A climate vulnerability assessment of cultural heritage in the La Fortaleza and San Juan National Historic Site World Heritage Site

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ABSTRACT

Climate change poses a threat not only to the environmental and physical aspects of the places where people live, but also to their identities and ways of living, as well as those of the communities around them. Conducted as part of the requirements of the Master of Advanced Studies in Marine Biodiversity and Conservation at Scripps Institution of Oceanography (SIO), this capstone project consists of a climate vulnerability assessment of the La Fortaleza and San Juan National Historic Site World Heritage Site in Puerto Rico, based on a literature review of existing scientific data. Its purpose is to inform a broader effort led by SIO's Human Ecology Lab, which will complement this top-down approach with a bottom-up assessment of climate change threats to the area based on the perspectives of local stakeholders. This project includes two products: the full climate vulnerability assessment presented below and an online summary of its main findings with interactive maps, which can be found at https://arcg.is/1quumK. Ultimately, this project contributes to the ongoing development of a climate vulnerability assessment tool for cultural heritage that can be used independently by stakeholders to meaningfully assess the vulnerability of their own cultural heritage to climate change through a decentralized process that can inspire local climate action, inform decision-making at different levels, and be repeated consistently as the components of vulnerability change over time.

INTRODUCTION

For people around the world, the idea of home is tied to a sense of place and belonging that is key to their cultural identities. Together with other tangible and intangible aspects that make people who they are – such as social values, behaviors, livelihoods, landscapes/seascapes and all the knowledge derived from human experience – cultural identities form the broader concept of cultural heritage. As climate change threatens the environmental and physical aspects of the places where people live, including sites of particular significance for cultural heritage, it also threatens their identities and ways of living, as well as those of the communities around them (Rivera-Collazo et al., 2021).

In coastal areas, climate change impacts such as sea level rise and the increased frequency and intensity of storms mean that coastal erosion and flooding are likely to displace entire communities whose cultural identities and livelihoods are directly dependent on the ocean. For people who consider natural cycles as essential elements of their worldview, climate change poses a threat not only through displacement, but also as it alters and disrupts the seasons of the year, the migration of animals and other patterns of nature (Bear, 2000).

Cultural heritage and archaeological research methods can help identify locally sensitive and relevant solutions for climate change adaptation and mitigation. By examining evidence of past human experience with changing climates, as well as the cultural values and identities of local communities in connection to archaeological sites, we can gain crucial insights to inform appropriate, sustainable, and fair climate policies capable of engaging people and motivating action. Ultimately, what is at stake here is not just losing our homes, but losing ourselves (ICOMOS Climate Change and Cultural Heritage Working Group, 2019; Kohler & Rockman, 2020; Rushfield, 2021).

Lying at the intersection of climate change, cultural heritage, and policy, this capstone project consists of a climate vulnerability assessment of the La Fortaleza and San Juan National Historic Site World Heritage Site in Puerto Rico, based on a literature review of existing scientific data. Its purpose is to inform a broader effort led by the Human Ecology Lab at Scripps Institution of Oceanography (SIO), which will complement this top-down approach with a bottom-up assessment of climate change threats to the area based on the perspectives of local stakeholders.

BACKGROUND

The California Climate Vulnerability Index (CA CVI)

The top-down climate vulnerability assessment conducted for this project represents the first step of an integrated climate vulnerability assessment tool for cultural heritage being developed by SIO and the State Historic Preservation Office of California as a collaborative process to be led by local stakeholders (Rivera-Collazo et al., 2021). The California Climate Vulnerability Index (CA CVI) was initially tested in California in 2021. Its goals are to:

1. evaluate the vulnerability of cultural heritage to impacts from climate change drivers;
2. collaborate with local stakeholders to identify existing risks and hazards; and
3. stimulate a conversation between stakeholders about how to prioritize actions to reduce heritage vulnerabilities to damage and loss.

To achieve these goals, the integrated assessment combines two approaches: the first is a top-down assessment of climate change threats to the selected site based on existing scientific data, and the second is a bottom-up assessment built through workshops with a broad range of local stakeholders to analyze their own perspectives about risk, value, and adaptive capacity. Unlike the initial top-down assessment, the bottom-up assessment is not limited to a previously identified site, such as the La Fortaleza and San Juan National Historic Site World Heritage Site in this case. Instead, during the workshops stakeholders get to define in their own terms the geographical boundaries that are relevant to them. They also determine which attributes of cultural heritage they want to consider, how valuable these are to them and which climate change threats are most concerning in their views. The idea behind this approach is to ensure the inclusion of people who are usually excluded from traditional climate vulnerability assessments of cultural heritage, despite being closely connected to it as producers and users of heritage.

The CA CVI Conceptual Framework

Under the CA CVI conceptual framework, the concept of vulnerability is defined as a function of exposure, sensitivity, and adaptive capacity (Rivera-Collazo et al., 2021). Since the impacts of climate change are experienced differently by different groups of people depending on social context, these three components of vulnerability are adjusted by four social factors: governance, access to resources, culture, and access to knowledge and information. This applies not only to tangible cultural heritage (such as the fortifications and walls of the San Juan National Historic Site World Heritage Site), but also to intangible cultural heritage, which comprises all the elements that people perceive as important for them, including cultural identity, traditional knowledge, memories, history, songs, food, landscapes, and ecosystems, among others.

Within this framework, exposure is determined by the geographic location of heritage and the physical impacts of the climate change drivers affecting it. Sensitivity refers to how cultural heritage is valued and what its loss would mean to society. Together, exposure and sensitivity make up potential for impact, which can be mitigated by adaptive capacity. Adaptive capacity depends on how much people are able and willing to act to mitigate potential for impact, and thus reduce vulnerability.

