PUERTO RICO COASTAL RESILIENCE ASSESSMENT

2020

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IMPORTANT INFORMATION/DISCLAIMER: This report represents a Regional Coastal Resilience Assessment that can be used to identify places on the landscape for resilience-building efforts and conservation actions through understanding coastal flood threats, the exposure of populations and infrastructure have to those threats, and the presence of suitable fish and wildlife habitat. As with all remotely sensed or publicly available data, all features should be verified with a site visit, as the locations of suitable landscapes or areas containing flood threats and community assets are approximate. The data, maps, and analysis provided should be used only as a screening-level resource to support management decisions. This report should be used strictly as a planning reference tool and not for permitting or other legal purposes.

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Report cover images: Coastline of Old San Juan, Puerto Rico (top); coqui (bottom)

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GLOSSARY OF RELEVANT TERMS

The analysis was developed in adherence to the following terms and their definitions adapted from the U.S. Climate Resilience Toolkit and NFWF.

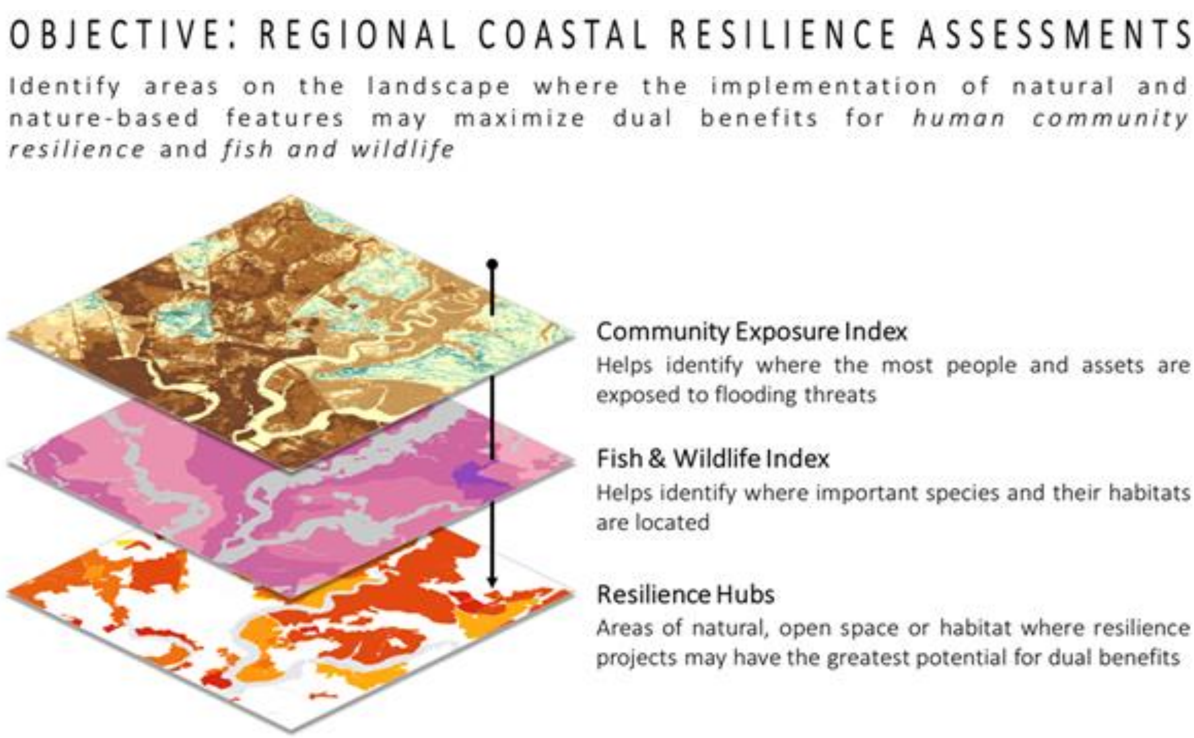
Term	Definition
Adaptive capacity	The ability of a person or system to adjust to a stressor, take advantage of new opportunities, or cope with change.
Ecosystem services	Benefits that humans receive from natural systems.
Exposure	The presence of people, assets, and ecosystems in places where they could be adversely affected by hazards.
Impacts	Effects on natural and human systems that result from hazards. Evaluating potential impacts is a critical step in assessing vulnerability.
Natural features	Landscape features that are created and evolve over time through the actions of physical, biological, geologic, and chemical processes operating in nature (Bridges et al. 2014).
Nature-based features	Features that may mimic characteristics of natural features, but are created by human design, engineering, and construction to provide specific services such as coastal risk reduction (Bridges et al. 2014).
Nature-based solutions	Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (IUCN).
Resilience	The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption.
Risk	The potential total cost if something of value is damaged or lost, considered together with the likelihood of that loss occurring. Risk is often evaluated as the probability of a hazard occurring multiplied by the consequence that would result if it did happen.
Sensitivity	The degree to which a system, population, or resource is or might be affected by hazards.
Threat	An event or condition that may cause injury, illness, or death to people or damage to assets.
Vulnerability	The propensity or predisposition of assets to be adversely affected by hazards. Vulnerability encompasses exposure, sensitivity, potential impacts, and adaptive capacity.

EXECUTIVE SUMMARY

Coastal communities throughout the United States face serious current and future threats from natural events, and these events are predicted to intensify over the short and long term. Dynamic processes such as coastal erosion, storm surge flooding, and river runoff exacerbate the threat from sea level rise. Intense hurricanes and extreme flooding have the potential to devastate both human communities and fish and wildlife habitats, as has been seen in recent years throughout the Caribbean. Recently, Puerto Rico has experienced numerous consecutive hurricanes and other major storm events that have left communities exposed to severe and devastating effects of coastal flooding. As communities begin to rebuild, decision-makers need tools and resources that allow for data-driven decision support in an effort to maximize available funding opportunities and other planning needs.

The Puerto Rico Coastal Resilience Assessment aims to support effective decision-making in order to help build resilience for communities facing flood-related threats. The National Fish and Wildlife Foundation (NFWF), in partnership with the National Oceanic and Atmospheric Administration (NOAA), is committed to supporting programs and projects that improve resilience by reducing communities' vulnerability to coastal storms, sea level rise, and flooding events through strengthening natural ecosystems and the fish and wildlife habitat they provide.

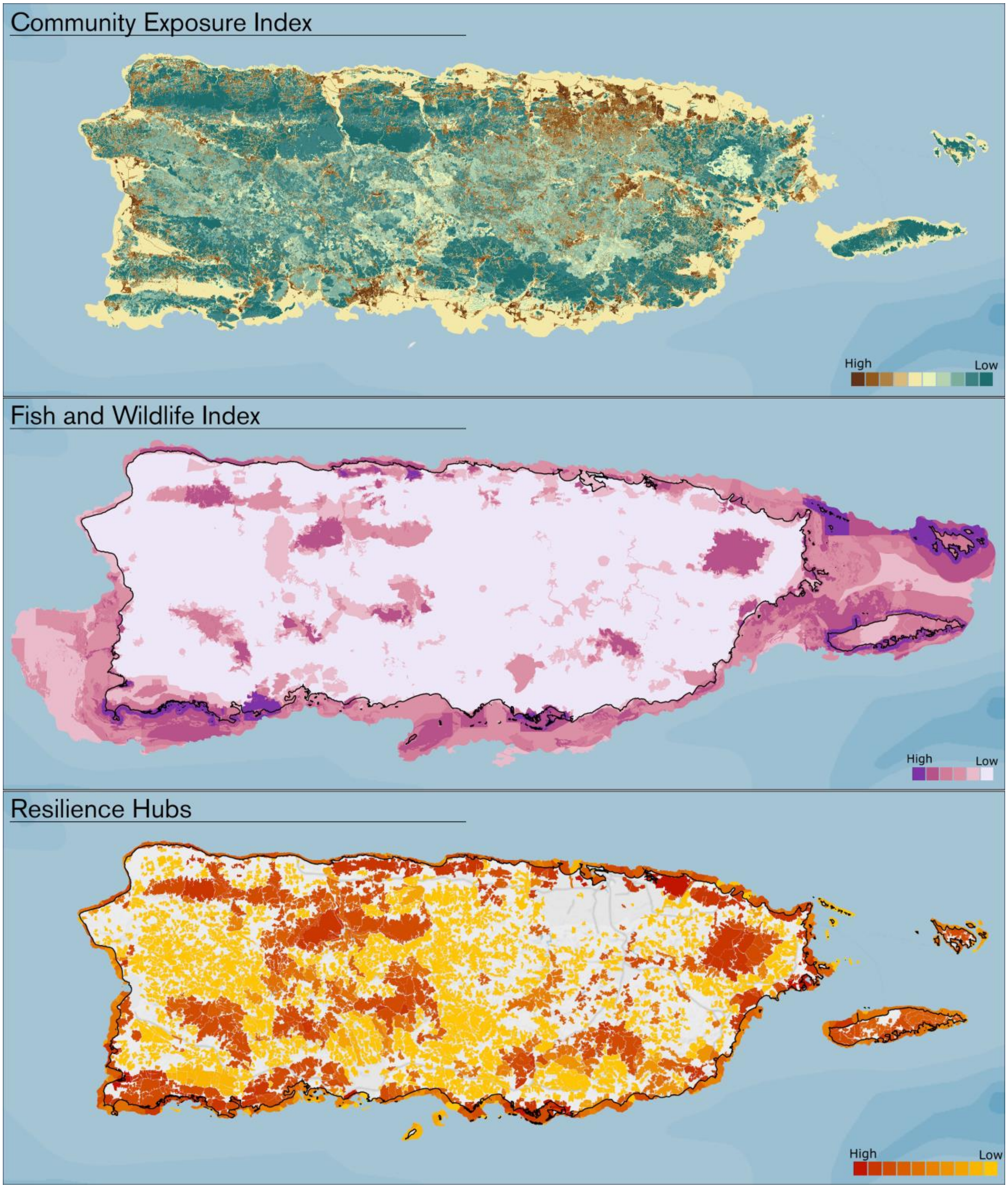
This Geographic Information System (GIS)-based Coastal Resilience Assessment combines spatial data related to land use, protected areas, human community assets, flooding threats, and fish and wildlife resources in order to identify and prioritize Resilience Hubs (see figure below). Resilience Hubs are large areas of natural, open space or habitat where, if investments are made in conservation or restoration, there is potential for improved human community resilience and benefits to fish and wildlife habitats and species.



The Assessment identified areas throughout Puerto Rico that are not only exposed to a range of coastal-flood related threats, but also contain higher concentrations of community assets. In addition, through the development of habitat extent and suitability models, the analysis identified terrestrial and nearshore marine areas with significant fish and wildlife resources. Together, the Assessment revealed natural areas of open space and habitat ideal for the implementation of resilience projects that may be capable of supporting both the people and wildlife of Puerto Rico. The primary mapping products from the Puerto Rico Assessment are shown below.

Local community planners, conservation specialists, and others can use the outputs of the Puerto Rico Assessment to help make informed decisions about the potential of restoration, conservation, or resilience projects to achieve dual benefits for both human and fish and wildlife communities.

This Puerto Rico Coastal Resilience Assessment report provides a detailed discussion of the data and methods used for the three analyses (Community Exposure, Fish and Wildlife, and Resilience Hubs), regional results, and case studies. In addition to the results presented in this report, NFWF has developed the Coastal Resilience Evaluation and Siting Tool (CREST), an accompanying GIS-based web tool that allows users to view, download, and interact with the inputs and results of this Assessment (available at resilientcoasts.org).



Final Community Exposure Index (top), Fish and Wildlife Index (middle), and Resilience Hubs (bottom) for the Puerto Rico Coastal Resilience Assessment. Higher values represent areas where a higher concentration of assets are exposed to flooding threats (Community Exposure Index), areas where numerous important species and their habitats are located (Fish and Wildlife Index), or areas where resilience projects may have the greatest potential to benefit both human communities and wildlife (Resilience Hubs).

INTRODUCTION

1.1 Puerto Rico

With over 480 kilometers of coastline, many communities throughout Puerto Rico are highly exposed to a variety of coastal-flood related threats, which can have devastating effects, particularly in densely populated areas. Puerto Rico's high population density and concentrated development along the coast leaves many communities highly vulnerable to coastal hazards. Although coastal areas face a wide range of flooding threats, inland communities are not immune from flood-related hazards, especially as they relate to heavy precipitation events and riverine or flash flooding. Furthermore, the effects of coastal flooding are often exacerbated when combined with heavy precipitation inland, suggesting efforts to build resilience should consider the benefits of a holistic, whole-island approach (Bush et al. 2009).

Local flooding threats range from coastal storms and hurricanes to the long-term threat of rising sea levels. Compound flooding associated with multiple, simultaneous or sequential heavy rain events and coastal storms can significantly impact both coastal and inland communities. For instance, in 2017, Hurricanes Irma and Maria caused widespread damage across Puerto Rico. Hurricane Maria is considered one of the worst hurricanes to hit the island in 80 years, causing a complete loss of electricity throughout the island and resulting in over $90 billion in damages (Pasch et al. 2019). The category four hurricane made landfall near Yabucoa on September 20, 2017, resulting in both extreme coastal flooding and inland flash flooding associated with heavy rains. Three years after the storm, much of Puerto Rico is still recovering.

In response to the 2017 hurricanes and other storms, numerous national and territory-level efforts were initiated in order to better understand the threats, needs, gaps, and nature-based approaches that could be applied to help build resilience in Puerto Rico. Such efforts include, but are not limited to, the results of the Resilient Puerto Rico Advisory Commission (Resilient Puerto Rico 2018) and the U.S. National Climate Assessment (USGCRP 2018). Such studies are critical to help communities understand, respond to, and prepare for future storm events. In addition to these studies, several recent meetings and workshops have made progress towards planning and implementation of both gray and green infrastructure designed to respond to the threat of flooding and storms. In August 2019, NOAA hosted stakeholder workshops in San Juan focused on green infrastructure and adaptation planning[1]. In an extensive and ongoing planning effort, the U.S. Army Corps of Engineers also hosted a recent workshop in San Juan in October 2019 to gain stakeholder feedback and advance the South Atlantic Coastal Study[2]. To enable broad and coordinated stakeholder engagement, the workshop included a special session focused on this Puerto Rico Coastal Resilience Assessment.

As Puerto Rico takes steps to lower its exposure and plan for a more resilient future, resources such as this Puerto Rico Coastal Resilience Assessment can equip decision-makers and stakeholders with valuable tools and information to help them better plan for future flood and storm events. This Assessment provides a framework for a holistic approach that includes not only considering human community resilience, but also fish and wildlife habitat.

[1] Information associated with the NOAA in the Caribbean Stakeholder Workshop available here.

