussed as a possibility. It was later decided that it was beyond the scope of the model and available data to try and represent different storms, and that the storm surge potential gave an accurate representation of potential risk. The storm surge proxy was compared to modeled values from SLOSH modeling conducted by the National Hurricane Center, and the relative relationship of surge potential across the region agreed well between the two methodologies (Rolle 1990).

Rank	Very Low	Low	Moderate	High	Very High
	1	2	3	4	5
Geomorphology	Rocky; high cliffs; fiord; **seawalls**	'Structure'; Medium cliff; bulkheads and **small seawalls**	Low cliff; rip-rap walls; **rocky coral shoreline**	Cobble beach; **muddy shoreline;** lagoon; bluff	**sandy beach**
Relief	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Natural Habitats	**coral reef; dense mangrove; coastal coppice forest**	High dune; marsh	**pine forest; sparse mangrove; swash/swamp**	**seagrass**	**no habitat**
Sea Level Change	current sea level	future sea level (2040)			
Wave Exposure	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile
Surge Potential	0 to 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

Table 1: Variables and ranking system included in the Coastal Vulnerability model for The Bahamas. Ranks for relief, wind and wave exposure, and surge potential are based on the distribution of values for these variables for all 250 m^2 coastal segments of The Bahamas (these change with the geographic scope over which the model is run). Bolded text indicate shoreline types (geomorphology) and natural habitats that were included in the analysis, grey text indicate those types which were not found in The Bahamas (they've been left in for context). Sea level change was included in a simple additive way, where current sea level was assigned a rank of '1' and future sea level over a 2040 planning horizon was assigned a value of '2'. This assumes that sea level in 2100 would be a '5'.

b. Beneficiaries

Census data at the supervisory district level from the 2010 Bahamian Census was obtained from the Department of Statistics. Light intensity (a proxy for where people live) was extracted from all supervisory districts in The Bahamas from NOAA's Nighttime Lights Times Series (v.4, 2011) (https://www.ngdc.noaa.gov/ eog/dmsp/downloadV4composites.html). For each supervisory district a "demographic metric per unit of light intensity (DM/LI)" was calculated by dividing the demographic variables for that supervisory district by the summed light intensity for that district. The DM/LI ratio was then multiplied by the entire nighttime lights raster for that supervisory district to spread the demographic variable across the district. This methodology allows the demographic variables to be mapped at a finer resolution by using the relative weighting of the light intensity. Demographic variables that were mapped during this analysis include total population (people/500 m^2), elderly people as a % of the total population (>65), and young people as a % of the total population (<15).

c. Data Inputs

Table 2. Data inputs to the Coastal Vulnerability model

Model Input	Description	Year	Extent	Source
Area of Interest	(Vector) This defines the Area of Interest (AOI) for the model run.	2016	The Bahamas	Created by Natural Capital Project.
Land Polygon	(Vector) This input provides the model with a geographic shape of the coastal area of interest, and instructs it as to the boundaries of the land and seascape.	2016	Global	NOAA Global self-consistent, hierarchical, high-resolution geography database (GSHHG)
Bathymetry and Topography	(Raster) This is used to calculate to relief in the Coastal Vulnerability model	2016	The Bahamas	BathyTopo (30m) created by Steve Schill of TNC Caribbean from (1) digitized nautical charts, (2) WRI bathymetry data, and (3) SRTM topography.
Natural Habitats	(Vector) Maps the type and extent of habitat.	Varies	Varies	See **Habitat** section below.
Shoreline Geomorphology	(Vector) Geomorphology is the shoreline type (sandy beach, rocky beach, low cliff, muddy shoreline, etc.).	2016	The Bahamas	Caribbean-wide maps created by TNC digitizing beaches and rocky shores were edited and expanded to include other shoreline types (e.g. muddy shorelines) by NatCap staff.
Wave and Wind Field	(Vector) These inputs are used by the model to	2005-2010	Global	Globally available NOAA WaveWatch III data is available as default data with the model and is considered adequate. Wave and wind exposure

	calculate wind and wave exposure.			are calculated based on six years of data.
Continental Shelf	(Vector) This input is used by the Coastal Vulnerability model to calculate storm surge rank.		Global	A globally available dataset of the continental margins was prepared by the Continental Margins Ecosystem (COMARGE) effort in conjunction with the Census of Marine Life, and is available as default data with the model.

Habitat	**Source**	**Year**	**Extent**	**Description**
Pine	Rapideye	2009	Andros Island	Interpretation of Rapideye Imagery
Pine	Digitized Topography maps	1970	The Bahamas (excepting Andros)	Digitized topo maps edited by NatCap staff to reflect large changes in land cover detectable on satellite imagery.
Coppice	Rapideye	2009	Andros Island	Interpretation of Rapideye Imagery.
Coppice	Digitized Topography maps	1970	The Bahamas (excepting Andros)	Digitized topo maps edited by NatCap staff to reflect large changes in land cover detectable on satellite imagery.
Mangrove	Landsat and Rapideye	2005, 2009	Andros Island	Interpretation of Landsat Imagery, excluding areas interpreted as pine or coppice with Rapideye. This was divided into dense mangrove and sparse mangrove/swash swamp.
Mangrove	Digitized Topography maps	1970	The Bahamas (excepting Andros)	Digitized topo maps edited by NatCap staff to reflect large changes in land cover detectable on satellite imagery. This was divided into dense mangrove and sparse mangrove/swash swamp.
Seagrass	National Coral Reef Institute (NCRI), Landsat	2010, 2005	Andros Island	NCRI data for seagrass within the bounds of NCRI coverage and Landsat seagrass data outside the bounds of NCRI.
Seagrass	Landsat	2005	The Bahamas (excepting Andros)	Landsat seagrass data.
Coral	National Coral Reef Institute (NCRI)	2010	Andros Island	All coral types restricted by depth (<20m).
Coral	Millenium Coral Reef Mapping Project	2009	The Bahamas (excepting Andros)	All coral types restricted by depth (<20m).

d. Data Gaps and how this project addresses and filled these gaps As with all modeling efforts, the best available data and science should be used. Updates to datasets should be conducted regularly to ensure significant on the ground changes are captured. As new data become available, the model should be re-run and the results in the viewer updated. With that said, we've highlighted below some key existing data gaps that should be prioritized for update and new data collection.

The key data gap in this analysis is out-of-date habitat data for Coppice, Pine and Mangrove forests for all islands of The Bahamas except for Andros. We compared these datasets to current satellite imagery and in many areas the habitat maps were remarkably accurate. Major discrepancies were corrected manually. There are Landsat data available for The Bahamas for these habitats from 2005, but when compared to the 1970 data the Landsat data was much more coarse resolution and had a lot of inaccuracies. As a result, we conducted the analysis with the older, higher resolution data with some manual editing of the input habitat layers to reflect the changes evident in the satellite imagery. However, a comprehensive update of these data layers should be a high priority moving forward.

A second data gap prior this analysis was that there was no layer reflecting shoreline geomorphology. NatCap staff created a shoreline geomorphology layer, which was shared with partners and attendees to the December 2016 workshop and training in Nassau.

Lastly, there is no country-wide database on the location of seawalls or other types of hardened shorelines. The model can accommodate these data, and it would be advisable to invest in collecting this type of information in order to update model results and to inform future coastal zone management decisions.

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