Title
The Impact of Climate Change on Puerto Rico’s Cultural Heritage

Author
Ezcurra, Paula

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Foreword:

This text encompasses my Capstone Project portion of the Scripps Institution of Oceanography Climate Science and Policy Master of Advance Studies Program. The project was completed under the guidance of Dr. Isabel Rivera-Collazo, Assistant Professor on Biological, Ecological and Human Adaptations to Climate Change at the Department of Anthropology and Scripps Institution of Oceanography. My project committee members also included Heidi Batchelor, Dr. Lynn Russell, and Dr. Ellie Farahani. Special thanks are due to Dr. Jennifer Haase for providing additional feedback.

The purpose of this project was to perform an assessment of climate change impacts to material cultural heritage. This assessment will be part of the Puerto Rico Climate Change Council's (PRCCC) 2017 Report on Society and Economy. The work presented here is a notable improvement from their previous 2013 Report, that dedicated less than one page to the topic of Cultural Heritage and Climate Change. The PRCCC works to communicate with relevant stakeholders, such as policymakers or cultural heritage managers. In this case, cultural heritage managers can utilize the information presented here to create climate change adaptation strategies for specific cultural heritage sites. The text presented encompasses only the content that will be submitted to the PRCCC, and therefore excludes detailed information on the project process. For this information please see Appendix C. The case study on sea-level rise will also be used as part of a state of the issue assessment for the Puerto Rico Institute of Culture.

The work created from this project has already been used in several dissemination efforts. This assessment contributed to two presentations at the 82^{nd} *annual meeting of the Society for American Archaeology (SAA). The first was for the Opening Session/President's Forum on* Climate Change, Archaeology, and Community Engagements. *The second presentation was part of a symposium entitled,* Burning Libraries: Environmental Impacts on Heritage and Science. *This information was also presented at the PRCCC's* 8^{th} *Summit earlier this year, and used by the PRCCC to provide comments on the United States Global Change Research Program's* $4^{t}h$ *National Climate Assessment. However, despite these dissemination efforts, there are still barriers to translating this information into policy implementation.*

This project stayed under the originally proposed budget of $1,400. These funds were utilized for travel, lodging, and food to attend the aforementioned SAA annual meeting in Vancouver, British Columbia, Canada. Future work to improve upon this project should include further geographic information system (GIS) analysis for all climate parameters discussed, as well as analysis of specific site in Puerto Rico.

I plan to continue working on climate impacts to cultural heritage beyond the scope of this project including a scientific publication of the sea-level rise assessment, as well as to pursue further detailed analyses on other climate parameters that may help identify additional vulnerable sites.

Paula Ezcurra

MAS, Climate Science and Policy

Scripps Institution of Oceanography

Approved: ____

Isabel Rivera-Collazo, Ph.D.
UCSD Department of Anthropology
Scripps Institution of Oceanography

The Impact of Climate Change on Puerto Rico's Cultural Heritage

Contribution to the PRCCC Working Group 3 2017 Report

Paula Ezcurra

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Contents

1 Description

Puerto Rico is home to several historic and culturally significant heritage sites that are presently under threat from climate change. Understanding the ways in which change will impact heritage is the first step in creating appropriate adaptive strategies for the management of these sites. This text will focus on how specific climate impacts in Puerto Rico will affect archaeological heritage sites, using sea-level rise as a case study for assessing vulnerability. Additionally, the text will discuss ways to incorporate adaptive strategies for climate change impacts into cultural heritage management.

Puerto Rico has a long and rich cultural history than is apparent throughout the island, in part through its cultural heritage sites. The impact of climate change will have several important implications. Puerto Rico depends heavily on its tourist industry as a source of income, earning $3.44 billion dollars in international receipts in 2015, a 4% increase from 2014 (*International tourism, receipts*, n.d.). Climate change will have negative effects on Puerto Rico's tourism sector, ranging from impacts to the coastal infrastructure that supports the vacation industry, to damage to destination spots, including archaeological assets (Carrubba et al., 2013).

Heritage can be natural or cultural, tangible or intangible. The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines cultural and tangible heritage as (*Tangible Cultural Heritage*, n.d.):

> ***Cultural heritage*** *is the legacy of physical artefacts and intangible attributes of a group or society that are inherited from past generations, maintained in the present and bestowed for the benefit of future generations.*
>
> ***Tangible heritage*** *includes buildings and historic places, monuments, artifacts, etc., which are considered worthy of preservation for the future. These include objects significant to the archaeology, architecture, science or technology of a specific culture.*

Cultural heritage sites not only attract tourism, but also have significant value to local communities by playing a strong role in shaping an individual's identity. Tangible cultural heritage, also known as material heritage, evokes a strong sense of place and belonging. Geographic location shapes one's community and culture. Heritage is what connects a person with their community, home, and past (Altman & Low, 1992), linking today's societies with past traditions.

Through their work, archaeologists uncover forms of material heritage and help form narratives from the past. Additionally, public archaeologists work alongside communities to record, preserve, and interpret the past, aiding in the incorporation of public input into cultural heritage management plans (Richardson & Almansa-Sánchez, 2015). Environmental archaeology is also an important branch of the study of climate change. Studying past societies provides useful information about lessons learned from how past societies adapted to and altered a changing natural environment. Knowledge of what has taken place in the past improves present-day decisions about development and adaptation. In this way, cultural heritage sites also play a key role in climate adaptation, allowing archaeologists and others to learn from past ecological and climatic changes (Sutter, 2015). Consequently, the loss of cultural and historic sites also represents a loss of cultural knowledge regarding adaptation, among other things.

Climate change and its impacts (e.g. sea-level rise, precipitation changes, and extreme weather events) directly threaten to damage and/or destroy material heritage sites. Assessing the vulnerability of these sites and creating appropriate adaptive management plans is imperative to the preservation of Puerto Rico's cultural heritage. Specific adaptive management strategies that will increase the resilience of cultural landscapes (Beagan & Dolan, 2015) and the adaptive capacities of cultural heritage sites (Phillips, 2015) are imperative. Management strategies should also include early identification of sites at risk of total loss in order to create historic records and collections from these sites.

2 Climate Change's Effects on Cultural Heritage

In the Caribbean, climate change is expected to modify general atmospheric patterns and cause a wide range of impacts, due to the multitude of microclimates in the region. Working Group 1 of the Puerto Rico Climate Change Council (PRCCC) has identified changes in seven climatic parameters specific to Puerto Rico: air temperature, precipitation, extreme weather events, tropical storms and hurricanes, ocean acidification, sea surface temperature, and sea-level rise. This Working Group has also outlined predicted effects from projected conditions for the immediate future (Canals et al., 2013). In addition, the National Park Service (NPS) 2016 Cultural Resource Impact Table highlights how climate change will impact archaeological resources, buildings, and structures (Morgan, Rockman, Smith, & Meadow, 2016). This section summarizes the PRCCC's findings on these seven climate parameters including an eighth, erosion, and discusses the NPS's on how these climate projections will impact material heritage sites in Puerto Rico.