The top-down climate vulnerability assessment of cultural heritage in the La Fortaleza and San Juan National Historic Site World Heritage Site conducted for this capstone project is the first step of a broader, integrated assessment of the area led by SIO's Human Ecology Lab, which is adapting the CA CVI model to the context of Puerto Rico.

METHODOLOGY

Using a top-down approach based on existing scientific data, this assessment consists of a review of the most up to date literature about climate change threats to the La Fortaleza and San Juan National Historic Site World Heritage Site in Puerto Rico, including both historical observations and future projections, when available. It focuses on the geographical boundaries of the La Fortaleza and San Juan National Historic Site World Heritage Site and on the exposure element of vulnerability as defined under the CA CVI conceptual framework, that is, the physical damage caused by climate change on the most tangible attributes of the cultural heritage found on site. This assessment also looks at the sensitivity element, considering the value of the site as recognized by its World Heritage status and inclusion in the National Register of Historic Places worthy of preservation. Following the CA CVI model, a broader range of perspectives will be included during the bottom-up portion of the assessment, which is beyond the scope of this capstone project.

Five main climate change threats relevant to Puerto Rico are covered in this document: increasing temperatures, decreasing precipitation, ocean acidification, sea level rise, and more frequent and intense storms (Puerto Rico Climate Change Council, 2022). As the last two are drivers of increased coastal flooding, an analysis of different coastal flooding scenarios based on geographic information system datasets available online is also presented to provide a visual indication of the impacts expected. The sea level rise maps were prepared with datasets downloaded from the Sea Level Rise Viewer online tool provided by the National Oceanic and Atmospheric Administration (NOAA), while the storm surge, threat index and landslide maps used datasets from the Coastal Resilience Evaluation and Siting Tool (Dobson et al., 2020).

ArcGIS Pro was used to overlay the coastal flooding datasets found with the geographical boundaries of the La Fortaleza and San Juan National Historic Site World Heritage Site, according to the most recent boundary modification adopted by UNESCO in 2016 (*La Fortaleza and San Juan National Historic Site in Puerto Rico – Maps)*. This analysis made it possible to quantify the area of the La Fortaleza and San Juan National Historic Site World Heritage Site affected under different scenarios and to identify which locations within the site are most threatened.

Finding data about all existing climate change threats to the La Fortaleza and San Juan National Historic Site World Heritage Site, especially geographic information system datasets to produce the maps that allow the visual identification of areas most threatened within the site, proved to be a challenge and there are significant gaps that need to be fulfilled by further research. There are no detailed long-term projections at the regional or local level about ocean acidification and ocean warming, for example. There are also no studies about how climate change may affect the intense winds that constantly batter the fortifications. Finally, it is important to note that these data-related challenges pose a serious barrier to the goal of developing a tool that can be used independently by local stakeholders to lead their own independent climate vulnerability assessments of cultural heritage.

This capstone project includes two products: the full climate vulnerability assessment presented in this document and a more accessible, online summary of its main findings with interactive maps, which can be found at https://arcg.is/1quumK. Published as an ArcGIS Story Map, the main

purpose of the online summary is to inform the stakeholder groups who will participate in the bottom-up portion of the assessment led by SIO's Human Ecology Lab.

THE LA FORTALEZA AND SAN JUAN NATIONAL HISTORIC SITE WORLD HERITAGE SITE

History & Description

The La Fortaleza and San Juan National Historic Site World Heritage Site is the only World Heritage Site found in Puerto Rico. Originally known as Borikén by the indigenous Taíno people, the island was claimed by Christopher Columbus for Spain during his second voyage to the Americas in 1493, marking the beginning of Spanish colonization. Over the next 400 years, Spain exploited Puerto Rico's natural resources and developed productive sugar cane, coffee, and tobacco farms. The forced labor imposed on the Taíno to build this system, together with the introduction of new diseases by the Europeans, quickly decimated the indigenous population and prompted Spain to bring African slaves to work on the island. Puerto Rico remained under Spanish rule until 1898, when it was ceded to the United States after the Spanish-American War. Today, the island is still an unincorporated territory of the United States and its population of over three million people is a mix of descendants of indigenous groups, white Europeans, and black Africans.

Puerto Rico is the first major island with fresh water on the route of ships sailing from Europe to the Americas. This strategic location in the northeast Caribbean made it a valuable target for foreign invaders during the colonial era, prompting the construction of a defense system in the capital San Juan to protect the city and harbor. The resulting complex of Spanish colonial masonry military fortifications was built between the 16th and 20th centuries, occupying a large portion of the islet of San Juan and including the outpost of El Cañuelo, which sits across the bay.

San Juan was founded in 1521 on the rocky and hilly islet of San Juan, at the entrance of a large bay of the same name. Although this region of Puerto Rico is mostly characterized by a low-lying alluvial plain broken by several large swamps, lagoons and sandy beaches along the shore, the west and north parts of San Juan islet are marked by steep cliffs ranging from 30 to 100 feet (ten to 30 meters) in height. This area consists of Quaternary beach deposits formed through the action of strong northeast trade winds that constantly batter Puerto Rico's north coast, packing grains of sand on top of each other until they become bonded by minerals, such as calcium carbonate, into solid and cohesive structures known as cemented sand dunes. Offshore, the seabed deepens rapidly, with many islets and rocks that mark the tops of submerged cemented sand dunes and pose significant navigational hazards. These rocky reefs protect the shoreline from heavy swells originating from North Atlantic storms and provide a platform on which coral reefs can grow (Kaye, 1959a; Kaye, 1959b; Bawiec, 1999).