[2] For information about the South Atlantic Coastal Study, visit https://www.sad.usace.army.mil/SACS/.

1.2 Overview of the Regional Coastal Resilience Assessments

The National Fish and Wildlife Foundation (NFWF) and the National Oceanic and Atmospheric Administration (NOAA) are committed to supporting programs and projects that improve community resilience by reducing communities' vulnerability to coastal storms, sea level rise, and flooding by strengthening natural ecosystems and the fish and wildlife habitat they provide. In response to growing coastal flooding threats, NFWF commissioned the University of North Carolina Asheville's National Environmental Modeling and Analysis Center (NEMAC) to develop an assessment to identify coastal areas that are ideal for the implementation of nature-based solutions that build both human community resilience and fish and wildlife habitat. The resulting Regional Coastal Resilience Assessments (referred to from here forward as the Regional Assessments or Assessments) aim to identify and rank open space areas and habitat cores where targeted investments can implement resilience-building projects before devastating events occur and impact surrounding communities.

The Puerto Rico Coastal Resilience Assessment is part of a broader effort that seeks to evaluate regional resilience for all U.S. coastlines. Regional Assessments are already complete for the U.S. Atlantic, Gulf of Mexico, and Pacific coastlines, the U.S. Virgin Islands, and the Commonwealth of the Northern Mariana Islands. Additional Assessments are expected for American Samoa, Guam, Hawaii, Alaska, and the Great Lakes (Figure 1).

Figure 1. The geographic extent of the Regional Coastal Resilience Assessments in dark gray and the Puerto Rico Assessment in orange. All Regional Assessments will be completed by 2021. Map not shown to scale.

Strategically implementing resilience projects can increase the ability of surrounding communities and habitats to withstand and recover from the impacts of coastal storms and flooding events (Narayan et al. 2017). Efforts to build resilience begin by determining the exposure of a community's assets to a hazard or threat. The Regional Assessments use a Geographic Information System (GIS)-based approach to model landscape characteristics and their potential impacts in order to identify places throughout the United States where assets are potentially exposed to flood threats. They combine human community assets, flooding threats, and fish and wildlife resource spatial data in order to identify and rank Resilience Hubs. Resilience Hubs are large areas of natural, open space or habitat where, if investments are made in conservation or restoration, there is potential for improved human community resilience and benefits to fish and wildlife habitats and species.

From a modeling standpoint, the Regional Assessments consist of three separate but interrelated analyses: (1) the Community Exposure Index, (2) the Fish and Wildlife Index, and (3) the Resilience Hubs (Figure 2). These three components make these Assessments unique as they look at resilience potential through the lens of both human and fish and wildlife communities. Specifically, the Community Exposure Index can guide land use and hazard mitigation planners in identifying potential development constraints and improve the understanding of potential risks to critical infrastructure and human populations. The Fish and Wildlife Index can inform where on the landscape important species and habitats occur. The Resilience Hubs then identify open spaces and habitat suitable for the implementation of projects expected to build communities' resilience to flood events while also benefiting fish and wildlife.

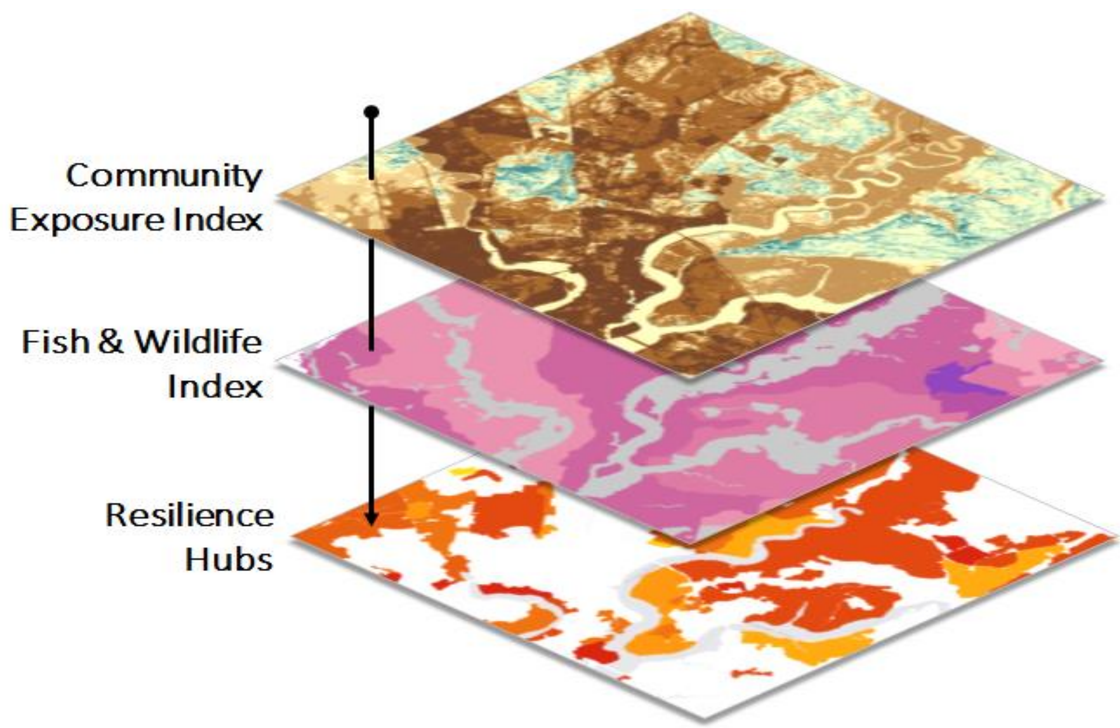


Figure 2. A conceptual model showing the separate, but interrelated components of the Regional Coastal Resilience Assessments.

While the Resilience Hubs are the primary output of the Regional Assessments, each component can be used individually or in combination to help community planners, conservation specialists, funding applicants, and others make informed decisions about the ability of potential restoration, conservation, or resilience projects to achieve dual benefits for both human community resilience and fish and wildlife species and habitats.

METHODS

2.1 Introduction

The foundation of the Regional Coastal Resilience Assessments is based on the coastal vulnerability research outlined in Gornitz et al. (1994). In 2011, the New Jersey Office of Coastal Management and Department of Environmental Protection adapted that research to assess existing and future hazard vulnerabilities on a local scale (NJ-DEP 2011). This research was integral to structuring the inputs and methodology of this analysis.

The following sections provide a brief overview of the methods used in the Puerto Rico Coastal Resilience Assessment (or Puerto Rico Assessment). For more details about overarching methodology and data sources common across all Regional Coastal Resilience Assessments, please refer to Dobson et al. (2020). To the extent possible, the Regional Assessments aim to use the same methodology and data across all regions. However, given the unique geographic characteristics of each region and the fact that data availability varies, some regionally-specific modifications were required. Additionally, given the smaller scale of Puerto Rico, it was recommended by the Advisory Committee that all GIS modeling be completed at a 10-meter resolution to best match the resolution common to the input data. The following sections briefly discuss pertinent methodological changes to the Community Exposure Index, Fish and Wildlife Index, and Resilience Hubs for Puerto Rico.

2.2 Study Area

The Puerto Rico Coastal Resilience Assessment includes the main island, as well as the islands of Vieques and Culebra just to the east of the main island. The extent of the study area extends offshore to the 30-meter depth contour or boundary according to bathymetry data (Figure 3). As described below, the 30-meter depth boundary was used for the Fish and Wildlife Index to allow for the inclusion of marine habitats with potential to host significant biodiversity. Based on the recommendation of technical experts, however, the Resilience Hub analysis only considered habitats less than 10-meters in depth since shallow water habitats are expected to provide greater coastal protection benefits through the implementation of nature-based solutions.

Puerto Rico is the eastern-most and smallest of the Greater Antilles in the Caribbean. It varies geographically and has a range of ecosystems, consisting of high elevation forests to coastal swamps. With a total land area of nearly 9,000 square kilometers, it is a densely populated island with over 3 million people. The main island contains over 480 kilometers of coastline, most of which feature natural beaches.

This Assessment is unique in that it not only takes into account the immediate coastline, as many other studies have done, but it also focuses on inland areas that can often directly contribute to coastal flood-related issues. For instance, intense rain and riverine flooding that then drains directly to the coast can exacerbate coastal flooding. In all regions, the boundary of the Assessments follow the U.S. Environmental Protection Agency's (EPA) designated coastal watersheds, which are watersheds that drain directly to the ocean and are represented at a hydrologic unit code eight scale (HUC-8)[3]. For

[3] According to the Environmental Protection Agency's Coastal Wetlands Initiative: https://www.epa.gov/wetlands/coastal-wetlands.

Puerto Rico, the HUC-8 watersheds cover the entire island and thus the study area also covers the entirety of each island (Figure 3).

Figure 3. The Puerto Rico Coastal Resilience Assessment study area, including all coastal and inland areas of Puerto Rico, Vieques, and Culebra. The 30m depth boundary is shown in black.

2.3 Data Collection and Stakeholder Engagement

The Project Team compiled an initial set of data from multiple national and regional data sources, including NOAA's sea level rise data and floodplain data from the Federal Emergency Management Agency (FEMA). In addition to reviewing publicly available data sources, the Puerto Rico Assessment relied on significant input from local and regional stakeholders to identify and inform the use of additional data sets.

To help guide the Assessment process, the Project Team established an Advisory Committee consisting of five members representing NOAA, the U.S. Fish and Wildlife Service, the Puerto Rico Department of Natural and Environmental Resources, and the Caribbean Integrated Coastal Ocean Observing System. The Advisory Committee met regularly with the Project Team to:

1. Provide guidance to the Project Team at key decision points in the analyses, including recommendations on data to be included;
2. Help identify additional local stakeholders within federal agencies, local and territorial governments, universities, non-governmental organizations, and others to provide input into the development of the Puerto Rico Assessment; and
3. Advise on final products and tools, including the effective dissemination of results.

With input from the Advisory Committee and building on initial data collection, the Project Team hosted a workshop to allow local stakeholders to review and provide input on preliminary Puerto Rico Assessment products. The Puerto Rico Stakeholder Workshop was held on October 7, 2019 in San Juan at the Department of Natural and Environmental Resources in conjunction with the U.S. Army Corps of Engineers' South Atlantic Coastal Study Workshop. Over 30 people attended the workshop, helping the Project Team:

1. Identify geographic features, flooding threats, cultural and socio-economic factors, and additional considerations that are unique to the region;

2. Identify, collect, and appropriately use GIS datasets related to flooding threats, community assets, and species and habitat;
3. Provide references and contact information for additional experts that may be able to contribute data or knowledge to the effort; and
4. Obtain overall buy-in to the Assessment process and solicit ways in which it can be used by local stakeholders in Puerto Rico.

Participants reviewed draft maps and data sources, and provided important feedback and recommendations to improve the analyses.

Following the stakeholder workshop, the Project Team reconvened with the Advisory Committee to assess the feedback, comments, and suggestions provided during the workshop and to determine which content and data to incorporate into revised products. NEMAC then followed up individually with Committee members and other key stakeholders to further discuss data and methodology as needed. Final results of the Puerto Rico Assessment were reviewed by the Advisory Committee and shared with local stakeholders via a public webinar.

2.4 Creating the Community Exposure Index

The Community Exposure Index was created by combining the Threat Index and Community Asset Index, depicting the spatial distribution of the potential exposure of assets to flood threats (Figure 4). The following equation calculates exposure:

Threat Index × Community Asset Index = Community Exposure Index

To accommodate local datasets and needs, the following text describes the specific methods used for the Puerto Rico Assessment. A complete list of datasets included for the Puerto Rico Assessment can be found in Appendix A. See Appendix D for a description of the methodology used to calculate the Community Exposure Index for Puerto Rico.

Figure 4. Elements of the Threat and Community Asset Indices used to create the Community Exposure Index.

2.4.1 Threat Index

Flood-related datasets are used to help communities understand what kind of threats are potentially present in their area. While other threats may exist, for the purposes of this analysis only those threats relevant to coastal flooding in Puerto Rico were included. Threats are defined as datasets that show coastal flood and severe storm hazards on the landscape. The Threat Index is a raster-based model with a cumulative scoring of inputs (Dobson et al. 2020). As in other Regional Assessments, the Puerto Rico analysis included data related to storm surge, sea level rise, flood-prone areas, soil erodibility, impermeable soils, areas of low slope, and geological stressors, each of which are described in detail in the Methodology and Data Report (Dobson et al. 2020).

Specific to Puerto Rico, tsunami inundation models from the Puerto Rico Seismic Network and Tsunami Program at the University of Puerto Rico at Mayagüez[4] were included recognizing that this seismically active area faces real danger of inundation from tsunamis. Additionally, Puerto Rico frequently experiences landslides triggered by extreme rainfall; landslides are classified as geologic stressors for the purposes of this Assessment. For example, Hurricane Maria triggered more than 40,000 landslides in at least three-fourths of Puerto Rico's 78 municipalities (Bessette-Kirton et al. 2019). Flooding and landslide susceptibility was a major concern of those that attended the stakeholder workshop. The Threat Index included the best available data at the time of modeling: a digitized 1979 map (Monroe 1979), updated in 2013 to include slopes greater than 50 percent[5]. Additional details on those data used to create the Threat Index for Puerto Rico can be found in Appendix A.1 and Appendix B.

2.4.2 Community Asset Index

The Community Asset Index included infrastructure and human population. The Index used datasets that quantify the number of assets present—not their magnitude of vulnerability or susceptibility to flood threats. The infrastructure and facilities that were incorporated into the Regional Assessments were chosen for their ability to help people respond to flood events.

In Puerto Rico, the Community Asset Index included population density, social vulnerability, and the full complement of critical facilities and infrastructure detailed in the Methodology and Data Report (Dobson et al. 2020). It was of utmost importance to include locally available data whenever possible. Therefore, based on feedback from the stakeholder workshop and Advisory Committee, additional infrastructure types such as heliports and marinas were included due to their importance in responding to storm and flood events on remote islands. The following types of critical infrastructure were included in the Puerto Rico Assessment:

- Primary roads
- Bridges
- Airports
- Ports & Heliports
- Power Plants & Substations
- Wastewater Treatment Facilities
- Railroads (urban train)
- Ferry Routes & Terminals
- Major Dams
- Petroleum Terminals
- Hazardous Sites
- Marinas

[4] Tsunami inundation models available on the Tsunami Program of Puerto Rico: http://redsismica.uprm.edu/Spanish/tsunami/programatsunami/prc/index.php.

[5] Updated 2013 landslide data available online at: http://www.gis.pr.gov/descargaGeodatos/Riesgos_Naturales/Pages/Riesgos-Geol%C3%B3gicos.aspx.