2.1 Air temperature

Puerto Rico is presently following a larger scale trend in warming air temperatures when compared to other islands in the Caribbean region. Since the 1950s, the island has seen an overall increase in annual mean temperature. Central regions of that are at higher elevation are experiencing faster warming rates than the rest of the island. Projections of future air temperature warming in Puerto Rico follow global patterns, except in urban areas such as San Juan, which are experiencing increased warming when compared to rural or vegetated regions. These increased warming rates in urban and coastal regions have been attributed to the urban heat island (UHI) effect. Studies in San Juan show a permanent UHI effect due to urban sprawl (Velazquez-Lozada, Gonzalez, & Winter, 2006), with an over 4°C increase in temperature (Murphy et al., 2011). This higher level of urban warming is projected to continue, with San Juan reaching an average temperature of 27°C by 2050, a 1.5°C increase from 1950 values.

San Juan has 69 known cultural heritage sites. Of these, 65 are historic and the remaining four are indigenous. Effects to cultural resources from increasing air temperatures include increased deterioration rates of recently exposed artifacts, and an increased rate of decay for organic material. Additionally, warming air temperatures will increase evaporation rates, leaving salt deposits on structures that can weaken them and lead to cracking. Such effects will occur not only in metropolitan areas, but also in higher elevation central regions that are also experiencing faster warming rates.

2.2 Precipitation

Due to its topography and geographical position in relation to trade winds and oceanic circulation, precipitation in Puerto Rico varies regionally. Climate change is expected to intensify these differences. Some regions, such as Old San Juan, exhibit a long-term trend of decreased precipitation (Lugo, González, & Pedraza, 2011), and future projections show a continuing decrease. On the other hand, southern regions of Puerto Rico which are historically drier, show a positive rainfall trend. The seasonal trends of precipitation distribution are also expected to intensify, with winters becoming wetter and summers drier. Overall, future projections predict a continuing decrease in rainfall.

Heritage sites in areas of Puerto Rico where rainfall is decreasing, and will continue to decrease, will experience drying soil that may heave or crack, leading to a loss of stratigraphic integrity, which is the preservation of sediment layers and important for determining the age of artifacts (Cassar, 2005). This drying will also make sites more vulnerable to the effects of fire or wind, and lead to the cracking and splitting of wood or organic materials.

In regions of the island where precipitation is increasing, higher relative humidity will accelerate the corrosion of vulnerable or less stable metals, increase the occurrence of mold, and increase the decay rate of organic materials. Further, the increasing intensity of individual precipitation events will cause erosion and soil destabilization, threatening structural stability of historic sites. Additionally, wooden materials will experience swelling and/or distortion, and ground around structures may erode, leaving them less supported. In cases where rainfall events are less frequent, but more intense, there will be more repeated wetting and drying of materials, accelerating their decay. In these regions, adobe materials are at particular risk of damage and loss from increased precipitation and drying (*Preservation of Historic Adobe Buildings*, 1978).

2.3 Erosion

Though erosion is a naturally occurring process, climate change impacts can increase the occurrence of erosion events and accelerate rates of erosion. For example, wave action, which causes erosion, increases with more frequent storm events and hurricanes. Projected rainfall trends of shorter, but more intense periods of rain will exacerbate erosion in many regions. Currently, some coastal regions of Puerto Rico are experiencing an increase of coastal erosion at an annual rate of up to 1 meter due to poor management and rising seas.

Erosion is difficult to predict, in part because there can be sudden and drastic erosion occurring over a short period. The potential for these sudden marked erosion events make it a particularly severe threat to heritage sites, which can lose structural stability in a short time and incur extensive damage. In some cases, the complete destruction of sites may even result. Erosion can also expose previously buried materials, which are then at risk from wind and wave action, as well as from looting.

2.4 Extreme weather events

Extreme temperature

Puerto Rico has shown similar extreme temperature trends to the rest of the Caribbean region, with the number of very warm days and nights increasing, while the number of very cool days and nights decreasing. Between 1900 and 1949, there were approximately 100 days per decade with temperatures 32.2°C, the same number observed in just one year in 2010.

The effects of extreme air temperature increases on material heritage in Puerto Rico will be like those expected to result from increased air temperatures described above. However, when temperatures reach extremes, materials suffer additional stress from sudden thermal expansion or shock. This causes cracking in materials, such as the pipes of historic buildings.

Extreme precipitation events

In North America, there has been a 20% increase on average in the amount of rain that falls in the heaviest downpours. This trend is projected to continue, with the largest increases taking place in the wettest regions. This trend can be seen in Puerto Rico, where there has been a 37% increase in very heavy precipitation. This does not mean that there has been more rain overall, but rather that there has been an increase in the intensity of individual rain events. Due to the rarity of extreme events, however, there is limited data available for making future projections. Because of this, there are conflicting projections for extreme precipitation in Puerto Rico. However, projections for the Caribbean region overall suggest increases in the incidence of extreme precipitation events, despite decreasing total rainfall. In other words, rain will be less frequent, but more intense.

Moreover, large quantities of rainfall during short periods of time increase the probability of flooding. Flooding will cause direct physical damage to material heritage, leading to destruction of sites, and in some cases their total loss. In addition, extreme flooding creates new flood channels—a major driver of erosion—which leaves sites damaged and structures weakened, increasing the chance of subsidence. Standing water that does not drain adds force to wall exteriors, potentially causing them to cave.

2.5 Tropical storms and hurricanes

Starting from the early 1760s to the early 1990s, the North Atlantic experienced a decrease in hurricanes2 Since 1995, however, hurricane activity has increased. This increase cannot be entirely attributed to anthropogenic climate change, and also may be a result of natural variability (Nyberg et al., 2007). Projections of future hurricane activity are difficult to make, especially on regional scales, due to uncertainties in modeling parameters. However, various studies predict a decrease in frequency, but increase in intensity of hurricanes on a global scale (see: (Gutowski et al., 2008)). Thus, in addition to occurring more often, hurricanes will have greater wind speeds and heavier precipitation, and therefore greater destructive power. On a local scale, winter swells may increase in intensity along the coast of Puerto Rico. Further, increased sea surface temperatures in Puerto Rico are likely lead to more intense rainfall, wind, and storm surge events, with the southern portion of the island receiving the most severe wind damage from Atlantic hurricanes.

Furthermore, these increasingly intense storms and hurricanes will cause stronger storm surges, which exacerbate the erosion of coastal sites. Underwater sites will also be impacted, often in the form of destabilization or damage from movement of sediments. Finally, stronger winds cause direct damage to materials, and secondary damage from wind-blown debris that may collide with site structures.