Puerto Rico's north coast does not have the same richness of coral reefs found in other parts of the island, likely because of turbid river water discharge and heavy swells that stir up bottom

sediment, smothering coral growth (Kaye, 1959b). However, these marine organisms are still key for the formation of critical coastal habitats that support highly biodiverse ecosystems on which local communities depend for their livelihoods, besides protecting the shoreline from waves, storms, and floods. Restoring coral reefs in Puerto Rico could generate $42 million in flood protection benefits every year, especially in densely populated areas like San Juan (Storlazzi et al., 2021).

Listed by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a World Heritage Site in 1983, the La Fortaleza and San Juan National Historic Site World Heritage Site has five main areas:

1. Castillo San Felipe del Morro, which spans six levels over the cliffs at the northwest tip of San Juan islet and was built to protect the bay and harbor from attacks coming from the sea.
2. Castillo San Cristóbal, the biggest European fortification in the Americas, built over a period of 150 years to protect the city from land-based attacks.
3. The old city walls, which run for approximately 2.5 miles (four kilometers) along the northern, western, and southern edges of the city of Old San Juan.
4. Fort San Juan de la Cruz at El Cañuelo, which used to be an island but is today connected to the mainland and Isla de las Cabras by a causeway, forming an artificial peninsula.
5. La Fortaleza, which has been used as a fortress, arsenal, and prison, but is today the seat and residence of the Governor of Puerto Rico.

Additionally, the site also contains archaeological resources and movable heritage, such as museum and archival collections.

Value & Cultural Identity

The status of World Heritage Site means the cultural significance of the La Fortaleza and San Juan National Historic Site World Heritage Site is "so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity" (*UNESCO World Heritage Centre – Compendium).* The site represents an amalgamation of European military architecture adapted to the Caribbean environment, thanks to a remarkable transfer of technology over several centuries. Despite various expansions, improvements, repairs, and conservation efforts conducted over their history, the fortifications remain an authentic example of their original defensive purpose, which was served until the mid-20th century (*La Fortaleza and San Juan National Historic Site in Puerto Rico*). The property is also on the National Register of Historic Places, which deems it significant at the national level for its contribution to the areas of military history, maritime history, architecture, ethnic heritage, social history, and archaeology (National Park Service, 2022).

Today, the La Fortaleza and San Juan National Historic Site World Heritage Site is a tangible reminder of the last 500 years of history that have shaped the modern cultural identity of Puerto Rican society. During the colonial era, the people of San Juan helped build these fortifications with their own hands, stood in them next to Spanish rulers to defend the city against attacks, and were imprisoned inside their walls for seeking an independence that never came. These people are still there today, living and working in communities that sprung up around the site as the city of Old San Juan grew, such as La Perla, La Puntilla, Puerta de Tierra, Cataño and Palo Seco.

While this top-down climate vulnerability assessment has a limited scope focused on the La Fortaleza and San Juan National Historic Site World Heritage Site, it is important to highlight the fact that these neighboring communities are going to suffer the same impacts, sharing its fate when it comes to climate change. This is why the bottom-up assessment that will follow the one presented in this document is critical to ensuring the inclusion of perspectives that are usually excluded from traditional climate vulnerability assessments of cultural heritage. Understanding how the concept of value is defined and by whom, and how it is assigned to cultural heritage, is crucial to developing a truly integrated climate vulnerability assessment that can answer the question: what would it mean to lose this cultural heritage because of climate change?

CLIMATE VULNERABILITY ASSESSMENT

Increasing temperatures

Caused by the unprecedented accumulation of greenhouse gases emitted by humans into the atmosphere, global warming is the main driver behind climate change. Between 2011 and 2020, global surface temperatures on Earth were 1.1°C (over 2°F) higher than those observed between 1850 and 1900 (*Ar6 Synthesis Report: Climate Change 2023)*. This trend is observed not only in

the atmosphere, but also in the ocean, which absorbs 90% of the extra heat associated with global warming (IPCC Working Group I Technical Support Unit, 2022).

In Puerto Rico, the number of days per year with temperatures above 32.2°C (90°F) has increased since the 1970s (USGCRP, 2018). This observed warming trend is more significant for average minimum nighttime temperatures at elevations below 300 meters, which have increased by 1.6°C (approximately 3°F) in the decade between 2011 and 2020, compared to the average between 1950 and 2020 (Puerto Rico Climate Change Council, 2022).

Therefore, fewer cool nights and more frequent hot days are expected into the future (USGCRP, 2018). By around 2050, scientists project that the region where San Juan Bay is located will be between up to 1.6°C (approximately 3°F) warmer than it was at the end of the 20th century, while Puerto Rico will have more than 50 days of unprecedented maximum and minimum temperatures every year, with some exceptional years exceeding 200 days (Bowden et al, 2020).

This mean that San Juan Bay is likely to be affected by stronger heat waves, experiencing more days of extreme heat. This will increase thermal stress on cultural heritage, accelerating the structural deterioration of the fortifications and walls within the La Fortaleza and San Juan National Historic Site World Heritage Site and increasing demand for air conditioning systems to maintain adequate climate control for museums and collections (ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

Regarding ocean warming, the Caribbean is already 2.3% warmer now than in 1992, which is double the global rate (Puerto Rico Climate Change Council, 2022). Not only does this contributes to the rapid intensification of the cyclones that batter Puerto Rico every year, it also poses a major threat to the island's coral reefs, which often become bleached and die during heatwaves (Alvarez et al., 2020). Although higher sea surface temperatures do not impact the La Fortaleza and San Juan National Historic Site World Heritage Site directly, they are expected to contribute to the reduction of the natural coastal protection offered by nearby coral reefs, making the site more vulnerable to the impacts of wave action and storm surges.