In addition, as with all other regions, the following list of critical facilities were included because of their relevance and widespread use following flood events or other disasters:

- Medical facilities (hospitals, nursing homes, etc.)
- Law enforcement (police, sheriff stations, etc.)
- Schools (public and private, universities)
- Fire stations

A detailed list of datasets used for all Community Asset Index inputs included in the Puerto Rico Assessment can be found in Appendix A.2. See Appendix C for a description of methods used to create the Community Asset Index for Puerto Rico.

2.5 Creating the Fish and Wildlife Index

The Fish and Wildlife Index, which consists of Marine and Terrestrial components, allows for a greater understanding of important habitat and fish and wildlife resources to aid in the identification of areas where implementing nature-based solutions may support coastal resilience and ecosystem benefits (Figure 5). The Index attempts to identify areas on the landscape where terrestrial, aquatic, and marine species and their habitats are located. For the purpose of the Puerto Rico Assessment, only those species of concern with federal- or state-level protection status and/or those included in resource management plans were considered. By nature, the Fish and Wildlife Index varies regionally; however, a detailed description of the general methods governing the Fish and Wildlife Index are available in the Methodology and Data Report (Dobson et al. 2020). Regional considerations for Puerto Rico are discussed below; a complete list of data can be found in Appendix A and a description of the methods used to create the Fish and Wildlife Index can be found in Appendix E.

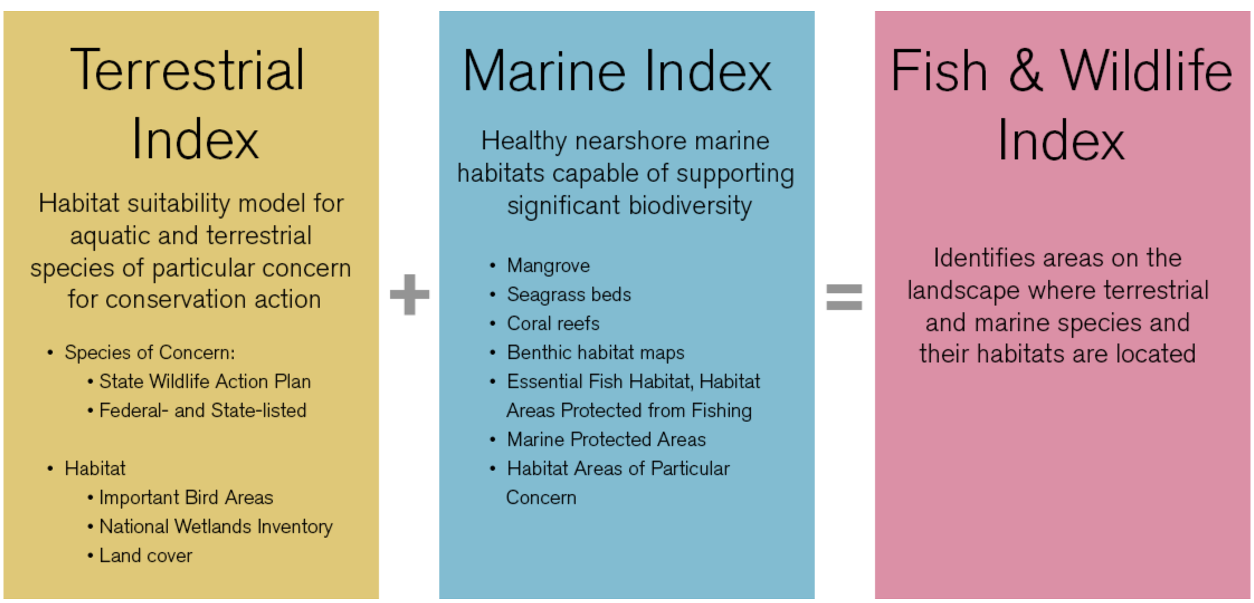


Figure 5. Elements of the Terrestrial and Marine Indices used to create the Fish and Wildlife Index.

2.5.1 Terrestrial Index

The Terrestrial Index aims to identify suitable habitats for major taxonomic groups using available land cover and habitat data. The Index is created relative to the habitat preferences and needs of the species of greatest conservation concern in the region, which were identified using the 2015 Puerto Rico State

Wildlife Action Plan (PR-DNER 2015) and species listed as threatened or endangered under the Endangered Species Act. Broad taxonomic groupings were used to model species' habitat preferences throughout the region including:

- Amphibians
- Reptiles
- Birds
- Freshwater, Brackish, Amphidromous and/or Diadromous Fishes
- Freshwater Invertebrates
- Terrestrial Mammals

Based on habitat preferences associated with each taxonomic group, the analysis modeled primary, secondary, and tertiary habitat suitability (for details, see Dobson et al. 2020). A complete list of species (organized by taxonomic group) included in the Puerto Rico Assessment is available in Appendix E.1.

In addition to using NOAA Coastal Change Analysis Program land cover, U.S. Fish and Wildlife Service's National Wetlands Inventory, and USGS National Hydrography Dataset to identify habitat types, the analysis utilized the 2006 USGS GAP Landcover, and Puerto Rico Department of Natural and Environmental Resources Critical Wildlife Areas. BirdLife International Important Bird Areas (IBAs) were also included. A complete list of datasets and methods used to create the Puerto Rico Terrestrial Index can be found in Appendix A.3 and Appendix E.1, respectively.

2.5.2 Marine Index

The Marine Index aims to identify marine habitat types that are capable of supporting significant biodiversity. In Puerto Rico, three important habitat types were considered: coral reefs, seagrass beds, and mangroves. While other marine habitat types may support significant biodiversity, the Puerto Rico Assessment focused on those habitat types where restoration and resilience projects may offer the multiple benefits of ecosystem enhancement, species richness, and coastal protection.

Benthic habitat maps, extending to a 30-meter depth bathymetry boundary around all islands, were used to define the spatial extent of coral reef and seagrass habitat. These data were also used to evaluate the percent cover of seagrass patches, where more species are assumed to occupy thicker patches (McCloskey & Unsworth 2015). To assess coral condition, estimates of live coral cover were obtained from NOAA's National Coral Reef Monitoring Program, which regularly implements stratified random sample surveys throughout Puerto Rico. Based on surveys from 2014-2016, areas with coral cover greater than seven percent were ranked highly (see Appendix E.2), and thus more likely to support higher numbers of reef associated species (Komyakova et al. 2013). Data on mangrove extent and health were also incorporated (Bunting et al. 2018), where mangrove habitat that is growing in spatial extent was considered more healthy and thus capable of supporting higher species richness.

In addition to the spatial extent and condition of these habitat types, the Marine Index calls upon a number of additional datasets including managed areas such as NOAA Habitat Areas of Particular Concern (HAPC), Essential Fish Habitat (EFH), and marine protected areas. Several Fisheries Management Plans designate EFH in Puerto Rico, including corals, queen conch, reef fish, spiny lobster, and highly migratory species. A complete list of datasets and methods used to create the Puerto Rico Marine Index can be found in Appendix A.4 and Appendix E.2.

2.6 Creating the Resilience Hubs

Resilience Hubs are areas of natural, undeveloped space that attempt to identify places that may be suitable for resilience-building conservation or restoration efforts that can help prepare for potential, adverse impacts to infrastructure and communities, while also improving the habitats of fish and wildlife species. Therefore, Resilience Hubs represent open spaces and habitats that have a high potential to provide benefits to both human communities and fish and wildlife. Accounting for natural spaces on both inland areas and in the nearshore marine environment, Resilience Hubs are formed based upon undeveloped landscapes and habitat types and create two outputs: Green Habitat Cores (inland) and Blue Habitat Cores (marine)(Figure 6).

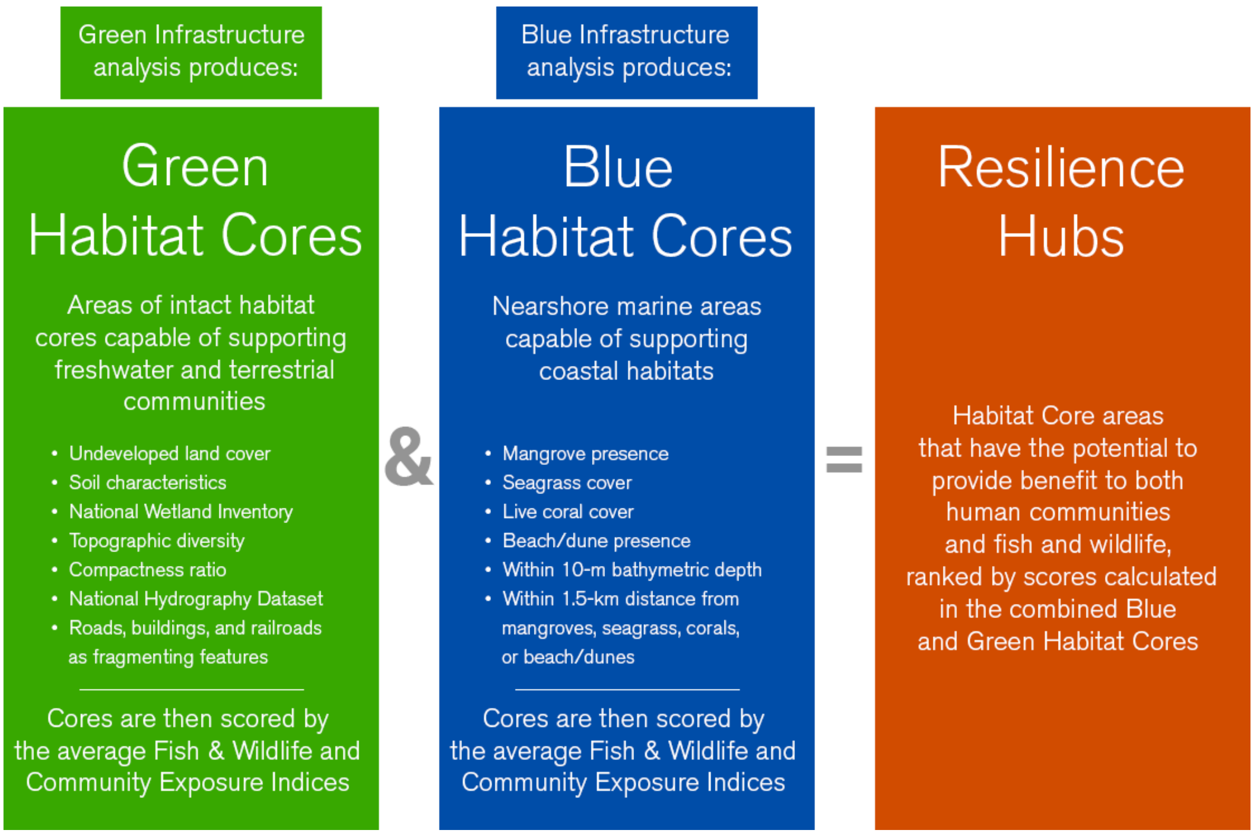


Figure 6. Elements of the Green and Blue Habitat Core outputs used to create the Resilience Hubs.

While the criteria differ between the Green and Blue Habitat Cores, both models rank Resilience Hubs according to the combined average values of the Community Exposure Index and the Fish and Wildlife Index (for a detailed description of methods see Dobson et al. 2020). To show variation within Resilience Hubs, the Habitat Cores are further subdivided and scored at a finer 4-hectare (10-acre) hexagon grid (Figures 7, 8, and 9). This scale was chosen for all Regional Assessments to facilitate local decision-making commensurate with the size of potential nature-based projects and solutions.

Figure 7. An initial step in creating the Green and Blue Habitat Cores. Note the Green Habitat Cores include both terrestrial and freshwater aquatic areas. The Blue Habitat Cores include estuarine, beach and dune, mangrove, and nearshore marine areas less than 10 meters in depth, but have not yet been grouped into Cores.

Figure 8. Green and Blue Habitat Cores converted to 4-hectare (10-acre) hexagons. Along with each Habitat Core, each hexagon is ranked to show variation within Resilience Hubs.

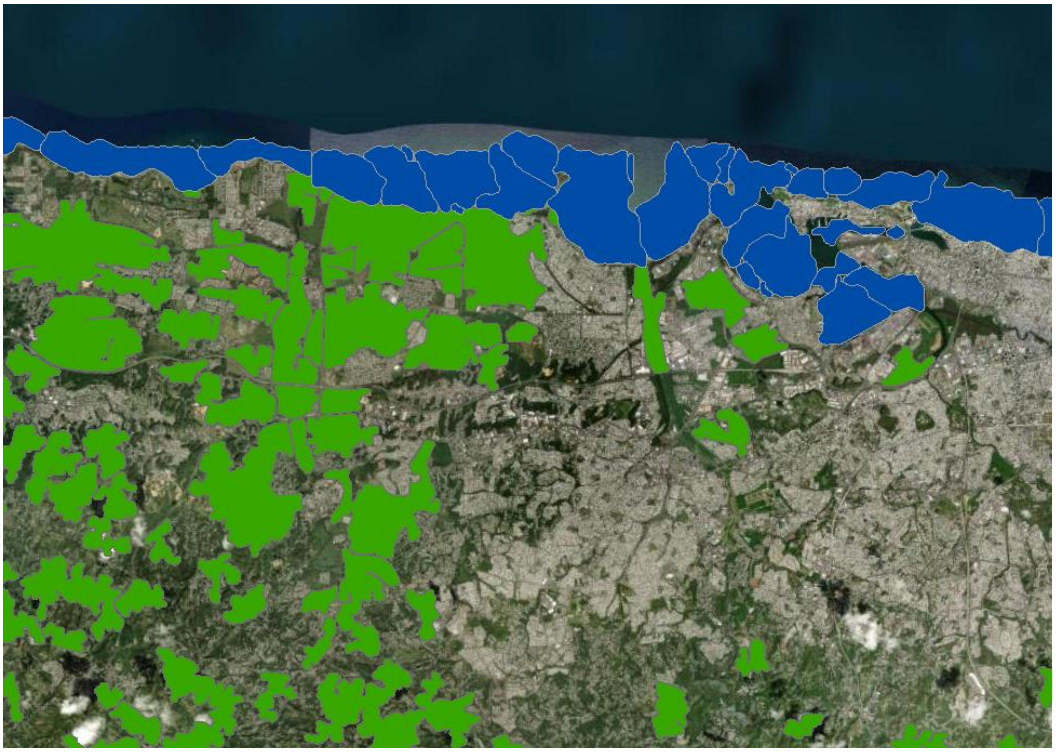


Figure 9. Green and Blue Habitat Cores. The Blue Habitat Cores are grouped by bathymetric basin. The Green and Blue Cores are then ranked to become Resilience Hubs.