2.6 Ocean acidification

As emissions of carbon dioxide (CO_2) into the atmosphere increase, oceanic uptake of CO_2 also increases, resulting in reduced pH and carbonate saturation states in the ocean, a phenomenon termed ocean acidification. These effects lead to decreased calcification rates and decreased precipitation of carbonate minerals (e.g. calcite, aragonite, etc.), which has adverse effects on marine biological and geophysical processes. Puerto Rico reflects regional and global trends in ocean acidification rates, showing a decrease in average pH and carbonate saturation state. Specifically, the values of aragonite saturation states are declining at a rate of 3% per decade in Puerto Rico. These patterns of ocean acidification are projected to continue with continued emissions.

Submerged cultural sites containing metal will experience corrosion with continued ocean acidification. In addition, coastal cultural resources with stonework constructions, especially those made from limestone or mortar, will degrade upon coming into contact with increasingly acidified ocean water. Lastly, cliffs with lime and shell components will erode faster.

2.7 Sea surface temperature

Caribbean Sea surface temperatures have warmed by 1.5°C over the last century. Sea surface warming trends on the Caribbean coasts of Puerto Rico are faster than those on the Atlantic coasts, and subsurface temperatures are increasing faster than surface temperatures. An increase greater than 1°C over a 50-year period can be expected, with temperatures above the threshold for coral bleaching occurring for approximately one-third of each year (Hoegh-Guldberg, 1999), and the threshold for deep convection storm formation exceeded year-round. In marine environments, sea surface temperature increases will accelerate the rusting of underwater and tidal zone cultural resources.

2.8 Sea-level rise

Sea-level rise trends measured in Puerto Rico are consist with global trends. Historical records from tidal gauges since 1900 show a sea-level rise rate of 1.7 mm yr^{-1}. Recent satellite data beginning from 1992 shows an almost doubling of this rate to 3.2 mm yr^{-1} (Parris et al., 2012). As with historic trends, future projections for Puerto Rico parallel global estimates. The National Oceanographic and Atmospheric Administration's (NOAA) 2017 technical report recommends updating sea-level rise bounds for end-of-century projection to 0.3 m from 0.1 m in the lower bound estimates, to 2.5 m from 1.8 m in the upper bound estimates (Sweet et al., 2017). Additionally, the Caribbean region, including Puerto Rico, has been highlighted as a region vulnerable to coastal flooding from sea-level rise (Nicholls & Cazenave, 2010).

An analysis conducted by Dr. Isabel Rivera-Collazo for the PRCCC demonstrates how sea-level rise affects, and will continue to affect, coastal cultural heritage sites in Puerto Rico. Using archaeological data from the Puerto Rico Institute of Culture (ICP for its Spanish name, *Insitituto Cultural Puertorriqueño*) along with sea-level rise projections from NOAA, Dr. Rivera-Collazo assessed the vulnerability of individual archaeological sites in Puerto Rico that lie below 20 meters in elevation. Sea-level rise values of 0 to 1.8 meters in increments of 0.3 m (representing projected values from present day to the end of the century) were mapped onto point data of individual sites to determine how many sites are at-risk of inundation at the highest high tide.

There are a total of 1,185 known archaeological cultural heritage sites in Puerto Rico (Figure 1). Of these sites, 27 are already inundated at high tide. With an increase of 0.6 meters in sea-level (projections for mid-century) 56 sites will be inundated at the highest high tide. The value of inundated sites jumps to 140 for a 1.8-meter projection in sea-level rise (estimate for the end of century).

Figure 1: 1,185 known cultural heritage sites in Puerto Rico that lie below 20 meters in elevation. Sites are broken down into era (historic, indigenous, multicomponent, or unknown). Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's online sea-level rise data download.

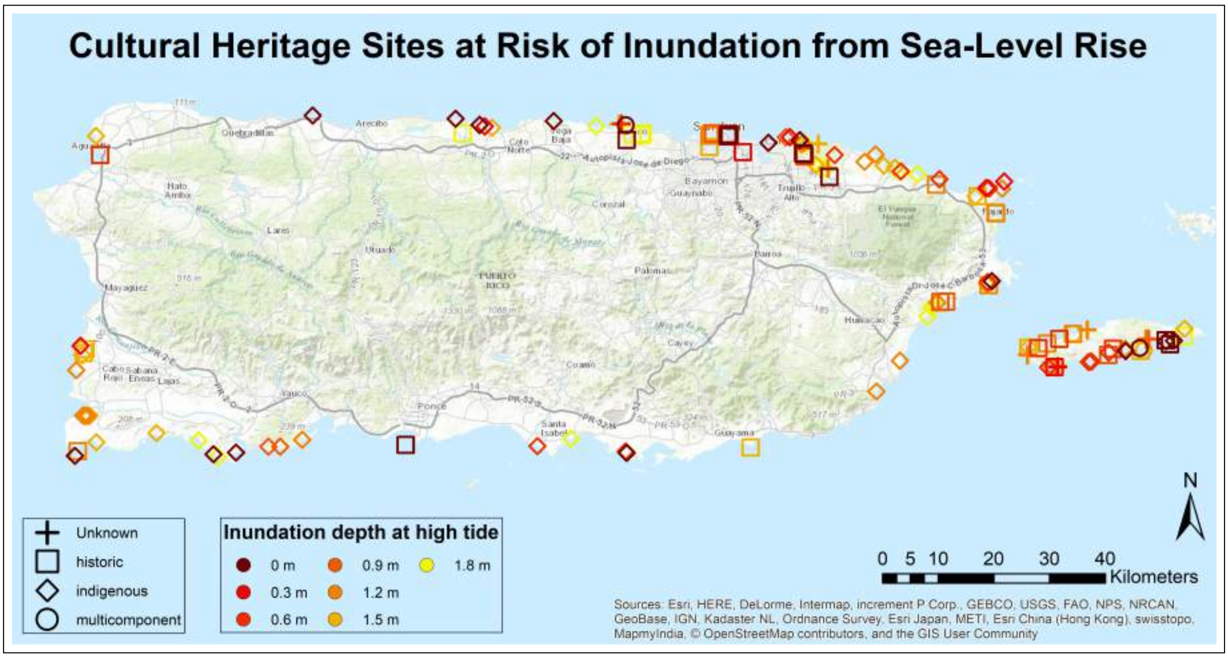

Figure 2: Sites at risk of inundation from 0 meters (present day) to 1.8 meters (projection for 2100). Sites are broken down into era (historic, indigenous, multicomponent, or unknown). Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's online sea-level rise data download.

The breakdown of sites by era can be seen in Table 1 below. Sites are categorized as either historic, indigenous, multi-component, or unknown. Of the overall 1,185 sites, 555 are historic, 534 are indigenous, 48 are multi-component, and the remaining 48 are unknown. Figure 2 displays these 140 sites, broken down by inundation at differing degrees of increasing sea-level. There are two regions for which there is no sea-level rise data: Isla de Mona, containing 21 of these sites (4 historic and 17 indigenous), and Isla Caja de Muertos, containing 1 historic site.