Decreasing precipitation

The global warming trend explained in the previous section intensifies the water cycle and disrupts atmospheric circulation patterns, which affects the distribution of precipitation around the world. Although there is a lot of regional variation, with some regions expected to experience heavier rainfall while others will see more prolonged droughts, in general precipitation is likely to increase in higher latitudes and decrease over large parts of the subtropics (*Climate Change Widespread, Rapid, and Intensifying).*

There is no clear trend observed for seasonal or annual average rainfall in Puerto Rico between 1925 and 2020, but more frequent droughts in recent years have been associated with lower levels of precipitation during the wet season (Puerto Rico Climate Change Council, 2022). This observation is aligned with climate model simulations that project a significant long-term reduction in precipitation in the island (Bowden et al, 2020), ranging from 20% to 30% by 2050 when compared to late 20th century levels (Bhardwaj et al, 2018).

The main consequence expected is longer dry periods that can damage buildings and structures within the La Fortaleza and San Juan National Historic Site World Heritage Site by increasing dry salt deposits, which hydrate and infiltrate during infrequent rain events, causing spalls and fractures. They can also increase the vulnerability of archaeological sites found in the area and the decay of organic materials within them (ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

Ocean acidification

The ocean absorbs around 30% of the carbon dioxide that is released into the atmosphere. As the concentration of carbon dioxide in the atmosphere continues to rapidly increase because of anthropogenic emissions, the amount of carbon dioxide taken up by the ocean is also increasing. More carbon dioxide dissolved in sea water leads to a higher concentration of hydrogen ions, which makes it more acidic. Since the industrial revolution, the ocean has already become 30% more acidic (*Ocean Acidification).* In the Caribbean, sea surface waters are now 12% more acidic than in 1988 (Puerto Rico Climate Change Council, 2022).

Ocean acidification reduces the saturation state of calcium carbonate in sea water, threatening marine organisms that use it to build their shells and skeletons, such as coral reefs. Therefore, it poses an indirect threat to the La Fortaleza and San Juan National Historic Site World Heritage Site in the same way as increasing ocean temperatures, since it can contribute to reducing the coastal protection offered by reefs.

Combined with greater coastal flooding driven by sea level rise and storm surges, a more acidic ocean also threatens the site directly as it can accelerate the corrosion of metals and the deterioration of calcium carbonate contained in the materials used in most buildings and structures. Ocean acidification may also increase the erosion of cliffs around the fortifications of El Morro and San Cristóbal (ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

Sea level rise

Another consequence of global warming, sea level rise is caused mainly by thermal expansion and by the melting of glaciers and ice sheets, which add water to the ocean. Thermal expansion occurs because water expands as it warms and, as mentioned previously, the ocean is warming as it absorbs most of the additional heat in the atmosphere caused by humans. Sea level rise is one of the most serious climate change threats to coastal areas because it increases coastal flooding, erosion, and saltwater intrusion into freshwater sources, besides exacerbating storm surges and the loss of key coastal habitats.

Although it varies across different regions, globally sea level has already risen by around 20 centimeters (approximately eight inches) since 1900. This is the fastest rate observed at any point in at least 3000 years and it is accelerating (IPCC Working Group I Technical Support Unit, 2022). Data collected from tide gauges in the bay of San Juan since the mid 20th century indicates that

relative sea level has been rising by 0.21 centimeters (0.08 inches) per year, a rate that is expected to accelerate (Puerto Rico Climate Change Council, 2022).

Figure 1 shows the latest sea level rise projections for Puerto Rico (*Interagency Sea Level Rise Scenario Tool)*. By mid-century, sea level will have risen between 0.9 and 1.3 feet (0.27 and 0.4 meters) over the level observed in the year 2000. This range represents only the intermediate, intermediate high and high scenarios because observations of local tide gauges since the 1970s show that the lower intermediate and low scenarios are very unlikely to happen, given how much sea level has already risen. By the end of the century, Puerto Rico can expect to see a sea level rise of between 3.4 and 6.8 feet (1.04 and 2.07 meters). In the longer term, by 2150, projections indicate a rise of between 6.5 and 12 feet (1.98 and 3.66 meters).