2.6.1 Green Infrastructure

The Green Infrastructure[6] analysis used in the Regional Assessments builds upon methodology developed by the Green Infrastructure Center for the continental United States (Firehock & Walker 2019). Since these data were not available for Puerto Rico, NEMAC replicated the analysis to create this important layer for the Puerto Rico Assessment. The analysis identifies “intact habitat cores,” or every natural area 40.5 hectares (100 acres) or greater, regardless of ownership or preservation status. The dataset is intended to guide local, regional, and urban planners in identifying important places to conserve prior to planning development projects. The dataset also helps to prioritize which landscapes to protect and connect—such as natural systems that mitigate flooding, provide recreational opportunities, and benefit air and water quality (Firehock & Walker 2019). Habitat cores also represent relatively intact habitat that is of a sufficient size to support more than one individual of a species and takes into account fragmenting features that may disrupt the movement of wildlife species.

Applying these methods to Puerto Rico, the Green Infrastructure analysis resulted in the creation of Green Habitat Cores, or inland habitat cores encompassing both terrestrial and aquatic habitats. The resulting Green Habitat Core features are then converted into a 4-hectare (10-acre) hexagonal grid (Figure 8). The hexagonal grid helps to highlight variation in the Community Exposure Index and Fish and Wildlife Index scores associated with each habitat core to help facilitate fine-scale decision-making. For full documentation on how the Green Habitat Cores were created, please refer to Dobson et al. (2020).

In summary, the Green Infrastructure approach—in determining both Green Habitat Cores and their subsequent hexagons—identifies contiguous natural landscapes composed of similar landscape

[6] Note that Green Infrastructure analysis—as it is referred to in this Assessment—pertains to a specific methodology and is not intended to represent other local planning and management projects.

characteristics. Lands identified have the potential to be of higher ecological integrity and thus may offer improved potential for both human and wildlife benefit. This allows for a more accurate determination of the boundaries of natural landscapes when forming and ranking the Resilience Hubs. See Appendix A.5 and Appendix F for more details.

2.6.2 Blue Infrastructure

Recognizing the prominence of valuable coastal marine habitats in Puerto Rico, the Assessment developed a Blue Infrastructure[7] analysis. Marine and coastal habitats, such as coral reefs, seagrass beds, mangroves, and beach and dune systems not only support significant biodiversity, but are also important natural features that can protect human communities and infrastructure. Unlike the methodology used in the Green Infrastructure analysis, marine environments typically lack the fragmenting features that are necessary to delineate and form open spaces into inland habitat cores. As a result, the Project Team developed a different approach in order to identify Blue Habitat Cores, or marine and coastal areas represented by habitats that may be suitable for the implementation of conservation or nature-based resilience projects. The Blue Habitat Cores were delineated by creating a 4-hectare (10-acre) hexagonal grid of all coastal and marine habitats less than 10-meters in depth and then by grouping hexagons according to Puerto Rico's bathymetric basins (according to extent of the HUC-8 watershed boundary) and the marine habitats they contain. Unlike the Fish and Wildlife Index, only habitats less than or equal to 10 meters in depth were considered in the Blue Infrastructure analysis since nature-based solutions are more likely to provide coastal protection when implemented in shallow water habitats. For full documentation on how the Blue Habitat Cores were created, please refer to Appendix F and Dobson et al. (2020).

2.6.3 Combining Habitat Cores and Ranking Resilience Hubs

To capture the potential impact the Green and Blue Habitat Cores may have on reducing the effects of coastal flooding on nearby community assets while also benefiting wildlife, the Habitat Cores were scored using the average values of the Community Exposure and Fish and Wildlife Indices to determine the rankings of Resilience Hubs. For details about how Green and Blue Habitat Cores were scored, see Dobson et al. (2020). As noted above, every habitat core feature was converted into a finer-resolution 4-hectare (10-acre) hexagonal grid. As a result, each hexagon also received its own individual ranking, allowing for a finer-scale view of areas within any given Habitat Core. When considered in combination with the Resilience Hubs, the hexagons can help identify areas that may be ideal for resilience-building efforts that achieve dual human community and fish and wildlife benefits. See Appendix A.5 and Appendix F for more details.

[7] Note that Blue Infrastructure analysis—as it is referred to in this Assessment—pertains to a specific methodology and is not intended to represent other local planning and management projects.

RESULTS

The Puerto Rico Coastal Resilience Assessment reveals abundant opportunities to use nature-based solutions to help build human community resilience while supporting fish and wildlife habitat and species. Nature-based solutions include actions that sustainably manage and utilize natural systems to address societal challenges such stormwater management, urban flooding, and heat islands while benefiting biodiversity and human well-being. Implementing nature-based solutions, such as beach and dune restoration, can provide tremendous co-benefits to people and wildlife as described in the case study presented below (see Section 4). The Community Exposure Index shows areas of high exposure are distributed across the main island. In contrast, higher Fish and Wildlife Index scores are prevalent along the coastline and nearshore marine areas, with relatively sparse concentrations of high-scoring inland areas. Finally, the Resilience Hubs show that for the most part, there are highly valued Hubs evenly distributed across Puerto Rico, both along the coast and inland.

3.1 Community Exposure Index

The Community Exposure Index for Puerto Rico shows that exposure is evenly distributed across the main island, where densely populated urban areas contrast with large areas of undeveloped natural, open spaces (Figure 10). With an average population density in 2018 of 362 people per square kilometer, populated areas are very evident in the Community Asset Index. In Puerto Rico, efforts were made to incorporate additional types of critical infrastructure, such as communication infrastructure, marinas, and ferry routes and terminals. The inclusion of these additional datasets further accentuates the more populous areas throughout the island. The highest values, indicated by the darker browns (Figure 10), are concentrated in several discrete areas of high population, such as San Juan, Caguas, Ponce, and Mayagüez. While the input of the Community Assets Index are readily apparent in the mapping products, the scores also include flood-related threats, which are clearly concentrated along the coast (Figure 10).

As seen in Figure 10, the inland city of Caguas, south of San Juan, scored highly in the Community Exposure Index. Caguas is surrounded by five nearby rivers (Río Grande de Loíza, Río Turabo, Río Caguitas, Río Cañaboncito, Río Bairoa and Río Cañas), which contribute to a high Threat Index score primarily driven by the flood-prone areas input. Additionally, this city is densely populated and contains high amounts of impermeable soils. Together, these inputs and others indicate that despite being inland, Caguas is exposed to flooding threats that may warrant the implementation of nature-based solutions to help build resilience.

In the southwestern portion of the island near Ponce and Mayagüez, predominant inputs from the Threat Index include low-lying areas and impermeable surfaces, but other inputs such as flood-prone areas and storm surge also contribute to the overall value. In addition, both Mayagüez and Ponce are densely populated, but Mayagüez appears to have more socially vulnerable communities as compared to Ponce, which contributes to a high value in the Community Exposure Index. For the islands of Vieques and Culebra, exposure values are much lower with each island only containing one area of higher values, found in the cities of Vieques and Culebra, respectively. These islands are much less populated and contain very few critical assets and infrastructure compared to the main island. Flood-related threats are also more limited to the immediate coastlines.

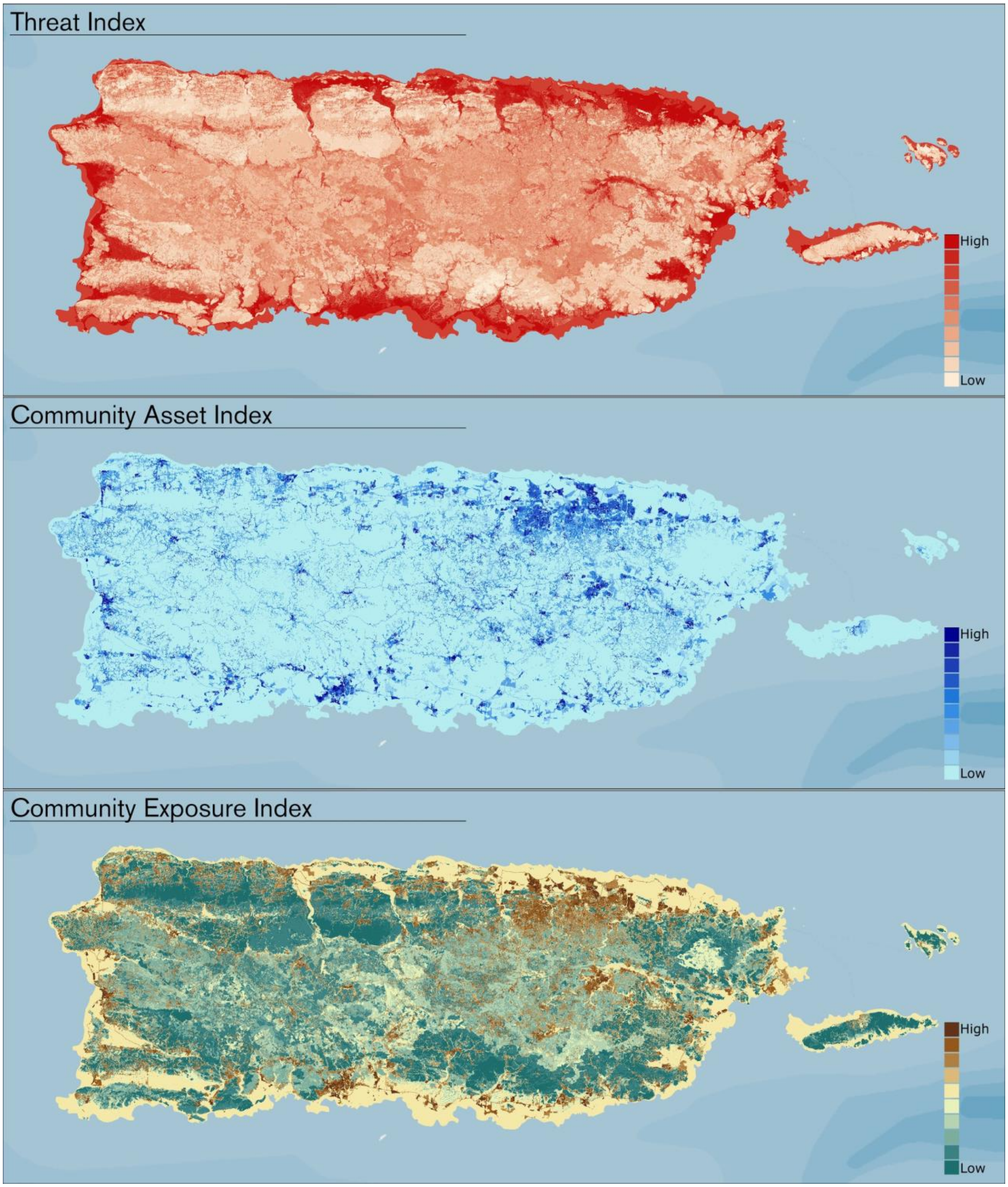


Figure 10. Threat, Community Asset, and Community Exposure Indices for Puerto Rico. The Threat and Community Asset Indices are multiplied to produce the Community Exposure Index, which shows areas where assets overlap flood threats.

In the areas surrounding San Juan (Figure 11), the Threat Index is driven by storm surge and the prevalence of impervious surfaces (impermeable soils inputs). As expected for a city of this size, the Community Asset Index is mostly driven by population density and the density of critical infrastructure and facilities. To explore the results of the analysis in more detail for any area of interest, visit the

Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to [Section 3.4](#).

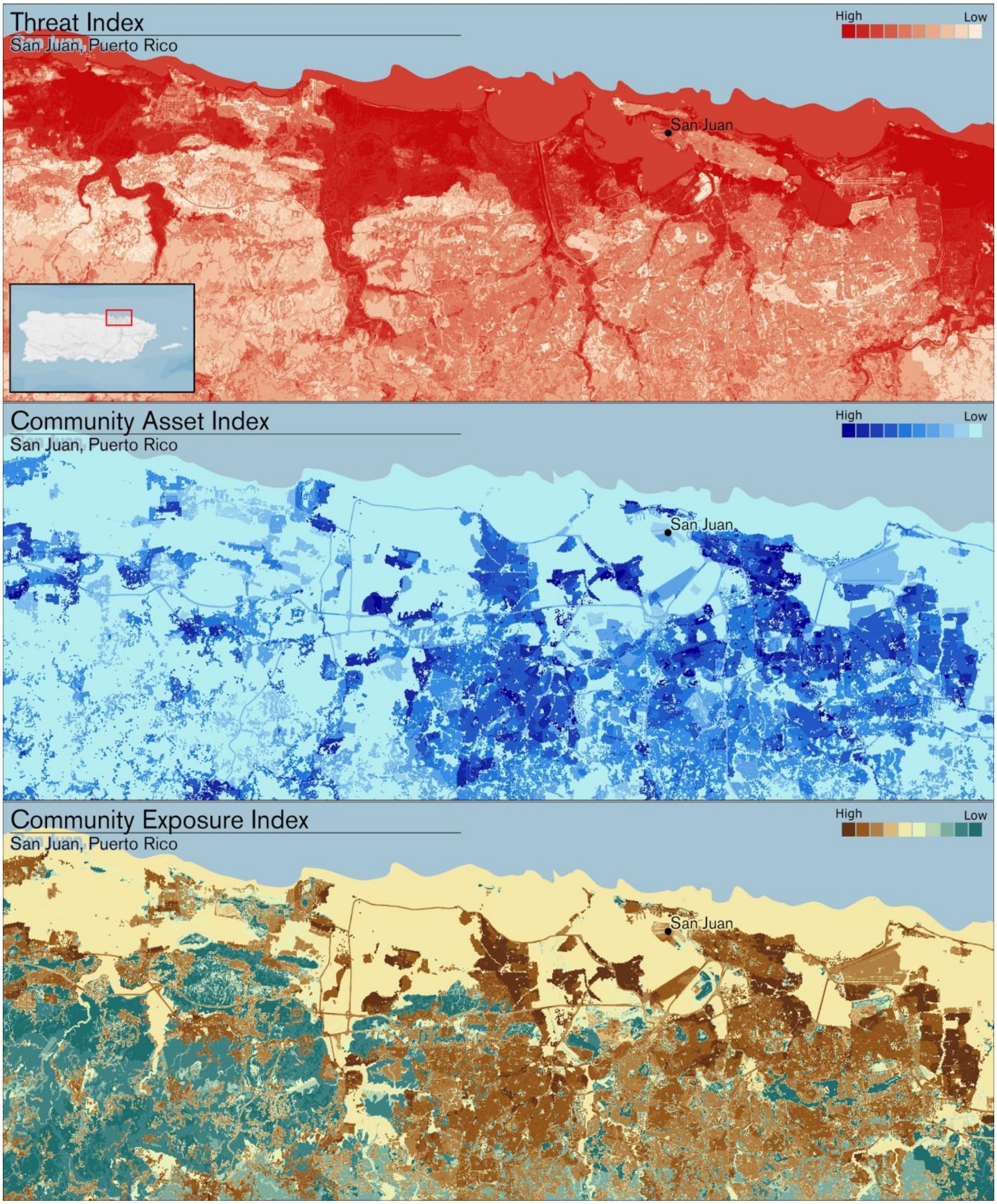


Figure 11. San Juan and surrounding communities show higher values of exposure, resulting from the combination of flood threats and community assets.