With a 0.6 meter rise in sea level, projection for mid-century, 69 sites lay within 1 meter above the high tide line. With a 1.8 meter rise in sea level, projection for end-of-century, 148 sites lay within 1 meter above the high tide line. Though not directly shown to be inundated by projected sea-level rise, these sites should site be noted as vulnerable for three reasons. First, as discussed above, recent recommended upper-bound projections for sea-level rise by 2100 are now well above 1.8 meters. This implies that sites not marked as inundated could potentially still experience inundation in extreme cases. Second, the archaeological data used to map each site is represented by a single point per site, but in reality, sites are multi-dimensional and expand beyond the point on the map in all directions. Therefore, it is likely that some of these sites do extend into the sea-level rise range. Finally, even if not at direct risk of inundation, sites with close proximity to the high tide line are increasingly vulnerable to other climate impacts including wave action and erosion.

Figures 3, 4, 5, and 6 in Appendix A highlight specific regions in Puerto Rico that have numerous sites at risk of sea-level rise. They are: Cabo Rojo, Loíza, San Juan, and South Vieques Island, respectively. The island of Vieques is projected to have a total of 33 sites affected, particularly across its southern coast. The northeast region of Puerto Rico, from San Juan to Fajardo is shows a total of 49 impacted sites. The southwest region of Puerto Rico, near and around Cabo Rojo, has 20 affected sites.

Rising seas will lead to the formation of a new intertidal zone, exposing formerly dry regions to periodic wetting and drying, thus increasing the rate of degradation of materials buried in that zone. Additionally, some coastal sites may become permanently flooded or submerged. This will limit access to sites and can lead to complete destruction or loss of a site. Further, salt water intrusion will lead to the deterioration of material, due to changes in the chemistry to surrounding soil and water (Colette & Cassar, 2007). This deterioration can include corrosion, salt deposits, and rusting. Ocean water encroachment along the coastline will also increase the height of the water table, damaging stratigraphy and buried artifacts, and increasing rot of organic materials. Finally, intrusion of salt water will alter the chemistry of the soils surrounding a site, increasing deterioration of artifacts from corrosion and rusting.

Table 1: Breakdown of site type, and how many of those types are projected to be inundated by 2050 and 2100. Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's online sea-level rise data download.

Site era	**Overall numbers**	**Inundation by 2050**	**Inundation by 2100**
Historic	555	18	46
Indigenous	534	34	81
Multicomponent	48	2	4
Unknown	48	2	9
TOTAL	1,185	56	140

3 Climate Change Adaptation Strategies

The ICP has identified 1,185 cultural heritage sites in Puerto Rico located below 20 meters in elevation. Providing adequate adaptive management to this large number of sites is a challenging task. In order to begin addressing how to incorporate climate impacts into adaptation management of cultural heritage in Puerto Rico, this section discusses three existing adaptation strategies. The first is a UNESCO strategy created for State Parties to implement appropriate management of World Heritage Sites in response to climate change from their 2007 report, *Climate Change and World Heritage* (Colette & Cassar, 2007). The second strategy comes from the National Park Service's (NPS) 2016 report, *Cultural Resources Climate Change Strategy*, which lists recommended directions for actions to best preserve and learn from cultural resources in the context of climate change (Rockman, Morgan, Ziaja, Hambrecht, & Meadow, 2016). Lastly, a model for prioritizing sites based on vulnerability designed by the Scottish Coastal Archaeology and the Problem of Erosion (SCAPE) Trust is also presented (Dawson, 2013).

3.1 UNESCO *Climate Change and World Heritage*

Though originally written for World Heritage Sites, this 2007 UNESCO Report also provides useful information on the local-level aspects of designing of management plans that account for climate change, and is therefore relevant to the management of any cultural heritage site. The main objective of the UNESCO Report is to introduce key topics that should be considered in the drafting and implementing of management plans that address climate change impacts. This section will focus on the local-level action that cultural heritage managers in Puerto Rico can take regarding adaptive management of heritage sites, as set out in the Report. Most notably, an adaptive management plan should be—as the name implies—adaptive, meaning that reevaluated management priorities should accompany refined climate projections. Additionally, once implemented, management actions should be monitored and continuously improved.

The Report highlights the need for conducting vulnerability assessments that interpret climate change data for local site impacts. This information can then be combined with maps of heritage sites to obtain an overview of risks to cultural heritage, as was done with sea-level rise in the previous section (see section 2.8: Sea-level rise). Information on site vulnerability makes it possible to develop detailed adaptation strategies by highlighting sites at risk of specific climate impacts. Assessing individual sites for vulnerabilities allows Puerto Rico cultural resource managers to incorporate site-specific action into management strategies. Such actions include: emergency preparedness planning, rigorous and ongoing monitoring and maintenance, and development and enhancement of traditional skills.

The UNESCO Report also outlines two aspects of site monitoring: community monitoring and professional monitoring. Professional monitoring includes the use of monitoring instruments, remote sensing products, and bio-sensing tools. In contrast, community monitoring is monitoring carried out by local members of the public, ideally after receiving education about the significance of heritage and the importance of observing and reporting changes to heritage sites.

Beyond monitoring, the Report also recommends that community participation be included in management planning and implementation to ensure that they reflect local knowledge systems and the way they understand and adapt to changes in climate. Along these same lines, communication and awareness programs are important parts of building political and public support for the preservation of cultural sites. These programs can include actions such as workshops, exhibitions, media campaigns, or publications providing local relevance to climate change phenomena.

The UNESCO Report emphasizes the importance of sharing knowledge on both local and regional scales. To preserve cultural heritage from climate change threats, communities need to interact between members of different generations. By learning of past climate events, present generations can learn from past knowledge about a given place and apply lessons about its adaptive capacity for future generations. On a more regional level, organizations should share management plans and strategies. By coordinating information on training courses, risk assessments, monitoring, and adaptation, these institutions will strengthen capacity building.

3.2 NPS *Cultural Resources Climate Change Strategy*

This 2016 NPS Report identifies directions for action under four overarching goals: "connect impacts and information," "understand scope," "integrate practice," and "learn and share." These actions are steps to address cultural resources and climate change. In addition, the Report provides an eight-part concept framework that displays the four pillars of climate change response (science, adaptation, mitigation, and communication) in the context of climate change impacts on cultural resources. The framework also displays the information that these resources can provide to teach us about past climate conditions. Table 2, found in Appendix B, displays the framework as presented in the NPS Report. Each pillar is divided between impacts (how a changing climate may affect the preservation and maintenance of a cultural resource) and information (how cultural resources can provide information about past human interactions with environmental change).

The NPS Report highlights that management decisions should prioritize cultural heritage based on its vulnerability and significance while engaging stakeholders. Areas found to be most at-risk should then be prioritized for inventory. Additionally, the Report also recognizes the potential for total loss of sites, and the importance of monitoring and record keeping. Like the UNESCO Report, this NPS Strategy emphasizes local, national, and international collaboration to learn from and share transferable tools and techniques on the subject of climate change and cultural heritage.