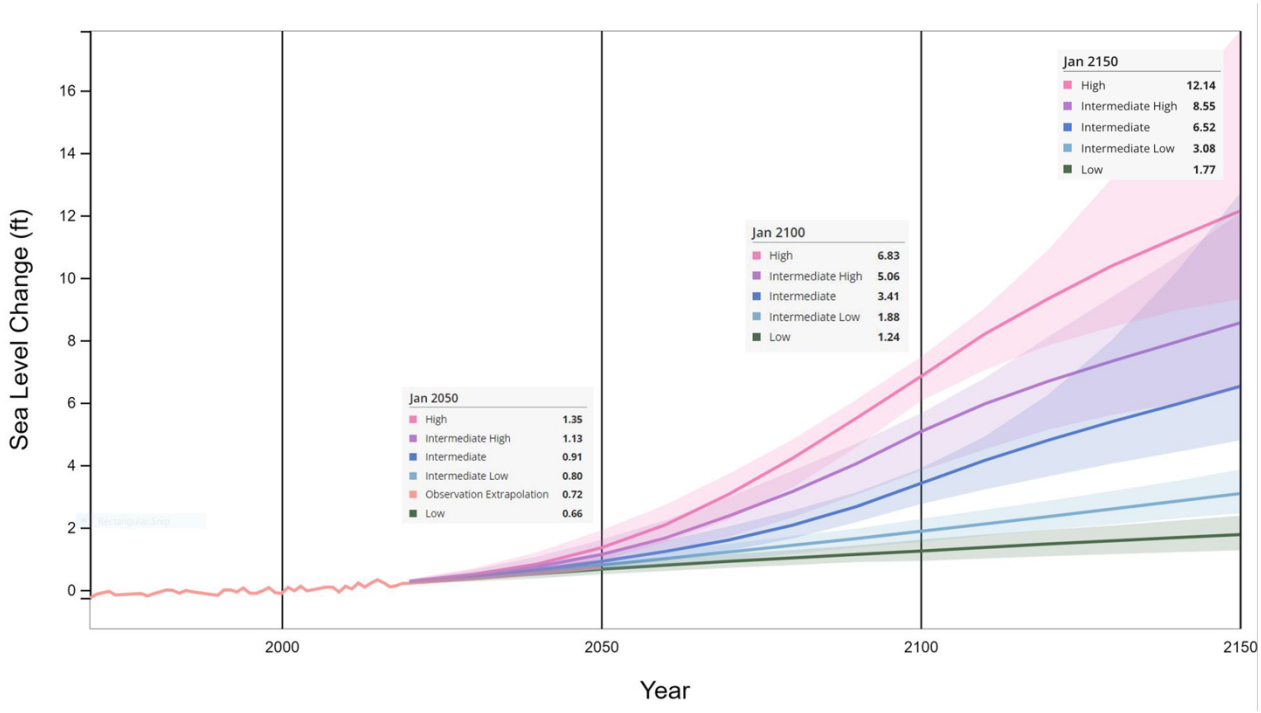

Figure 1: sea level rise projections for Puerto Rico in 2050, 2100 and 2150 (Interagency Sea Level Rise Scenario Tool).

The main consequence of sea level rise is the permanent inundation of low-lying coastal areas. In addition to this, sea level rise also worsens storm surges and increases coastal erosion, both of which have been identified as serious threats to the fortifications and old city walls within the La Fortaleza and San Juan National Historic Site World Heritage Site. Finally, sea level rise can also damage buried archaeological sites by raising the water table (ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

Figure 2 shows what San Juan Bay may look like in 2100: the darkest blue areas are expected to be inundated by a sea level rise of one feet (0.3 meters), which is projected to happen by 2050. The other three shades of blue roughly match the three scenarios projected for 2100, getting lighter in color to show areas progressively flooded by three feet (0.9 meters), five feet (1.5 meters) and seven feet (2.1 meters) of sea level rise.

Figure 2: areas flooded around San Juan Bay under different sea level rise scenarios (map produced in ArcGIS Pro with data from NOAA's Sea Level Rise Viewer online tool).

Examining *Figure 2,* it is evident that many areas around the bay will be severely affected by sea level rise in the long term, even under the intermediate scenario of 3.4 feet (1.04 meters) by 2100. This is especially concerning for the south part of San Juan Island and for the communities of Palo Seco, Cataño and La Puntilla. *Table 1* reveals how much of the La Fortaleza and San Juan National Historic Site World Heritage Site's total area is projected to be flooded under the four scenarios illustrated in *Figure 2*:

Sea level rise	**Percent of total area flooded**	**Approximate corresponding scenario**
1 ft (0.3 m)	7.88%	2050 intermediate/intermediate-high
3 ft (0.9 m)	10.31%	2100 intermediate
5 ft (1.5 m)	14.09%	2100 intermediate-high
7 ft (2.1 m)	15.63%	2100 high

Table 1: area of the La Fortaleza and San Juan National Historic Site World Heritage Site flooded under four sea level rise scenarios projected for the years 2050 and 2100.

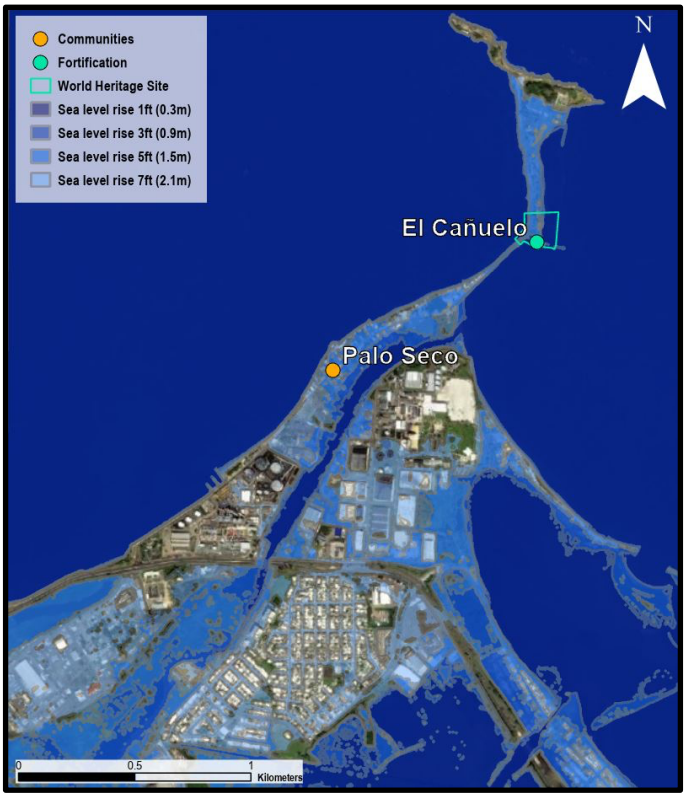

Figure 3: sea level rise impact on El Cañuelo and the neighboring community of Palo Seco (map produced in ArcGIS Pro with data from NOAA's Sea Level Rise Viewer online tool).