3.2 Fish and Wildlife Index

The combined Fish and Wildlife Index shows that habitat types expected to support wildlife species are also fairly concentrated along the coastlines of all three islands, although there are sparsely distributed areas inland that support high concentrations of important habitat (Figure 12).

As noted in the Methods section, the Terrestrial Index evaluated habitat suitability across taxonomic groups. Due to the proportionally low number of native mammals, freshwater/brackish fishes and invertebrates, and reptiles listed in the Puerto Rico State Wildlife Action Plan, birds and amphibians dominated the Terrestrial Index. The Terrestrial Index clearly shows higher concentrations of wildlife assets along the coastlines due to the importance of coastal habitats for sea birds and reptiles, particularly leatherback and hawksbill sea turtles (Figure 12). Of course, several areas in the interior of the main island also received higher values in the Terrestrial Index, including the Rio Abajo State Forest, Guajataca State Forest, and Toro Negro State Forest. Nearly all portions of the El Yunque National Forest included either primary, secondary, or tertiary habitat for each taxonomic group included in the Puerto Rico Assessment, highlighting its importance for the conservation of biodiversity.

The Marine Index shows that some of the highest values are found in the southwestern portion of the main island near the cities of Pole Ojea and La Parguera (Figure 13). This is a result of the combination of several inputs to the Index, including moderate to high amounts of seagrass and coral cover and the presence of Essential Fish Habitat, Habitat Areas of Particular Concern, and Marine Protected Areas. The northeastern part of the main island within the Northeast Ecological Corridor Nature Reserve also features higher marine values. Due in part to the protections offered by the Reserve, this is likely driven by high seagrass and coral cover and the presence of mangroves and Essential Fish Habitat. As highlighted by these two examples, the presence of healthy coral reef and seagrass beds coupled with managed areas frequently coincided with areas of high rank. To explore the results of the analysis in more detail for any area of interest, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4.

When combined into the Fish and Wildlife Index, the patterns evident in the Marine and Terrestrial Indices remain prevalent. As may be expected, the La Parguera Nature Reserve in southwestern Puerto Rico shows some of the highest Fish and Wildlife scores. Similarly, the marine reserves in northeastern Puerto Rico and Culebra as well as the coastlines of Vieques all score highly. However, there are significant fish and wildlife assets throughout the islands, indicating there are ample opportunities for habitat conservation and restoration projects to sustain Puerto Rico's incredible biodiversity.

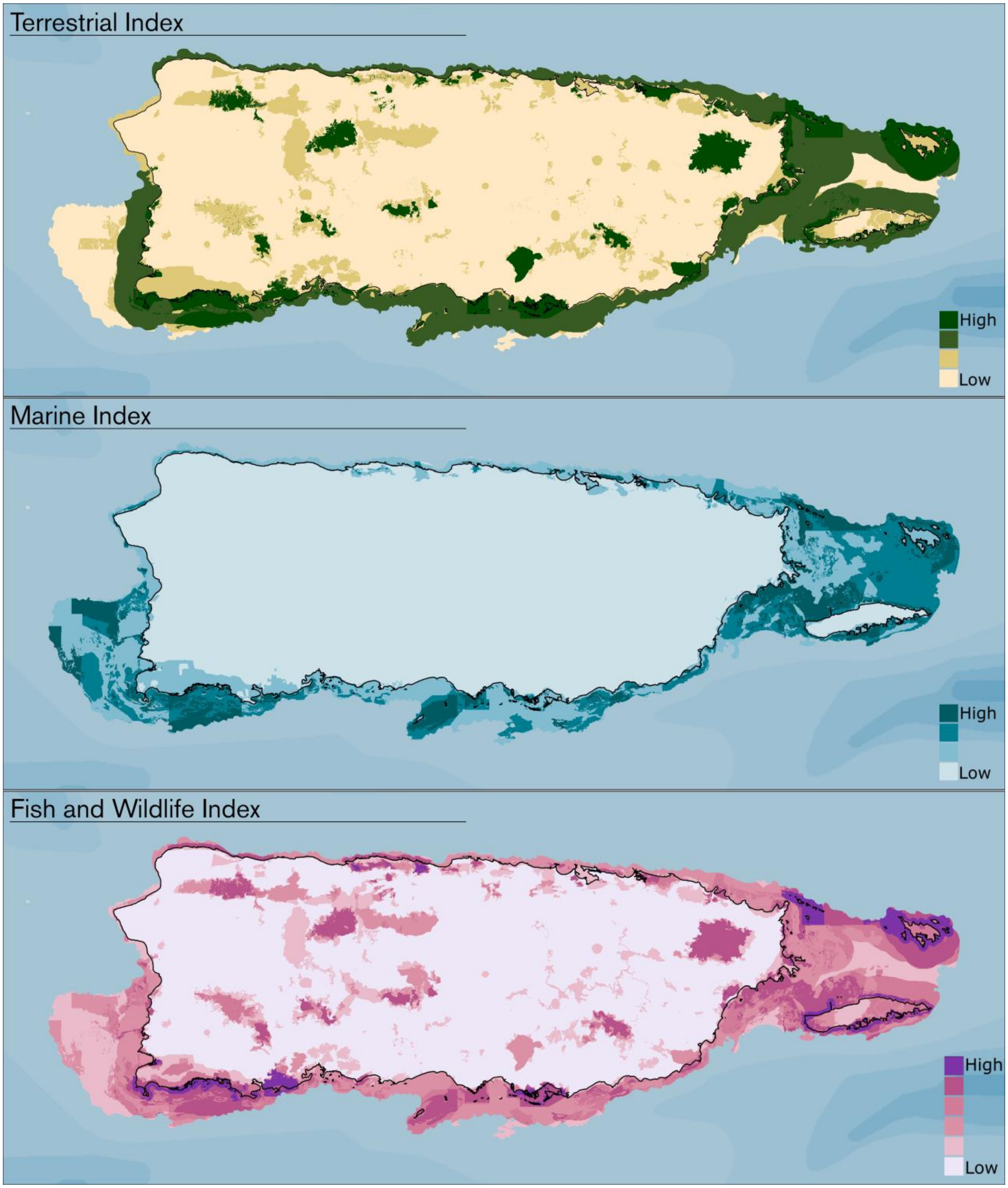


Figure 12. Terrestrial Index, Marine Index, and the resulting Fish and Wildlife Index for Puerto Rico.

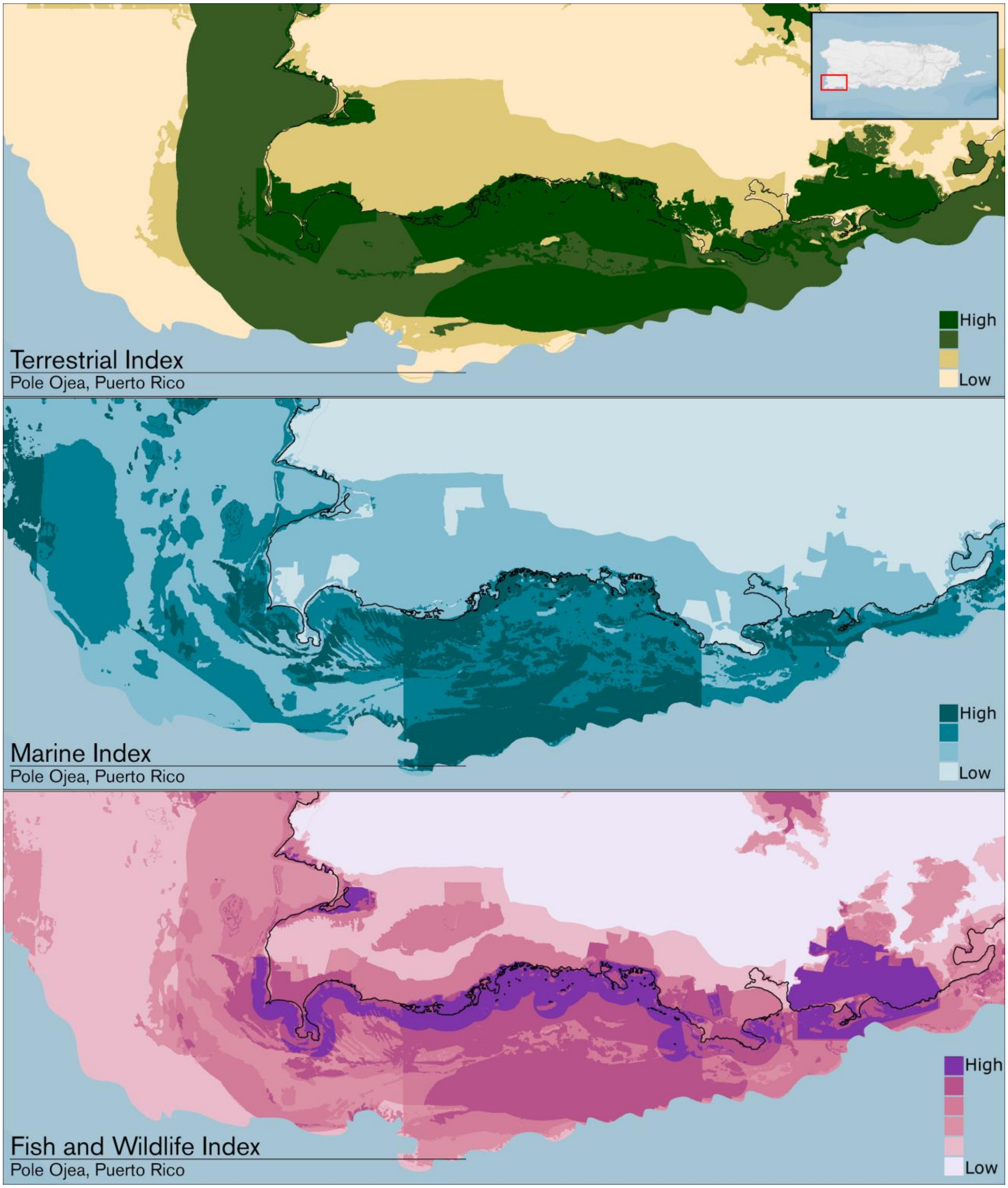


Figure 13. Pole Ojea is an area with high values in both the Terrestrial and Marine Indices, resulting in moderate to high values in the Fish and Wildlife Index. This is a result of a combination of the presence of several important marine and coastal habitat types and the presence of habitat preferred by species such as sea birds.

3.3 Resilience Hub Analysis

The Resilience Hubs analysis shows that Resilience Hubs are dispersed fairly evenly across all of Puerto Rico, including the islands of Vieques and Culebra (Figure 14). Resilience Hubs with the highest values are not just limited to the coastline, but are also found in the interior sections of all three islands. The Fish and Wildlife Index contributes significantly to the Hubs' ranking, as shown by the high values in the El Yunque National Forest and the Guajataca Forest Reserve.

The final Resilience Hub *rankings* are the product of the Community Exposure Index and Fish and Wildlife Index. As described in the Methods section above, the actual boundaries of the Resilience Hubs are formed through the Green and Blue Infrastructure analysis, which identifies Green and Blue Habitat Cores. The following maps show the ranked Blue and Green Habitat Cores and how they are combined to create the final Resilience Hub ranking.

Some of the highest values observed in the Blue Habitat Cores are along the east coast. This is driven largely by high values from both the Community Exposure Index and the Fish and Wildlife Index. In addition, this area includes corals, mangroves, and seagrass, which increased the Blue Habitat Core score due to the increased cumulative coastal protection benefits associated with the presence of multiple habitat types (Guannel et al. 2016). This area may represent an opportunity to implement a suite of coordinated nature-based solutions to maximize the potential to protect surrounding coastal communities from storm and flood events. The areas containing the highest ranking Green Habitat Cores are among the wetlands near the San Juan Bay, which is also driven by both high values in the Fish and Wildlife and Community Exposure Indices.

The Puerto Rico Assessment was completed at a 10-meter resolution, facilitating a finer-scale analysis of results. For instance, in the area surrounding Ponce on the southern coast of the main island there are a range of Resilience Hub scores (Figure 15). Sites that might be suitable for restoration efforts (darker red colors) exist along the immediate coastline, but Hubs are also found further inland. For instance, numerous nearshore marine and coastal sites may be suitable for nature-based solutions such as mangrove, coral reef, or seagrass restoration (darker shades of blue in Blue Habitat Cores map). Further inland, there are additional sites that may be well suited for coastal wetland conservation or restoration projects (darker shades of green or red in the Green Habitat Cores and Resilience Hubs maps, respectively). To explore the results of the analysis in more detail for any area of interest, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4.

