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Original article

An assessment of the impacts of climate change on Puerto Rico's Cultural Heritage with a case study on sea-level rise

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ABSTRACT

In this paper, we summarize how current and projected climate changes are expected to impact material cultural heritage in Puerto Rico. As case study, we also conducted a spatial analysis vulnerability assessment of coastal heritage sites below 20 meters in elevation. Results from the analysis show that of the 1185 known cultural heritage sites below 20 m in elevation in Puerto Rico, 27 sites are inundated at today's highest high tide, 56 will be inundated by mid-century when assuming a 0.6 m rise in sea-level, and 140 sites will be inundated by end-of-century when assuming a 1.8 m rise in sea-level. Spatial analysis of sites adjacent to the high tide line demonstrate that these values are likely conservative, as there are many sites located within 1 m of the highest high tide line that should also be considered vulnerable. Finally, we present an introductory proposal that addresses the need for vulnerability assessments to aid cultural heritage managers in developing adaptive strategies for climate change impacts to material heritage.

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1. Research aims

Understanding the ways in which climate change impacts threaten cultural heritage is the first step towards creating appropriate adaptive strategies for mitigation. This paper focuses on identifying how the predicted climate impacts for Puerto Rico can be expected to affect archaeological and historical heritage sites and focuses on the predicted impact of sea-level rise over coastal heritage contexts. We address the need for vulnerability assessments and present an introductory proposal for the development of adaptive strategies for climate change impacts regarding cultural heritage management.

2. Introduction

Climate change is altering the biotic and abiotic processes and conditions that have led to the preservation of tangible cultural heritage at a globally [1–4] and in the Caribbean in particular [5,6]. Within the context of increasingly rapid change, and an urgent need to identify successful adaptation strategies – often in an instant – the loss of cultural heritage can intensify social vulnerabilities.

Puerto Rico has a long and rich cultural history that is apparent throughout the island and reflects its more than 5000 years of social processes. Aside from its expected physical, economic and social impacts, climate change will also have severe impacts to the material evidence of this cultural history. This issue is important to assess because tangible heritage is the physical basis for social identity [7–9], which supports community investment for action and protection of their natural environments [10].

Cultural heritage can also open the door to conversations about climate change and help transform the abstract numbers provided by scientists, into tangible, real life impact to local identities [11]. It also provides a significant means of revenue linked to cultural tourism [12,13]. Puerto Rico depends heavily on its tourist industry as a source of income, earning \$ 3.44 billion dollars in international receipts (expenditures by international inbound visitors) in 2015, a 4% increase from 2014 [14]. Climate change will negatively impact 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 [15].

Assessing the vulnerability of heritage sites and creating appropriate adaptive management plans is imperative to the preservation of Puerto Rico's cultural heritage, including specific adaptive management strategies that will increase the resilience of cultural landscapes [16] and the adaptive capacities of cultural heritage sites [17]. Management strategies should also include early

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identification of sites at risk of total loss to create historic records and collections from these sites.

3. Climate change 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 region's multitude of microclimates. 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 (SLR). This Working Group has also outlined predicted effects from projected conditions for the immediate future. In addition, the National Park Service (NPS) 2016 document, *Climate Change Impacts on Cultural Heritage*, highlights how climate change will impact archaeological resources, buildings, and structures. Here, we summarize the PRCCC's findings on the seven climate parameters including their effect on erosion, and discuss the NPS's review of how these climate projections will impact material heritage sites in Puerto Rico [18,19].

3.1. 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 the island – 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 [20], with an over 4 °C increase in temperature when compared to surrounding rural areas [21]. 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.

Effects to cultural resources from increasing air temperatures include increased deterioration rates of recently exposed artefacts, and an increased rate of decay for organic material [22]. As air temperature rises, relative humidity within the exposed artifacts falls, affecting its structural stability as well as the rate of microbial growth contributing to decay [23]. Additionally, warming air temperatures will increase evaporation rates, leaving salt deposits on structures that can weaken them and lead to cracking [19]. Such effects will occur not only in metropolitan areas, but also in higher elevation central regions that are also experiencing faster warming rates. This situation can be particularly detrimental for the preservation of sites with monumental architecture, such as coffee haciendas and indigenous ceremonial sites with ballcourt plazas such as the Late Ostionoid (ca. 1300–1600 AD) site of Caguana in Utuado.

3.2. 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 [24], 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. Future projections predict a continuing overall decrease in rainfall.

Heritage sites in areas with decreasing rainfall will experience drying soil that may heave or crack, leading to a loss of stratigraphic integrity, or the preservation of sediment layers. 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. Wild fires, fed by drying vegetation, changes in wind intensity, and higher temperatures pose a threat to historic *jíbaro*¹ and manor houses, tobacco and agricultural sheds, haciendas, ballcourts and shell middens, and many other cultural contexts, affecting the integrity and preservation of fragile objects.

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 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 and structures. Additionally, wooden materials will experience distortion, and the 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, clayey or poorly consolidated construction materials are at particular risk of damage and loss from increased precipitation and drying [22]. Sites with historic rainwater management infrastructure, such as irrigation channels or brick aqueduct tunnels, including the historic cities of San Juan, Arecibo, San Germán, Ponce, Guayama, and others, might not be capable of managing the increased water flow and may be damaged due to increased precipitation intensity [25].

3.3. Extreme weather events

3.3.1. Extreme temperature

Puerto Rico has shown extreme temperature trends within ranges similar to those observed in 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 has decreased. 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 changes on material heritage in Puerto Rico have been discussed above in Section 3.1. 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.

3.3.2. Extreme precipitation events

In North America, there has been a 20% average increase in the amount of rainfall during the heaviest downpours. This trend is projected to continue, with the largest increase, 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 [26], marked by higher occurrence of very intense individual rain events, although not an increased precipitation average. Due to the rarity of extreme events, however, there is limited data available for future projections. Therefore, there are conflicting projections for extreme precipitation in Puerto Rico. However, projections for the Caribbean region overall suggest increases in the incidence of extreme precip-

¹ *Jíbaro* is a local term that refers to the rural population who often lived off the land and/or worked for European landlords in the countryside, and their descendants in the present. *Jíbaro* ascendancy is a thick mix of ethnicities in different proportions, including people from indigenous, European (Spanish) and African heritage.

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