Within the La Fortaleza and San Juan National Historic Site World Heritage Site, the area at greatest risk is El Cañuelo (*Figure 3)*, where Fort San Juan de la Cruz would be completely inundated by 2100 under the intermediate high scenario, with five feet (1.5 meters) of sea level rise. Any of the projected sea level rise scenarios will significantly increase the stress that El Cañuelo is already suffering, especially from coastal erosion. Combined with a rising water table, this can compromise the foundation of the building (National Park Service, 2018). Other structures affected include the western section of the old city walls, the Paseo del Morro boardwalk, the cliffs around El Morro (*Figure 4)*, and the northern section of the San Cristóbal fortification (*Figure 5)*. Most of this flooding is expected to happen under the intermediate scenarios projected for 2100. Under the end-of-century high scenario, the west portion of the old city walls is expected to suffer even more.

Figure 4: sea level rise impact around El Morro and on west portion of the old city walls (map produced in ArcGIS Pro with data from NOAA's Sea Level Rise Viewer online tool).

Figure 5: sea level rise impact north of Castillo San Cristóbal and on south part of San Juan Island (map produced in ArcGIS Pro with data from NOAA's Sea Level Rise Viewer online tool).

More frequent and intense storms

Anthropogenic climate change is widely recognized as a significant factor contributing to an increasing occurrence of extreme weather events, including more frequent and intense storms, which are associated with higher atmospheric and sea surface temperatures (IPCC Working Group I Technical Support Unit, 2022).

The number of cyclones hitting Puerto Rico has increased since the mid 1990s (Puerto Rico Climate Change Council, 2022), and they are expected to become more intense and frequent as temperatures in the region increase (USGCRP, 2018). This means that extreme events like Hurricane Maria, which killed thousands of people and caused over $90 billion in damages to Puerto Rico and the U.S. Virgin Islands (Pasch et al, 2017), are likely to occur more often, which may not give communities enough time to recover from an extreme event before they are hit by the next one.

Tropical cyclones bring torrential rains and strong winds, causing widespread and severe physical damage to all types of structures, increasing erosion, triggering landslides, and temporarily flooding areas with storm surges, which happen when storms cause an abnormal rise in sea level (ICOMOS Climate Change and Cultural Heritage Working Group, 2019). They can also cause widespread damage to coral reefs and reduce the coastal protection provided by them, as was observed after Hurricanes Irma and Maria in 2017 (Storlazzi et al, 2021).

Figure 6 shows areas around San Juan Bay projected to be temporarily flooded by different levels of storm surge. The darker purple color indicates areas inundated by a category one storm, and the lighter colors represent areas inundated by stronger storms, up to category five in the lightest purple. The darker color indicates areas at higher risk because weaker storms are more likely to occur than stronger storms. The map shows that flooding caused by storm surges is even more widespread than that projected to happen because of sea level rise, but it is important to remember that these two drivers are related and make each other worse. Again, the south part of San Juan Island and the communities of Palo Seco, Cataño and La Puntilla are particularly threatened.

Figure 6: areas flooded around San Juan Bay by storms of different categories (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

Table 2 reveals how much of the La Fortaleza and San Juan National Historic Site World Heritage Site's total area would be flooded by different levels of storm surges, as illustrated in *Figure 6*:

Storm category	Percent of total area flooded
1	8.73%
2	11.21%
3	12.84%
4	15.09%
5	15.7%

Table 2: area of the La Fortaleza and San Juan National Historic Site World Heritage Site flooded by storms of different categories.

Figure 7: storm surge impact on El Cañuelo and Palo Seco (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

Weaker storms of categories one and two are enough to produce storm surges capable of flooding over 10% of the site. El Cañuelo is again at greatest risk (*Figure 7)*, with Fort San Juan de la Cruz completely flooded by category three storm surges, in addition to damages caused by heavy rainfall, strong winds and wind-born debris. When combined, these multiple threats have the potential to undermine the building's foundation and cause structural damage or collapse from blunt force (National Park Service, 2018). The low-lying areas around the west portion of the old city wall, the cliffs and boardwalk around El Morro (*Figure 8)* and the northern part of the San Cristóbal fortification (*Figure 9)* are also very affected by storm surges, like what projections indicated for sea level rise.