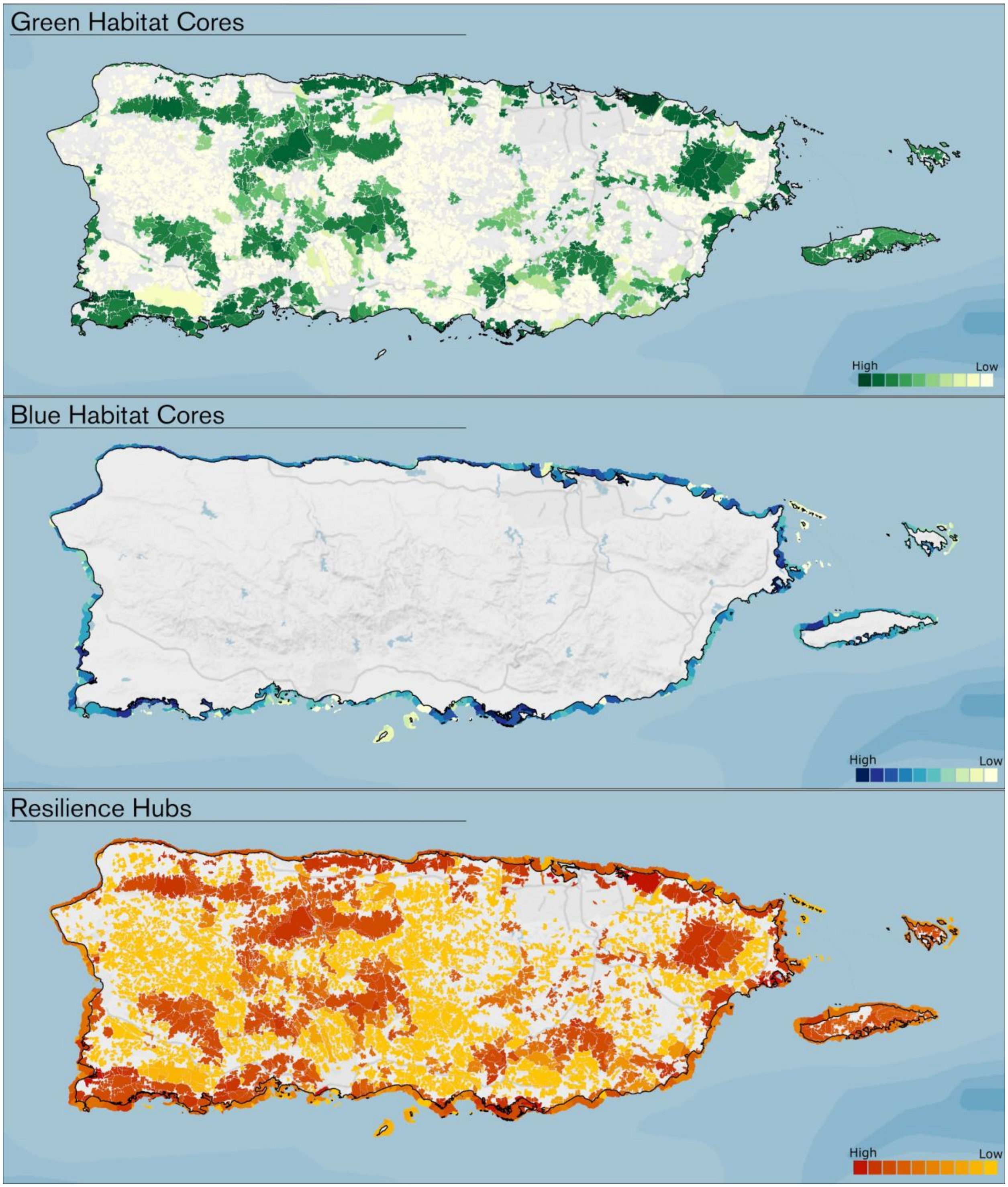


Figure 14. Resilience Hubs for Puerto Rico. Darkest reds show areas with higher potential for resilience building efforts that offer dual benefits to both human and fish and wildlife communities.

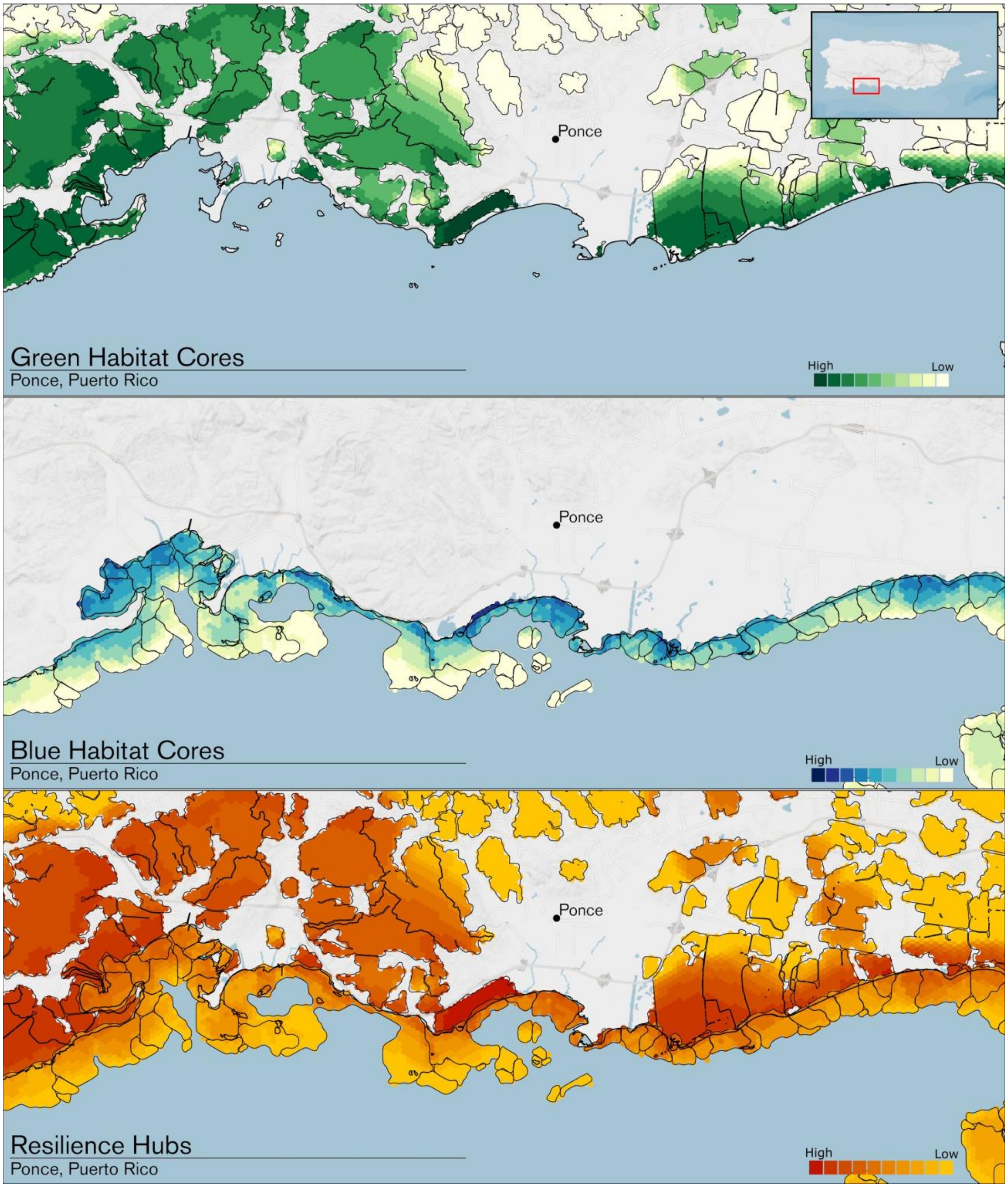


Figure 15. The area around Ponce shows a range of ranked Resilience Hub scores.

3.4 Coastal Resilience Evaluation and Siting Tool

To provide an online interface to allow users to interact with key Assessment data, including input data and final models for the Community Exposure Index, Fish and Wildlife Index, and the Resilience Hubs, the Coastal Resilience Evaluation and Siting Tool (CREST) was developed as an accompanying GIS-based web tool (available at resilientcoasts.org). CREST helps users make informed decisions about proposed project sites and address other key questions about how to build resilience within their community. It also allows users to have full access to the Puerto Rico Assessment data so they may incorporate those data into their own GIS applications or other planning processes. Additionally, CREST provides access to the Assessment results even if the user does not have a GIS background or access to GIS software.

Users can directly access results of the Puerto Rico Assessment straight from the CREST homepage. In addition to simply exploring the results of the Regional Assessments, CREST allows users to analyze results for specific areas of interest. For instance, if a user has already identified a potential project location, they can draw or upload the project boundary within the tool to view site-specific results for the Resilience Hubs, Community Exposure Index, Fish and Wildlife Index, and the results for each of the model inputs. Alternatively, if a user does not have a specific project location in mind, but is interested in evaluating opportunities within a particular region, they can draw a broad area of interest to view results. In both cases, the user can view the results in CREST or download the results in tabular or GIS formats for additional analysis.

CASE STUDY

4.1 Increasing Local Resilience through Dune Restoration

Vegetated sand dunes line most of Puerto Rico's north coast. These dynamic coastal land formations serve as important habitats for wildlife and offer essential storm damage mitigation benefits for coastal communities. These sand dunes are located in 13 municipalities along the north coast. Approximately 48 percent of sand dunes are found in the municipalities of Isabela, Dorado, and Loiza, most of which are in very close proximity to densely populated areas and main access roads. In particular, the northwestern coast of Puerto Rico, including the area of Middles Beach in the municipality of Isabela, contains dramatic scenery, steady waves, and popular surf beaches (Figure 16). The natural dune system protects the surrounding community from storm surge and flooding.

Figure 16. Map showing the general location of the Middles Beach area in northwest Puerto Rico.

Unfortunately, these sand dunes were severely exploited commercially for approximately 40 years, resulting in a significant reduction in volume and total area. In turn, this has resulted in a significant reduction in the protection offered by these landforms to coastal communities, making these areas less resilient to storms and other effects of climate change. In recent years, the dunes have also been severely impacted by hurricanes Irma and Maria and winter storm Riley. The north coast of the island received waves up to 13 meters during Hurricane Maria in September 2017 and Winter Storm Riley in March 2018 produced waves up to 5 meters.

Coastal dunes in Puerto Rico now consist of a very fragile system of landforms with severe conservation threats including illegal sand extraction, non-directed foot traffic and invasive green iguanas damaging vegetation, illegal use of all-terrain vehicles, and lack of education about their value. Puerto Rico also lacks relocation programs for displaced sand, resulting in large volumes of sand being lost every year from the beaches. There are existing laws protecting dunes in Puerto Rico, but they could benefit from more enforcement.

In order to address these needs and restore critical beach and dune systems, the researchers and students at the Center for Conservation and Ecological Restoration of the University of Puerto Rico (UPR) Aguadilla along with other local partners, have been working to implement interventions that can help restore these natural dunes. With funding from the National Coastal Resilience Fund[8] and other sources, UPR is implementing two projects that together will restore approximately 4 hectares (10 acres) of beach and dune habitat across 21 sites along the entire north coast of Puerto Rico. While the projects utilize similar restoration activities across all sites, the Assessment Project Team visited several sites in Isabela and Aguadilla in October 2019 to learn more about the types of interventions used to reduce coastal threats in the region.

The following text describes the specific restoration activities undertaken at Middles Beach, Isabela using the Puerto Rico Assessment results to demonstrate the utility of various outputs to evaluate potential locations to site resilience efforts. For instance, Figure 17 shows the impact of sea level rise on the approximate project footprint and surrounding areas, highlighting one of the coastal flood-related threats impacting this region.

Figure 17. Impacts of sea level rise within and surrounding the Middles Beach project site (black rectangle). Dunes help protect coastal communities from flood threats such as sea level rise. Over time, sea level rise will exacerbate other flood-related threats.

To help build resilience against coastal flood threats, the project includes building wooden boardwalks to provide beach access, installing biomimicry matrices (wood from pallets) in the sand to discourage foot traffic and promote sand deposition, and planting native vegetation to promote sand accumulation and decrease erosion and trampling of the native dune (Figure 18). Native plants used include beach bean (*Canavalia rosea*), sea grapes (*Coccoloba uvifera*), milkweed (*Calotropis gigantea*), buttonwood mangrove (*Conocarpus erectus*), and beach morning glory (*Ipomea pes-caprae*). The leaves of the plants slow the wind creating turbulence that promotes sand deposition, while dissipating rain and surge energy, and thus protecting the dune. The root systems of these plants also contribute to holding the

[8] See NFWF's National Coastal Resilience Fund website for details about the program: https://www.nfwf.org/programs/national-coastal-resilience-fund

sand, further preventing erosion. The taller the vegetation and the more roughness, the greater the benefits derived from dissipating winds and promoting sand deposition.

Figure 18. Nature-based features such as dunes along Puerto Rico's north coast at Middles Beach near Isabela provide a mitigation solution for communities and community assets. Left: Students and faculty from UPR build wooden boardwalks across fragile dunes to allow beach access without causing damage. Right: Dunes planted with grasses and sea grapes. The over wash area in the background will be planted to repair this breach. Photo credits: Bridget Lussier, NOAA.

In addition to the numerous physical benefits of planting vegetation, native plants and healthy beach ecosystems also provide important habitat for wildlife. Together, these activities benefit important fish and wildlife species (Figure 19), while also protecting the communities behind the dunes (Figure 20).

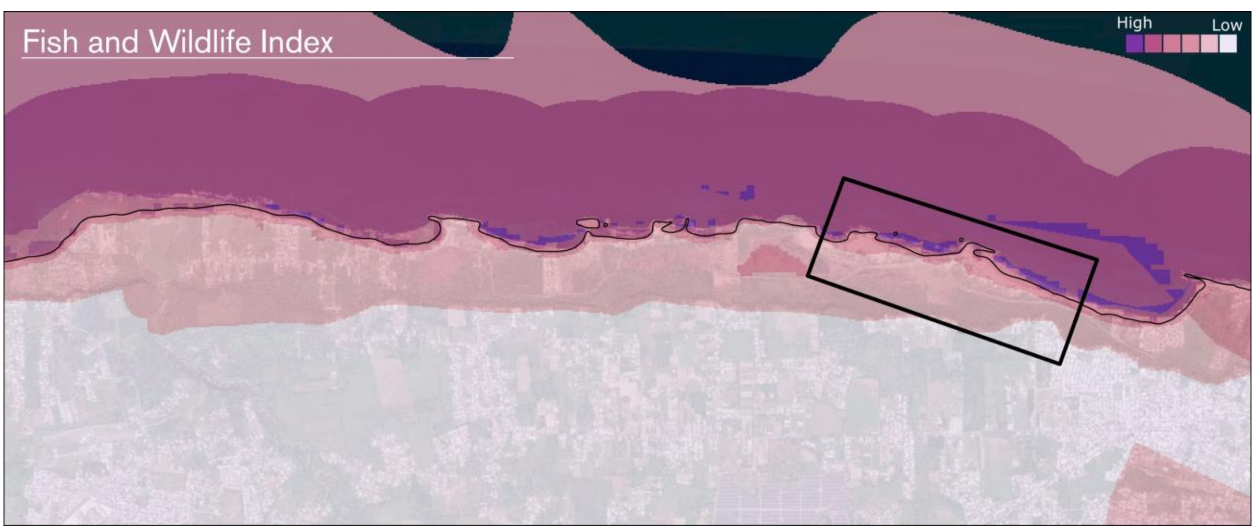


Figure 19. The Middles Beach project site (black rectangle) contains a range of moderate to very high values in the Fish and Wildlife Index. This is likely due to the habitat resources available to species in the nearshore marine environment and immediate coastal zone.