NPS's framework and directions for actions are applicable to Puerto Rico's adaptive management of its cultural heritage. In one case presented, the San Juan National Historic Site restored historical waster cisterns in two fortifications. By combining current technology with engineering from the 18th Century, seven cisterns were restored with a combined total capacity of 932,000 gallons for rainwater storage, supplying non-potable water for park utilities. This example demonstrates how aspects of the NPS concept framework have been applied to cultural resources.

In the Report, the NPS presents programs that help meet their fourth goal (learn and share) which includes coordinating with partners to learn from and share approaches to dealing with climate impacts to cultural resources. One such example that has transferable tools and techniques created by the SCAPE Trust is discussed below.

3.3 Nine-step model for site prioritization

In order to assess the threat of erosion to Scottish cultural heritage, the SCAPE Trust undertook a site prioritization project. From this project, a nine-step model emerged to determine the vulnerability of individual sites and to subsequently set a priority level for each site. The model, as described by Dawson (2013), collects physical data on the parameter in question, such as erosion, and combines that data with geographic data of cultural heritage site location to assess which sites are most vulnerable. The model then categorizes the sites based on their type (e.g. historical, indigenous, etc.) and archaeological importance (e.g. era, time period, etc.). The vulnerability level combined with the group classification together sets a priority level for the sites. This way, cultural heritage managers can begin to sort through their many at-risk sites and address them in a specific order. The model also suggests actions for specific sites. The first action is to visit the site to assess its current state. This is important, especially when considering erosion, as many changes may have taken place since the site's original survey, and a new priority level may be more appropriate. Subsequent actions may depend on what was found during the first action, and includes options such as desk assessment, survey, monitoring, excavation, management plan, or nil. There is often more than one necessary action. Though created in Scotland, this model can be applied to coastlines in other regions (Dawson, 2013). The work presented earlier in this text for assessing sea-level rise impacts to Puerto Rico's cultural heritage sites—creating a database and standardizing records—demonstrates the first two steps of the nine-step model as applied to sea-level rise impacts on the island's cultural heritage sites.

As Dawson points out, the current nine-stage model assesses priority based on the site's group classification and physical vulnerability, but this could change when the needs of the community are taken into consideration. The SCAPE Trust's most recent project, Scottish Coastal Heritage at Risk (SCHARP), incorporates citizen science monitoring of at-risk sites using a mobile application. Having local community members that are visiting a site utilize the application allows for the updating of site records while instilling a sense of ownership and stewardship in local communities. SCHARP also uses *ShoreDig*, a project that works to consider the value and meaning that at-risk cultural heritage has to local communities, and alters preservation options to incorporate community input and concerns. Puerto Rico can utilize these existing tools to incorporate multiple voices into the discussion of priorities. Notably, SCHARP has already been adapted for new programs in other parts of Europe (Rockman et al., 2016). Site databases should include not only priorities for researchers and governments, but also for communities. This way the final priority level determination reflects a multitude of inputs.

4 Research Needs

As mentioned above, the most at-risk regions should be prioritized for inventory. While there are 1,185 known sites in Puerto Rico below 20 meters in elevation, there are potentially many more unidentified sites both along the coast and across the island. Adaptive management strategies are incomplete without a comprehensive list of known sites. In Puerto Rico, this means prioritizing regions of the island that are likely to experience the greatest impact from climate change, such as the coasts. A comprehensive survey of the coast of Puerto Rico will assist in identifying all sites, and improve the capability of any adaptive strategy utilized.

As mentioned earlier, Puerto Rico depends heavily on tourism, but the breakdown of earnings between tourism sectors is unclear. In order to assess the economic value that heritage sites provide, an economic assessment into what proportion of tourism earnings stems from cultural resources would allow for the measurement of costs to the island from damaged or destroyed sites.

There remain several gaps in knowledge regarding climate impacts to heritage. Though several impacts to cultural heritage sites have been mentioned here, there remain many uncertainties as to how climate parameters may alter, damage, or degrade material heritage (Curran, Routhier, & Mulukutla, 2016). There is also a need for research into new methodologies for the preservation of sites by record, in anticipation of total loss of certain sites (Murphy et al., 2011).

5 Conclusion

Climate change has already, and will continue to, impact Puerto Rico. These impacts include: changes in precipitation, with heavier and more intense rainfall occurring in many regions; increased air and sea surface temperatures; increased acidification of the ocean; increased rates of erosion from wind and wave action; more extreme weather events such as extreme heat, extreme precipitation, cyclones, and hurricanes; and rising sea-levels. These climatic impacts will affect physical heritage in many ways. Exposed artifacts will experience higher rates of deterioration. Some organic materials will decay faster. Wooden structures will become more susceptible to swelling, warping, or cracking. Ground around structures may erode, reducing the stability of sites. Buried materials exposed to increased wetting and drying will experience faster rates of decay. Extreme weather events can cause sudden damage, including damaging pipes of historic buildings, collapse of walls from flooding, and large rates of erosion occurring in short periods of time. Heritage in marine environments will additionally be at risk of corrosion, rust, and structural damage.

To address these climate impacts, both UNESCO and the NPS have produced reports to guide adaptive strategies for the management of cultural resources. Adaptation strategies must be implemented in a site-specific manner, in light of sites' unique management needs. Management plans should be revised in light of new information either about specific climate impacts, or success of specific adaptation strategies. Plans should also recognize the potential for total loss, and incorporate necessary record-keeping of certain sites. Lastly, communities, regional organizations, and international groups should all collaborate to learn from and share management tools to increase the resilience of management plans.

Following other organizations' existing models of assessment and prioritization will simplify the task of implementing site-specific adaptation strategies. For example, the SCAPE Trust's nine-step model for addressing erosion and cultural heritage is adaptable to other regions and other climate impacts, such as sea-level rise. The nine-step model allows for a methodical approach to ensure that the most at-risk regions are addressed. In addition, SCAPE's newest projects, SCHARP and *ShoreDig*, use citizen science to aid in the monitoring of sites. These projects promote stewardship in local communities, and help incorporate public concern and opinion.

Climate change impacts pose a specific threat to material cultural heritage. Historic and indigenous cultural sites are found across Puerto Rico, with over one-thousand located in low elevation coastal regions. Even if future climate change mitigation takes place, many of the projected impacts are already in motion, and adaptive response will be necessary in many sectors of Puerto Rican society. Puerto Rico's management of cultural heritage should incorporate adaptive strategies to ensure best practices, increased management resilience, and preparedness for potential loss of sites. To do this, a full assessment of the island, starting with the coast, is critical. Additionally, utilizing citizen science and public archaeology will serve as useful next steps in Puerto Rico's management and preservation of its cultural heritage. In Puerto Rico, public archaeology inclusive of communities that live near or value local heritage sites will lead to effective management practices by not only incorporating societal needs in prioritization, but also using citizen science to aid in the management and monitoring of these sites.