Figure 8: storm surge impact around El Morro and the west portion of the old city walls (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

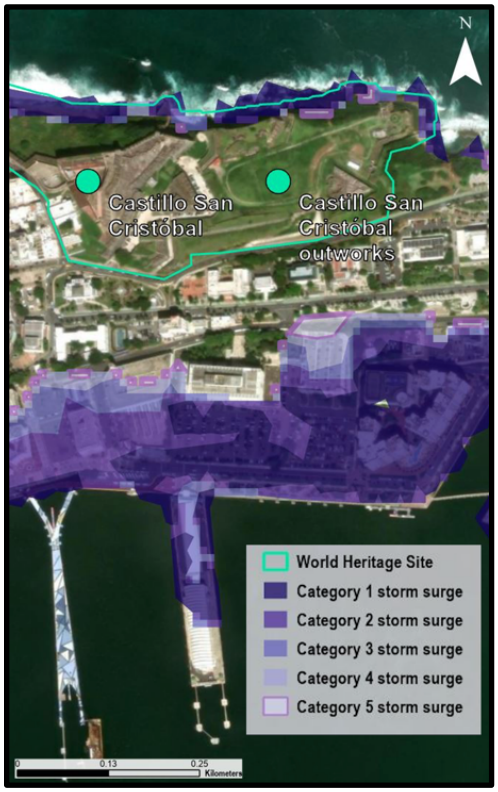

Figure 9: storm surge impact north of Castillo San Cristóbal and on the south part of San Juan Island (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

Other factors that contribute to coastal flooding

As seen above, coastal flooding is one of the most serious climate change threats to cultural heritage in the La Fortaleza and the San Juan National Historic Site World Heritage Site. Its most obvious impact is the loss of cultural heritage that becomes temporarily or permanently submerged in the ocean. However, by raising water tables and boosting coastal erosion and saltwater intrusion, coastal flooding can lead to several other negative effects, including widespread structural damages to the fortifications and old city walls; increased rusting, corrosion, and deterioration of materials; increased vulnerability and damage to buried archaeological sites; and even the potential destruction of structures and buildings within the La Fortaleza and San Juan National Historic Site World Heritage Site (ICOMOS Climate Change and Cultural Heritage Working Group, 2019).

However, sea level rise and storm surges are not the only factors that contribute to this phenomenon. Other dynamic processes, such as erosion, are key for accurately assessing the threat that coastal flooding poses to a particular site. *Figure 10* shows San Juan Bay under a flood-related threat index from the Coastal Resilience Evaluation and Siting Tool, which considered not only data about sea level rise and storm surges, but also flood-prone and low slope areas, soil erodibility and permeability, potential tsunami inundation and landslide susceptibility (Dobson et al., 2020). It is important to note that this index only considers sea level rise from one to five feet, so it does not include data related to the seven feet high scenario projected for 2100. The index ranges from one to ten, with areas at lowest risk shown in light yellow and areas at highest risk in dark red.

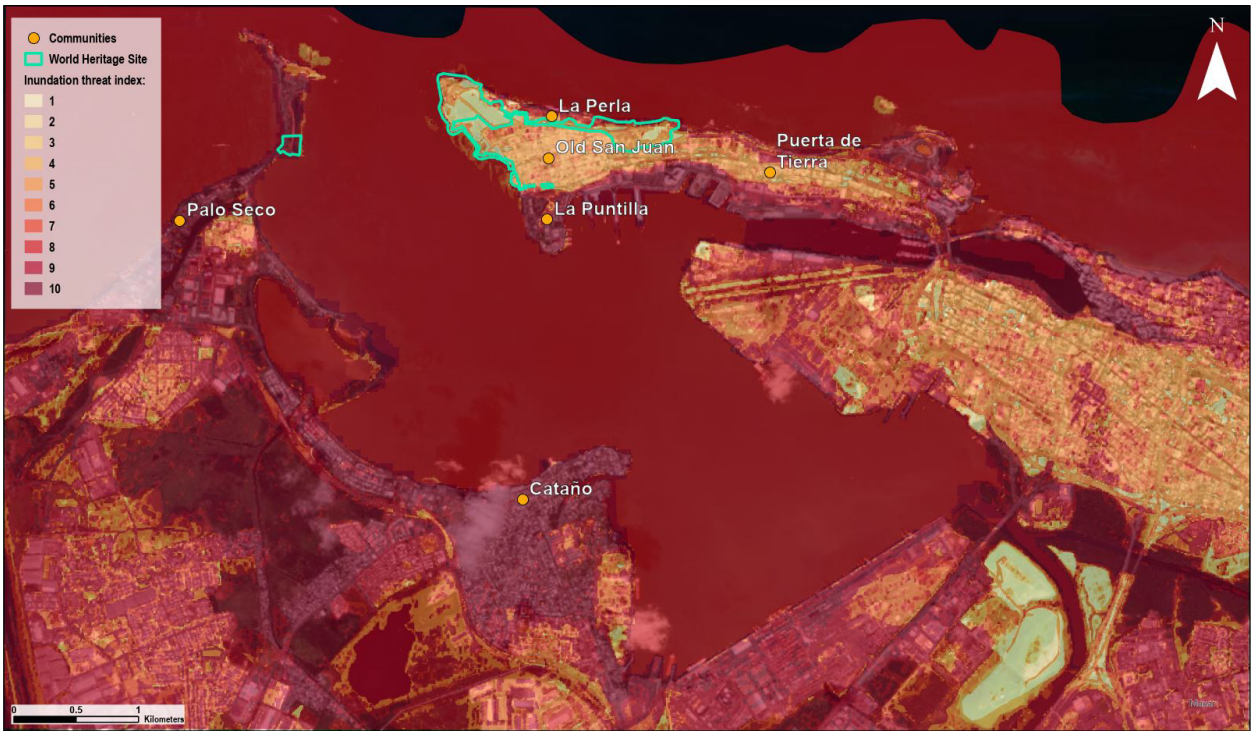

Figure 10: the threat index allows the identification of areas most at risk of flooding around San Juan Bay (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

In line with what the isolated maps for sea level rise and storm surge scenarios showed, the south part of San Juan Island and the communities of Palo Seco, Cataño and La Puntilla appear severely threatened. Additionally, the community of La Perla, which is squeezed between the north portion of the old city walls and the ocean, appears to be at a higher risk under this threat index than it did in the isolated sea level rise and storm surge maps. Within the La Fortaleza and San Juan National Historic Site World Heritage Site, El Cañuelo is at highest risk, while the low-lying areas around the west portion of the old city wall, La Fortaleza, the cliffs and boardwalk around El Morro, and the northern part of the San Cristóbal fortification also appear to be severely threatened.