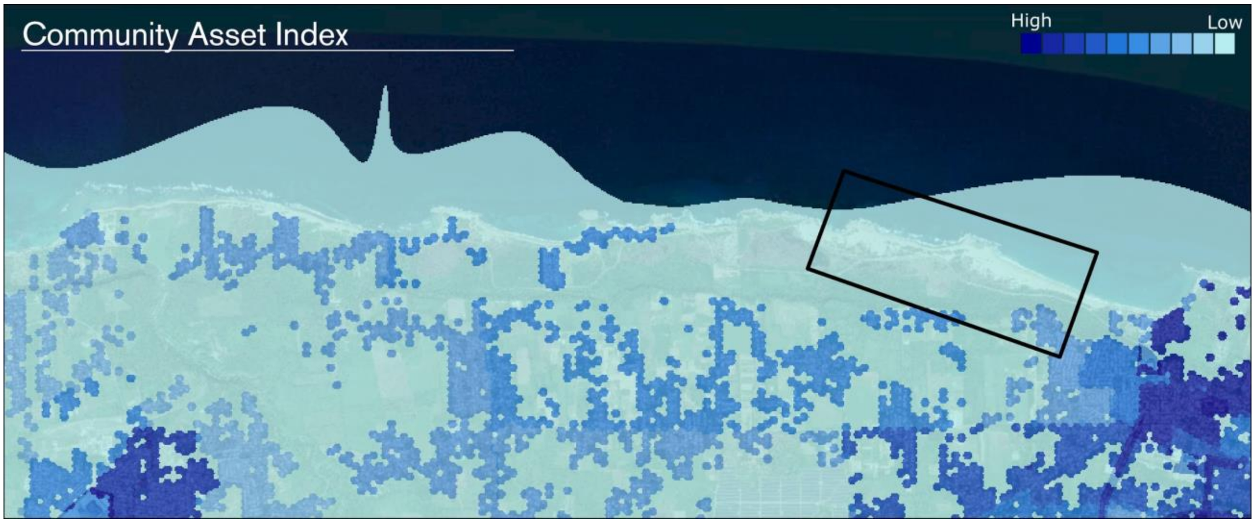


Figure 20. The Community Asset Index results within and surrounding the Middles Beach project site (black rectangle). Dune restoration projects have the potential to improve overall community resilience to impacts from flood threats.

With the presence of considerable flooding threats, concentrations of coastal community assets, and wildlife habitat, the Middles Beach restoration project demonstrates the importance of placing resilience projects in areas that can achieve dual benefits for communities and fish and wildlife. The Assessment reveals how Resilience Hubs are a useful tool to identify areas suitable for nature-based, resilience-building interventions. In the areas surrounding Middles Beach, a range of high ranking Hubs are visible (Figure 21). Additionally, by visualizing the 4-hectare (10-acre) hexagonal grid, the user can access finer-resolution information to understand the variation in scores within a Resilience Hub. The Resilience Hubs along the coast, and throughout Puerto Rico, can help support the prioritization of habitats for other similar types of projects.

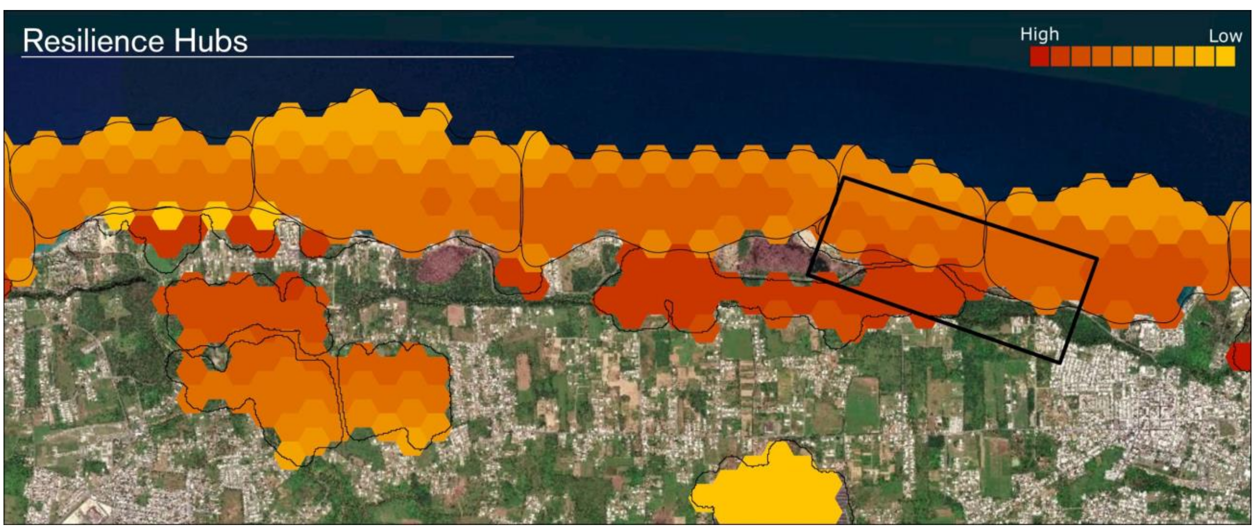


Figure 21. Resilience Hubs (black outlines) in this area indicate that there are multiple areas potentially well suited for restoration projects including the Middles Beach project site (black rectangle). Note the 4-hectare (10-acre) hexagons show variation in scores within Resilience Hubs.

To achieve successful results, the project deployed a diverse suite of tools and resources, including sand trapping, dune planting, boardwalk construction, education and outreach through signage about the projects, and a native plant nursery to grow plants used in restoration (Figure 22). These critical restoration efforts will continue to provide important benefits to local communities and wildlife. The UPR project team monitors restoration sites through the use of drones and photogrammetry software in order to help demonstrate the positive impacts of natural and nature-based features. Working with the local residents and landowners to find common ground has, and will remain critical to their success. For more information about this project and others like it, visit the [National Coastal Resilience Fund's website] and [NOAA's Digital Coast].

Figure 22. Nature-based features such as dunes along Puerto Rico's north coast at Middles Beach near Isabela provide a mitigation solution for communities and community assets. Left: looking west along dunes at Middles Beach where the dune system has been restored. Right: Slats of wood from pallets cause sand to collect, and discourage foot traffic, causing sand to develop into dunes. Photo credits: Bridget Lussier, NOAA.

CONCLUSION

5.1 Summary and Key Takeaways

As coastal and inland communities across Puerto Rico deal with current and future flooding threats from natural events, tools such as this Assessment can help decision-makers and other stakeholders use data to make informed decisions about how to identify areas that may be suitable for resilience-focused and nature-based restoration projects. NFWF and NOAA remain committed to supporting programs and projects that improve community resilience by reducing communities' vulnerability to coastal storms, sea-level rise, and other types of coastal flooding by strengthening natural ecosystems and the fish and wildlife habitat they provide.

With over 480 kilometers of coastline, Puerto Rico remains highly exposed to a variety of coastal-flood related hazards in many areas. This is compounded in areas with higher populations and community assets, such as San Juan and Ponce. Inland communities are not immune from flood-related threats either, especially as it relates to heavy precipitation events and riverine or flash flooding. Furthermore, the effects of coastal flooding are exacerbated when combined with heavy precipitation inland, suggesting efforts to build resilience should consider the benefits of a holistic, island-wide approach.

Puerto Rico is ecologically diverse, with an abundance of wildlife assets in terrestrial, aquatic, and marine environments. Combining this information in the Fish and Wildlife Index with the Community Exposure Index, the Puerto Rico Assessment identifies Resilience Hubs, or areas where resilience-building projects may benefit both human and wildlife communities.

5.2 Future Work

The Regional Coastal Resilience Assessments were developed through an iterative process supported by substantial guidance from technical and regional experts. The Regional Assessments and the associated Coastal Resilience Evaluation and Siting Tool (CREST) will continue to be updated, refined, and expanded in the future as appropriate. The overarching methodology will continue to be vetted and refined as needed through ongoing Regional Assessments across the United States. The application and continued development of the Assessments will assist NFWF and others in the implementation of nature-based solutions that build community resilience to flooding threats while benefiting fish and wildlife populations nationwide.

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APPENDIX

The following sections describe the data used for the Puerto Rico Coastal Resilience Assessment in detail, as well as any regional deviations from the methodologies outlined in the Methodology and Data Report (Dobson et al. 2020).

The Puerto Rico Assessment was completed at a 10-meter resolution, using the projection *NAD 1983 State Plane Puerto Rico Virgin Islands FIPS 5200* (WKID 32161).

A. Data Summary

A.1 Threat Index

The following is a comprehensive list of datasets used to create the Threat Index for the Puerto Rico Coastal Resilience Assessment. **Bolded layer names indicate the source data were specific to the Puerto Rico Assessment.**

Layer Name	Dataset and Source
Flood-prone Areas	FEMA National Flood Hazard Layers, USDA-NRCS SSURGO (2.2 or later)
Sea Level Rise	NOAA Office for Coastal Management Sea Level Rise Inundation Database (2015 or later)
Storm Surge	NOAA/NHC Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model (2014 or later)
Areas of Low Slope	USGS National Elevation Dataset, 10-meter resolution (most recent available)
Soil Erodibility	USDA-NRCS SSURGO (2.2 or later)
Impervious Surfaces	USDA-NRCS SSURGO (2.2 or later), NOAA Coastal Change Analysis Program Landcover (2010)
Geologic Stressors: Landslide Susceptibility	USGS/Office of Management and Budget via Puerto Rico Geodata Download (2013)
Tsunami Inundation	Dept. of Geology, Seismic Network, University of Puerto Rico at Mayagüez via Puerto Rico Geodata Download

A.2 Community Asset Index

The following is a comprehensive list of datasets used to create the Community Asset Index for the Puerto Rico Coastal Resilience Assessment. **Bolded layer names indicate the source data was specific to the Puerto Rico Assessment**.

Layer Name	Dataset and Source
Population Density	U.S. Census Bureau, 2016 American Community Survey - block group geography
Social Vulnerability	U.S. EPA Environmental Justice Screening and Mapping tool (2016 or later)
Critical Facilities	Fire Stations: USGS National Structures Dataset; Police Stations, Schools, and Medical Facilities: Data identified during stakeholder workshop.
Parcels	Local data identified during stakeholder workshop (Parcel Register PR, 2017)
Building Footprints	Open Street Maps

Critical Infrastructure *(Various Inputs, see below)*

Primary roads	*Data identified during stakeholder workshop and from Highway and Transportation Authority via Puerto Rico Geodata Download*
Bridges	*Federal Highway Administration: National Bridge Inventory (v.7 or later)*
Airport runways	*Puerto Rico Planning Board via Puerto Rico Geodata Download*
Ports/Heliports	*Puerto Rico Planning Board via Puerto Rico Geodata Download, additional Heliports digitized by NEMAC team where applicable*
Power Plants/Substations	*Data identified during stakeholder workshop and from Electric Power Authority via Puerto Rico Geodata Download*
Wastewater treatment facilities	*Water and Sewage Authority via Puerto Rico Geodata Download*
Railroads (urban train)	*Highway and Transportation Authority via Puerto Rico Geodata Download*
Ferry Terminals	*Locations digitized by NEMAC team*
Major dams	*USDOT/Bureau of Labor Statistics's National Transportation Atlas Database (2015 or later)*
Petroleum terminals	*U.S. Energy Information Administration: EIA-815, Monthly Bulk Terminal and Blender Report*
Hazardous Sites	*U.S. EPA Facility Registry Service (2016 or later)*
Marinas	*Locations digitized by NEMAC team*

A.3 Terrestrial Index

The following table lists those datasets that were used to create the Terrestrial Index for Puerto Rico.

Dataset Name	Source and Year
C-CAP Land cover	NOAA Office for Coastal Management (2010)
National Wetlands Inventory	U.S. Fish & Wildlife (most recent available)
National Hydrography Dataset	USGS (most recent available)
GAP Land cover	USGS (2006)
Important Bird Areas & Key Biodiversity Areas	BirdLife International (2020)
Environmental Sensitivity Index Species Habitat	NOAA Office of Response and Restoration (2000)
Critical Habitat Designations	NOAA & U.S. FWS (most recent available)
State Wildlife Action Plan species list	Puerto Rico Department of Natural and Environmental Resources (2015)
Habitat Classification Scheme	IUCN Red List of Threatened Species (Version 3.1)
Protected Areas Database of the U.S. (PADUS)	USGS (Version 2.0)
Critical Wildlife Areas	Puerto Rico Department of Natural and Environmental Resources (2015)

A.4 Marine Index

The following table lists those datasets used to create the Marine Index for Puerto Rico.

Dataset Name	Source and Year
Critical Habitat Designations	NOAA & U.S. FWS (most recent available)
Essential Fish Habitat	NOAA Fisheries (2018)
Essential Fish Habitat Areas Protected from Fishing	NOAA Fisheries (2018)
Habitat Areas of Particular Concern	NOAA Fisheries (2018)
Benthic Habitat Maps	NOAA National Centers for Coastal Ocean Science (2015)
Coral Cover Surveys	NOAA National Coral Reef Monitoring Program (2014, 2016)
Global Mangrove Watch	UNEP and others (2010/2016)
Protected Areas Database of the U.S. (PADUS) - Marine Protected Areas	USGS (Version 2.0)

A.5 Resilience Hubs

The following table lists those datasets used to create the Resilience Hubs for Puerto Rico.

Dataset Name	Source and Year
C-CAP Land Cover Atlas	NOAA Office for Coastal Management (2010)
National Wetlands Inventory	U.S. Fish & Wildlife (most recent data available)
National Hydrography Dataset	U.S. Geological Survey (USGS) 1:24,000
Bathymetry	NCEI's U.S. Coastal Relief Model
Coral Cover Surveys	NOAA National Coral Reef Monitoring Program (2014, 2016)
Benthic Habitat Maps	NOAA National Centers for Coastal Ocean Science (2015)
Global Mangrove Watch	UNEP and others (2010/2016)
National Elevation Dataset	U.S. Geological Survey (USGS), EROS Data Center
SSURGO Soils Survey	USDA, NRCS
Roads polyline	OpenStreetMap (latest data available)
Railroads polyline	OpenStreetMap (latest data available)

B. Detailed Methodology: Threat Index

The Threat Index for Puerto Rico was created by following the methodology outlined in the Methodology and Data Report (Dobson et al. 2020). For any inputs not described here, refer to Dobson et al. (2020) for more detail.

B.1 Geologic Stressors: Landslide Susceptibility

This dataset models landslide susceptibility for Puerto Rico, Vieques, and Culebra Island and identifies all slopes greater than 50 percent as having a high risk of landslides. To incorporate these data into the model, the highest two classifications of landslide susceptibility were used and ranked according to the table below.