Climate change and cultural heritage have an intrinsic connection to one another. This nexus is one reason why the preservation of heritage is important, as highlighted by both the UNESCO and NPS strategies discussed earlier. Cultural heritage is not just at risk from climate change, it also plays an important role in the mitigation of climate change. Environmental archaeologists study past societies that provide useful information about how they adapted to and altered a changing natural environment. Knowledge of what has taken place in the past improves present-day decisions about development and adaptation. Also, heritage also strengthens an individual's identity within a specific place, and that attachment means they will care more and work harder to preserve that place. This is a major reason why engaging communities in public archaeology is a crucial step in climate adaptation.

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Appendices

A Sea-level rise regional maps

These maps represented four regions of Puerto Rico that contained a higher concentration of cultural heritage site at-risk of sea-level rise.

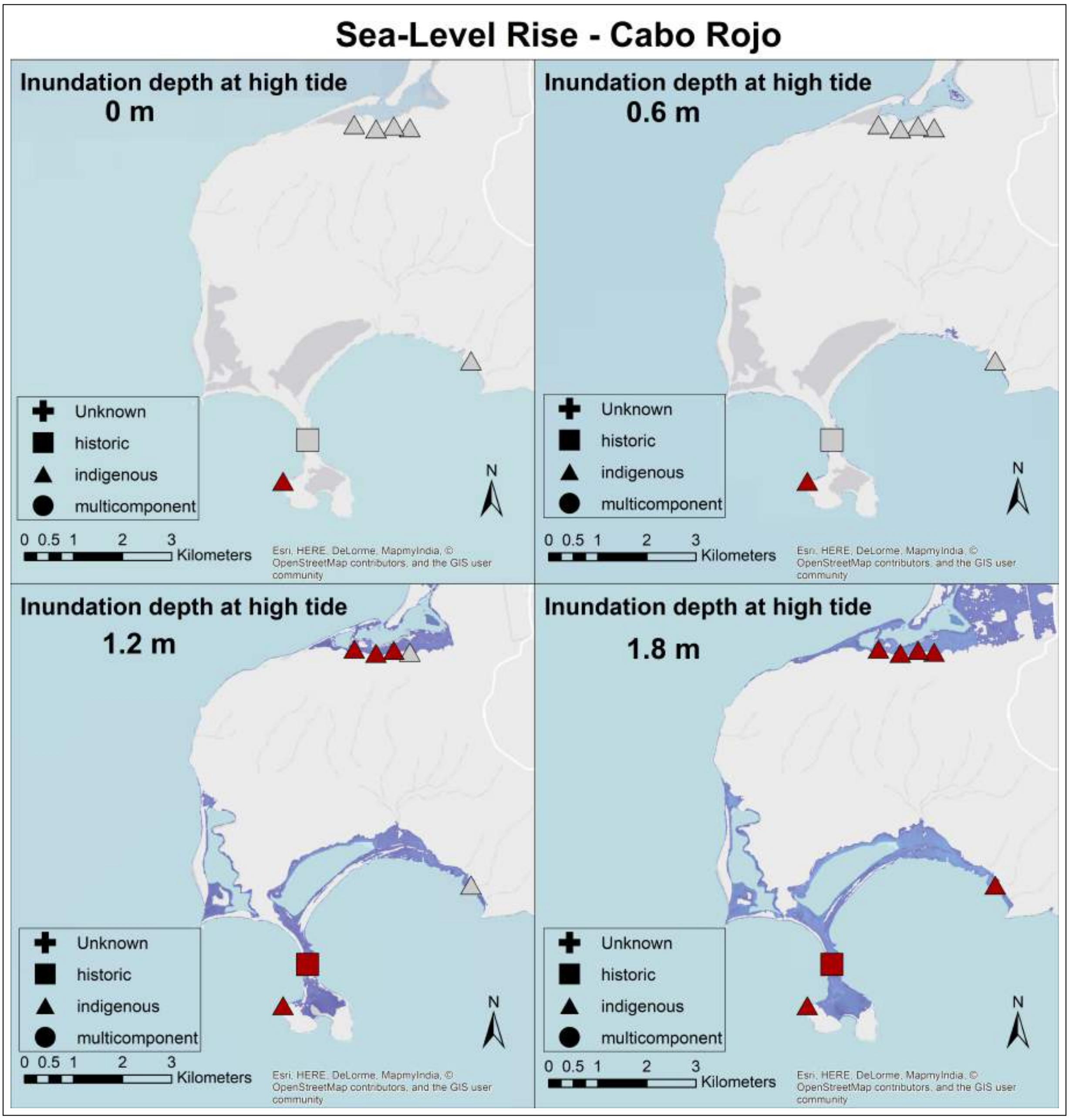

Figure 3: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in Cabo Rojo, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea-level rise projection for each quadrant. Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's sea-level rise data download.