Table 3 shows the area of the site classified along the threat index, from lowest (one) to highest (ten) risk. Almost half of the La Fortaleza and San Juan National Historic Site World Heritage Site is classified at the intermediate risk levels five and six and over 21% is classified at a level eight or higher. Only 25% of the site is at the lowest risk level one, and these can be easily identified as the higher elevation areas that are part of the El Morro and San Cristóbal fortifications and the north portion of the old city walls.

Threat index level	**Percent of total area threatened**
1	24.55%
2	3.93%
3	0.72%
4	0.03%
5	38.67%
6	10.42%
7	0.66%
8	5.19%
9	9.75%
10	6.06%

Table 3: area of the La Fortaleza and San Juan National Historic Site World Heritage Site classified along a flood-related threat index, with one representing lowest risk and ten highest risk.

Examining the isolated variables that make up the flood-related threat index, landslide susceptibility is one that brings relevant information about the La Fortaleza and San Juan National Historic Site World Heritage Site. *Figure 11* shows three areas highlighted in yellow that have been identified as having a moderate risk of landslides: the north part of Castillo San Cristóbal, the southwest part of El Morro and a section of the west wall and La Fortaleza. Considering that the site has already experienced significant landslides in other areas, specifically north of El Morro's walls on the slope that sits at the base of an original structure of the fort, it is recommended that this data is reviewed and discussed by local stakeholders during the bottom-up assessment (F. López, personal communication, April 29, 2023).

Figure 11: the three areas highlighted in yellow were identified as having a moderate risk of landslides (map produced in ArcGIS Pro with data from the Coastal Resilience Evaluation and Siting Tool, Dobson et al., 2020).

CONCLUSION

The data reviewed for this top-down climate vulnerability assessment suggests that cultural heritage within the La Fortaleza and San Juan National Historic Site World Heritage Site is significantly exposed to climate change impacts, particularly sea level rise and more frequent and intense storms, both of which enhance the threat posed by coastal flooding. *Table 4* provides a summary of the main findings of this assessment:

Climate change threat	**Expected impacts in San Juan**	**Effects on cultural heritage**
Increasing temperatures	By 2100, temperatures 1.5°C-3°C (3°F-6°F) higher than in 2020; ocean warming	Increased thermal stress that leads to structural deterioration and degradation of fortifications; loss of coastal protection from coral reefs

Decreasing precipitation	10%-40% less rain by 2100; more consecutive dry days even in wet season	Drought damage to fortifications from spalls and fractures caused by increasing dry salt deposits; increased vulnerability of archaeological sites and decay of organic materials within them
Ocean acidification	A significantly more acidic ocean reduces the saturation state of calcium carbonate in contact with sea water	Accelerated corrosion of metals and deterioration of calcium carbonate within the fortifications; increased cliff erosion; loss of coastal protection from coral reefs
Sea level rise	Around 1ft (0.3m) sea level rise by 2050; 3-7ft (1-2m) sea level rise by 2100; 6.5-12ft (2-3.6m) sea level rise by 2150	Permanent inundation of El Cañuelo by 2100 and other low-lying areas; damage to buried archaeological sites; increased coastal erosion and storm surges
More frequent and intense storms	More category 4 and 5 storms; 15% increase in tropical cyclones rainfall rate and 3% increase in wind intensity.	Severe physical damage to fortifications; increased erosion; higher risk of landslides; temporary flooding of low-lying areas, especially El Cañuelo; loss of coastal protection from coral reefs

Table 4: summary of the main findings of climate change threats to the La Fortaleza and San Juan National Historic Site World Heritage Site.

The online summary of these main findings with interactive maps can be found at https://arcg.is/1quumK. Published as an ArcGIS Story Map, its main purpose is to inform the stakeholder groups who will participate in the bottom-up portion of the assessment led by SIO's Human Ecology Lab. Following the CA CVI model, the focus of this next stage of the assessment should be on identifying how stakeholders perceive risks from climate change, how they value the site's cultural heritage (both tangible and intangible), and what it would mean for them to lose different elements of it because of climate change.

The activities to promote this discussion should be based on the CA CVI model, but with enough flexibility to allow adaptation to the Puerto Rican context, ensuring that the needs of local stakeholders are met for engagement to be successful. For example, it may be necessary to hold different workshops in each community, since bringing all stakeholders together in one location may create a barrier for those who live farther away or have difficulties with mobility. At the end of the process, the workshop facilitators will analyze the results of the activities and integrate their findings into the top-down assessment presented here to produce a final report.

When combined with the information that will be generated by stakeholders, the findings of this top-down assessment can provide valuable evidence to inform decision-making on climate

adaptation and mitigation strategies to protect not only the cultural heritage within the La Fortaleza and San Juan National Historic Site World Heritage Site, but also the local communities whose cultural identities are inextricably connected to it. Ultimately, this capstone project contributes to the ongoing development of a climate vulnerability assessment tool for cultural heritage that can be used independently by stakeholders to meaningfully assess the vulnerability of their own cultural heritage to climate change through a decentralized process that can inspire local climate action, inform decision-making at different levels, and be repeated consistently as the components of vulnerability change over time.

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