Landslide Susceptibility for Puerto Rico	Rank Value
Below 50% slope	0
"High susceptibility to landsliding"	1
"Highest susceptibility to landsliding"	2

B.2 Tsunami Inundation

The Puerto Rico tsunami flood elevation raster (2012) was developed by the University of Puerto Rico's Tsunami Ready Program in collaboration with the Marine Science Department and Geology Department, University of Puerto Rico at Mayagüez. The MOMRAS (Maximum of Maximum Tsunami Flood Elevation Raster) dataset models inundation height above the ground for a particular point (i.e., the tsunami propagation and inundation model output data) and converted to a grid file.

Tsunami Inundation Distribution for Puerto Rico	Rank Value
0	0
<= 0.30	1
<= 0.61	2
<= 1.01	3
<= 1.81	4
<= 15.9	5

B.3 Calculating the Threat Index

The Threat Index was classified into 10 classes in order to multiply them and ultimately create the Community Exposure Index. Below is the classification that was used for the Puerto Rico Threat Index.

Puerto Rico Threat Index Distribution

Threat Index Break Value	0	1	2 - 3	4	5	6 - 8	9	10	11 - 15	16 - 35
Final Rank Value	1	2	3	4	5	6	7	8	9	10

C. Detailed Methodology: Community Asset Index

C.1 Population Density

Following the methodology for population density is detailed in the Methodology and Data Report (Dobson et al. 2020); the distribution shown in the table below was used to rank population density in Puerto Rico.

Population Density Distribution for Puerto Rico	Rank Value
0	0
<= 21.771	1
<= 40.194	2
<= 101.6	3
<= 221.33	4
<= 553.461	5

C.2 Social Vulnerability

Following the methodology for social vulnerability as detailed in the Methodology and Data Report (Dobson et al. 2020), the distribution shown in the table below was used to rank social vulnerability in Puerto Rico.

Social Vulnerability Distribution for Puerto Rico	Rank Value
0	0
<= 88.745	1
<= 90.956	2
<= 90.256	3
<= 96.062	4
<= 100	5

C.3 Modifications Made to the Critical Infrastructure and Critical Facilities Inputs

Specific critical infrastructure and facilities need to be reviewed for each region to identify any data that is non-applicable and/or any additional inputs that should be considered. The table in section A.2 identifies data source and data inputs that were included in the Puerto Rico Assessment.

Infrastructure and facility data inputs were included in the analysis following the same methodologies found in the Methodology and Data Report (Dobson et al. 2020).

C.4 Calculating the Community Asset Index

The Community Asset Index was classified into 10 classes in order to multiply them and ultimately create the Community Exposure Index. Below is the classification that was used for the Puerto Rico Community Asset Index.

Puerto Rico Community Asset Index Distribution

Asset Index Break Value	0	1	2	3	4	5	6	7 - 8	9	10 - 16
Final Rank Value	1	2	3	4	5	6	7	8	9	10

D. Detailed Methodology: Community Exposure Index

After classifying both the Threat and Community Asset Indices into 10 classes each, they are multiplied to create the Community Exposure Index. Exposure is the overlap of community assets and flood threats. As this multiplication results in a final index with values from 1-100, the Community Exposure Index is further classified to make it easier to work with and understand the results. The distribution used for the Community Exposure Index in Puerto Rico is shown below.

Puerto Rico Community Exposure Index Distribution

Exposure Index Break Value	0 - 2	3	4	5	6 - 7	8 - 10	11 - 17	18 - 30	31 - 54	55 - 100
Final Rank Value	1	2	3	4	5	6	7	8	9	10

E. Detailed Methodology: Fish and Wildlife Index

E.1 Calculating the Terrestrial Index

The Terrestrial Index for Puerto Rico is based on the same methodology described in the Methodology and Data Report (Dobson et al. 2020). However, because of regional differences, the taxonomic groups between regions may differ. Taxonomic groups included are dependent on the species of concern as determined by each region's State Wildlife Action Plan and species listed under the Endangered Species Act. Habitat preferences for these species were then identified in the IUCN Red List of Threatened Species. The following taxonomic groups and associated species were incorporated into the Terrestrial Index for Puerto Rico.

Amphibians

Puerto Rican Crested Toad	Richmond's Coqui	Mona Island Coqui
Grass Coqui	Burrowing Coqui	Warty Coqui
Cricket Coqui	Wrinkled Frog	Puerto Rican Mountain Coqui
Hedrick's Coqui	Golden Coqui	Web-footed Coqui
Mottled Coqui	Cave Coqui	

Birds

White-cheekd Pintail	Antillean Nighthawk	Cape May Warbler
Puerto Rican Woodpecker	Puerto Rican Nightjar	Prairie Warbler
Puerto Rican Tody	Plain Pigeon	Black and White Warbler
Yellow-billed Cuckoo	Key West Quail-Dove	American Redstart
Puerto Rican Lizard-Cuckoo	Bridled Quail-Dove	Northern Waterthrush
Green Mango	Limpkin	Caribbean Elaenia
Green-throated Carib	Purple Gallinule	Black-whiskered Vireo
Puerto Rican Emerald	Willet	Elfin Woods Warbler
Puerto Rican Screech Owl	American Oystercatcher	Yellow-shouldered Blackbird
Short-eared Owl	Wilson's Plover	Yellow Warbler
Puerto Rican Flycatcher	Broad-winged Hawk	Northern Parula
Loggerhead Kingbird	Least Grebe	Ovenbird
Puerto Rican Vireo	Pied-billed Grebe	Ruddy Duck
Piping Plover	Least Bittern	Roseate Tern
Grasshopper Sparrow	Louisiana Waterthrush	Red Knot
Bicknell's Thrush	Puerto Rican Tanager	Sooty Tern
Golden-winged Warbler	Puerto Rican Spindalis	Brown Noddy
Red-footed Booby	Puerto Rican Oriole	Masked Booby
Brown Booby	White-crowned Pigeon	Audubon's Shearwater
Magnificent Frigatebird	Lesser Antillean Pewee	West Indian Whistling Duck
Brown Pelican	Snowy Plover	Red-billed Tropicbird
Bridled Tern	White-tailed Tropicbird	
Sharp-shinned Hawk	Black Swift	

Freshwater, Brackish, Amphidromous, and/or Diadromous Fishes

Emerald Sleeper	Fat Sleeper	River Goby
Spotted Algae Eating Goby	Large Scaled Spinycheek Sleeper	Short-tail River Pipefish
American Eel	Bigmouth Sleeper	Burro Grunt

Freshwater Invertebrates

River Shrimp Buruquena		

Reptiles

Culebra's Giant Lizard Puerto Rican Twig Anole Mona Island Iguana	Green Sea Turtle Hawksbill Sea Turtle Leatherback Sea Turtle	Desecheo Island Gecko Monito Island Gecko

Terrestrial Mammals

Red Bat Jamaican Fruit Bat Fishing Bat	Red Fruit Bat Parnell's Mustached Bat Big Brown Bat	Cave Bat Brazilian Free Tailed Bat

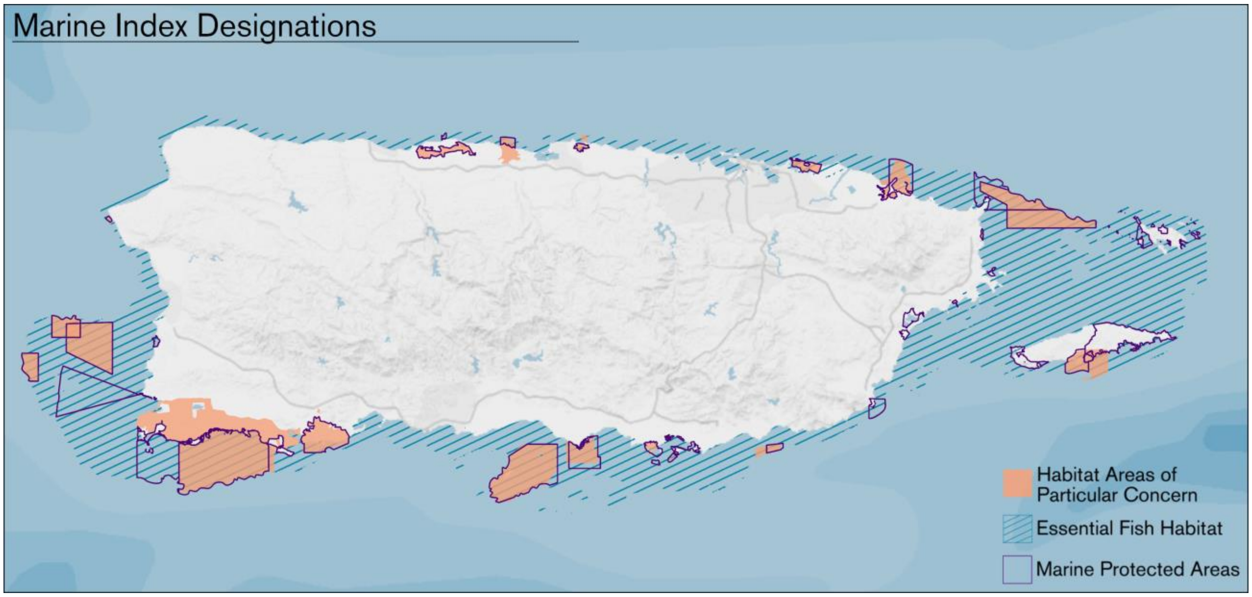
The distribution for the Puerto Rico Terrestrial Index is displayed below. The final rank value for the Index was determined using a quantile distribution and is then combined with the Marine Index to create the Fish and Wildlife Index.

Puerto Rico Terrestrial Index Distribution

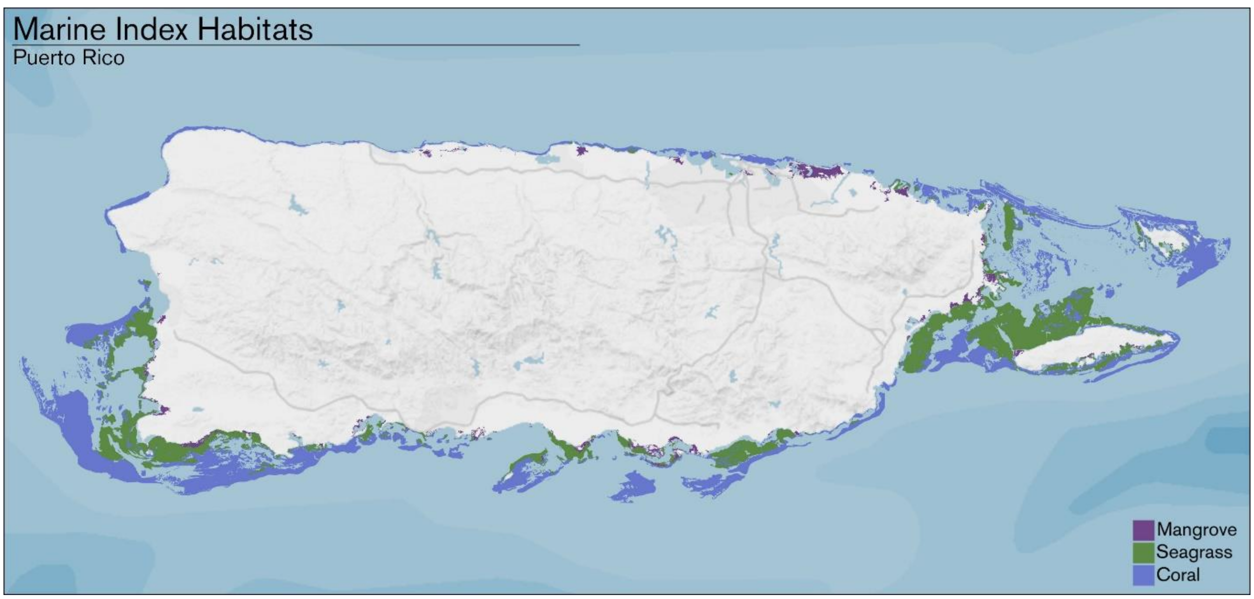
Terrestrial Index Break Values	0	1 - 6	7	8 - 18
Final Rank Value	1	2	3	4

E.2 Calculating the Marine Index

The methodology outlined in the Methodology and Data Report (Dobson et al. 2020) was followed exactly for Puerto Rico. The only deviation was to exclude one Essential Fish Habitat Area, the Caribbean EEZ Gear Restriction area, as it was irrelevant to the goals of this Assessment. Additionally, Essential Fish Habitat for Atlantic Highly Migratory Species (HMS) was included in the Caribbean; higher values were given to larval, juvenile, or neonate life stages for HMS as compared to adult life stages. As there are multiple highly migratory species with EFH in and around Puerto Rico, areas with EFH for multiple species/lifestages received a higher value. See Appendix A.4 for details on datasets used in this analysis and the map below for the distribution of Essential Fish Habitat, Marine Protected Areas, and Habitat Areas of Particular Concern used in the Assessment.



The spatial extent of coral reefs, seagrass bends, and mangroves included in the Puerto Rico Assessment are shown in the map below. Rankings for coral cover and seagrass cover in Puerto Rico are shown in the tables below, using data collected from 2014 to 2016. These distributions differ by region. Note that coral cover was ranked on a 5-class scale to match that of seagrass cover.



Percent Coral Cover in Puerto Rico	Rank Value
0	0
<= 2.19	2
<= 6.25	3
<= 7.82	4
<= 10.04	5

Seagrass Cover in Puerto Rico	Rank Value
0	0
Patchy, 10 - <30%	1
Patchy, 30 - <50%	2
Patchy, 50 - <70%	3
Patchy, 70 - <90%	4
Continuous	5

The distribution for the Marine Index is displayed below. The final rank value was determined using a natural breaks distribution for the Index and was then combined with the Terrestrial Index to create the Fish and Wildlife Index.

Puerto Rico Marine Index Distribution

Marine Index Break Values	0	1 - 4	5 - 7	8 - 18
Final Rank Value	1	2	3	4

E.3 Calculating the Fish and Wildlife Index

Below is the distribution for the Puerto Rico Fish and Wildlife Index. As discussed in the Methodology and Data Report (Dobson et al. 2020), the Terrestrial and Marine Indices are classified into four classes before they are added together to create the Fish and Wildlife Index.

Puerto Rico Fish and Wildlife Index Distribution

Fish & Wildlife Index Break Values	2	3 - 4	5	6	7 - 8	9 - 11
Final Rank Value	1	2	3	4	5	6

Using a quantile distribution, the Fish and Wildlife Index was reclassified to remain consistent between Regional Assessment regions and allow readers to more easily distinguish values.

F. Detailed Methodology: Resilience Hubs

The methodology outlined in the Methodology and Data Report (Dobson et al. 2020) for creating the Resilience Hubs was followed exactly for Puerto Rico.