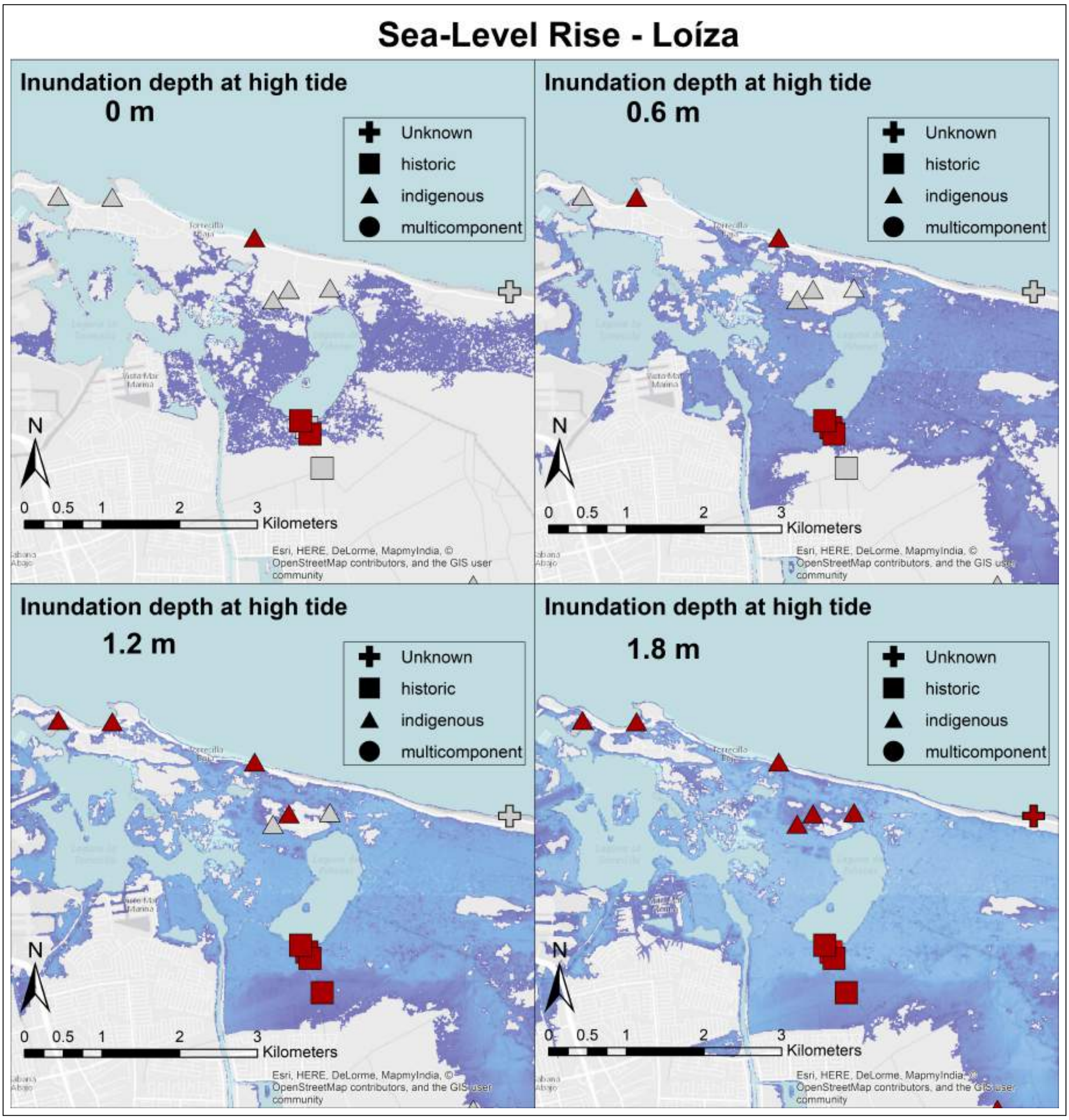

Figure 4: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in Loíza, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea-level rise projection for each quadrant. Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's sea-level rise data download.

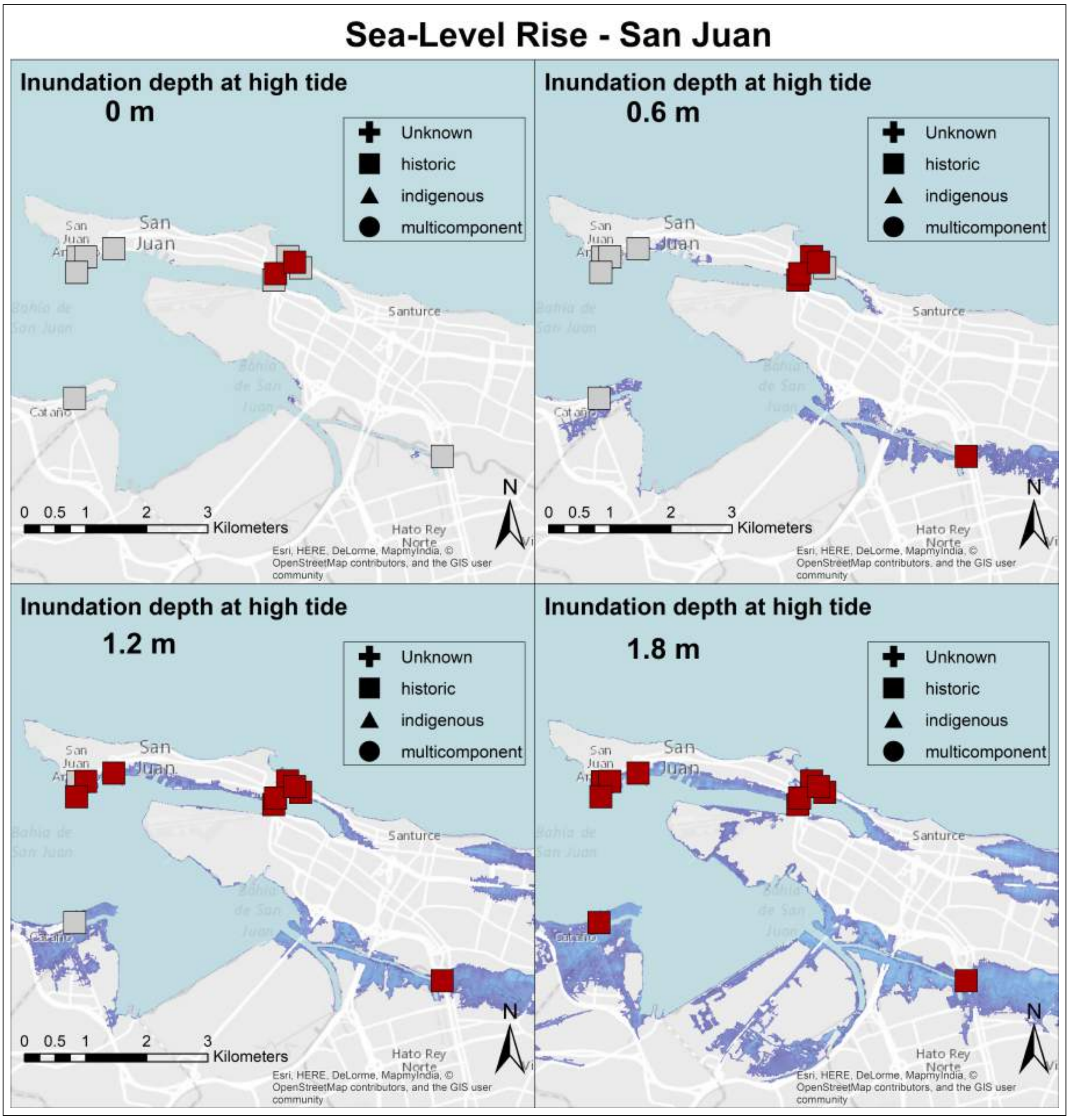

Figure 5: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in San Juan, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea-level rise projection for each quadrant. Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's sea-level rise data download.

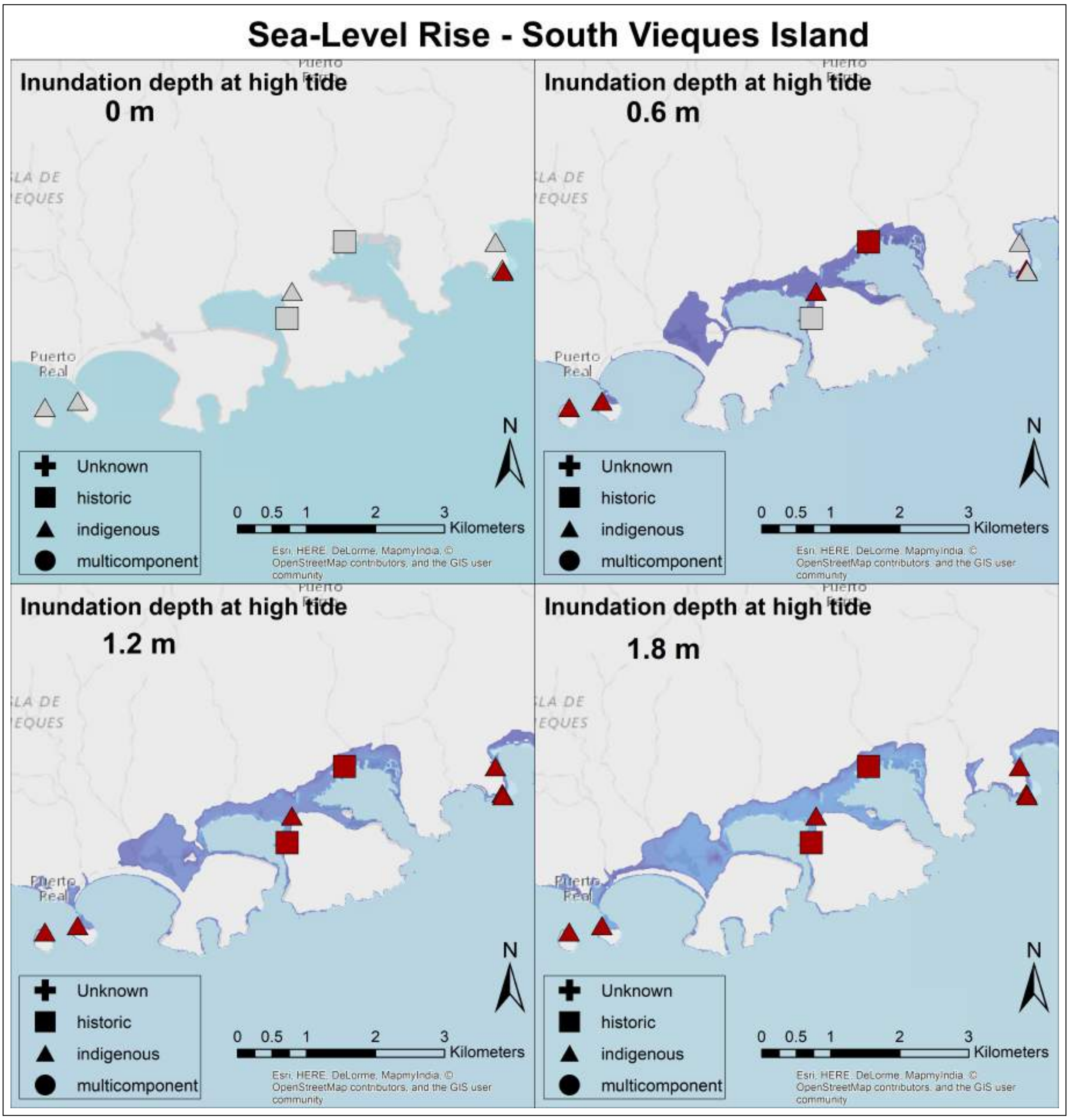

Figure 6: Sea-level rise projections of 0 m, 0.6 m, 1.2m, and 1.8m in the southern portion of Vieques, Puerto Rico. Red icons signify inundation at the highest high tide at the specific sea-level rise projection for each quadrant. Data sources: Archaeological data source obtained from the Puerto Rico Institute of Culture; sea-level rise data obtained from NOAA's sea-level rise data download.

B Table

Table 2: Concept Framework from the National Park Service for Cultural Resources and Climate Change (Rockman *et al. 2016*). This framework displays the four pillars of climate change response: science, adaptation, mitigation, and communication. Each pillar is divided between impacts (how a changing climate may affect the preservation and maintenance of a cultural resource) and information (how cultural resources can provide information about past human interactions with environmental change).

SCIENCE		**MITIGATION**	
Impacts	Information	Impacts	Information
· Climate science at cultural heritage-relevant scales	· Paleoclimate / paleoecology	· Integration of historic buildings into energy through historic or native landscapes	· Past architectural and landscape techniques suited to local environments
· Cultural resources (CR) vulnerability assessments	· Traditional ecological knowledge	· Reduce carbon footprint of CR management practices efficiency plants	· Cultural heritage to conserve/reestablish sense of place and community stewardship
· CR inventory / monitoring techniques and protocols	· Social climatic thresholds	· Resource conservation	
· Integrated CR databases-geographic information system (GIS)	· Shifting baselines		
· Preservation science	· Past land use and human impacts on environments		
· Documentation science	· Paleogenetics		
ADAPTATION		**COMMUNICATION**	
Impacts	Information	Impacts	Information
· Scenario planning	· Past social adaptability per environmental change	· Cultural resource climate change (CR-CC) literacy	Every place has a Climate Story:
· Adaptation options	· Traditional ecological knowledge	· Dialogue between impacts and information in all pillars	· Change in material culture
· Decision frameworks	· Relating past adaptability to current issues, methods, and decisions	· Links between CR-CC managers (local-tribal-intl.)	· Change in experience and lifeways
· Disaster risk reduction/response connections		· CR-CC links to public	· Insights on change from past societies
· Policies and standards			· Origins of the modern climate situation

C Project Methodology

C.1 Climate Change Vulnerabilities

The information gathered to determine climate change impacts specific to Puerto Rico came from the PRCCC 2013 Working Group 1 Report, and citations therein. Information regarding impacts of climate change to material heritage came from the NPS 2016 Cultural Resources Climate Change Strategy. An additional literature review was done for specific impacts to cultural heritage from sea-level rise for the case study assessment.

Decisions on which climate adaptation strategies to discuss here were based on recommendations from experts, and they reflect the most up-to-date and relevant information currently available for cultural heritage.

C.2 Data

Two datasets were used for this the sea-level rise analysis portion of the report, and are described below.

Archaeological data

This dataset was provided by the Peuerto Rico Institute of Culture (*Instituto de Cultura Puertorriqueña*), and contains all known archaeological heritage sites in Puerto Rico that lie below 20 meters in elevation, represented as point data. Though most sea-level rise analyses use a 10 meter limit to define low elevation coastal zones (LECZs), we requested data for 20 meters to have a more comprehensive list of sites that may be useful for future studies on other climate parameters. This data is not publicly available, and must be requested directly from the Institute.

Sea-level rise data

This dataset was obtained from the National Oceanographic and Atmospheric Administration's (NOAA) online (Sea Level Rise Data Download), searching specifically for Puerto Rico. The data set includes sea-level rise of 0.3-1.8 meters, presented by inland extend and relative depth of inundation above mean higher high water. For more information see the online accompanying metadata.

C.3 Analysis

This data was analyzed using a Geographic Information System (GIS). Both datasets were manipulated using ESRI's ArcMap software version 10.3.1. The maps displayed were created by overlaying the archaeological site data with the raster version of the sea-level rise data. The archaeological data was analyzed for number of site at risk from different degrees of sea-level rise, as well as for type of site (indigenous, historic, multicomponent, or unknown). The overlaying sea-level rise data was used to assess what sites were projected to be inundated with different degrees of rising seas (between 0.3 and 1.8 meters), as well as how many sites were within one meter of the highest high tide line.