GUAM COASTAL RESILIENCE ASSESSMENT

2021

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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.

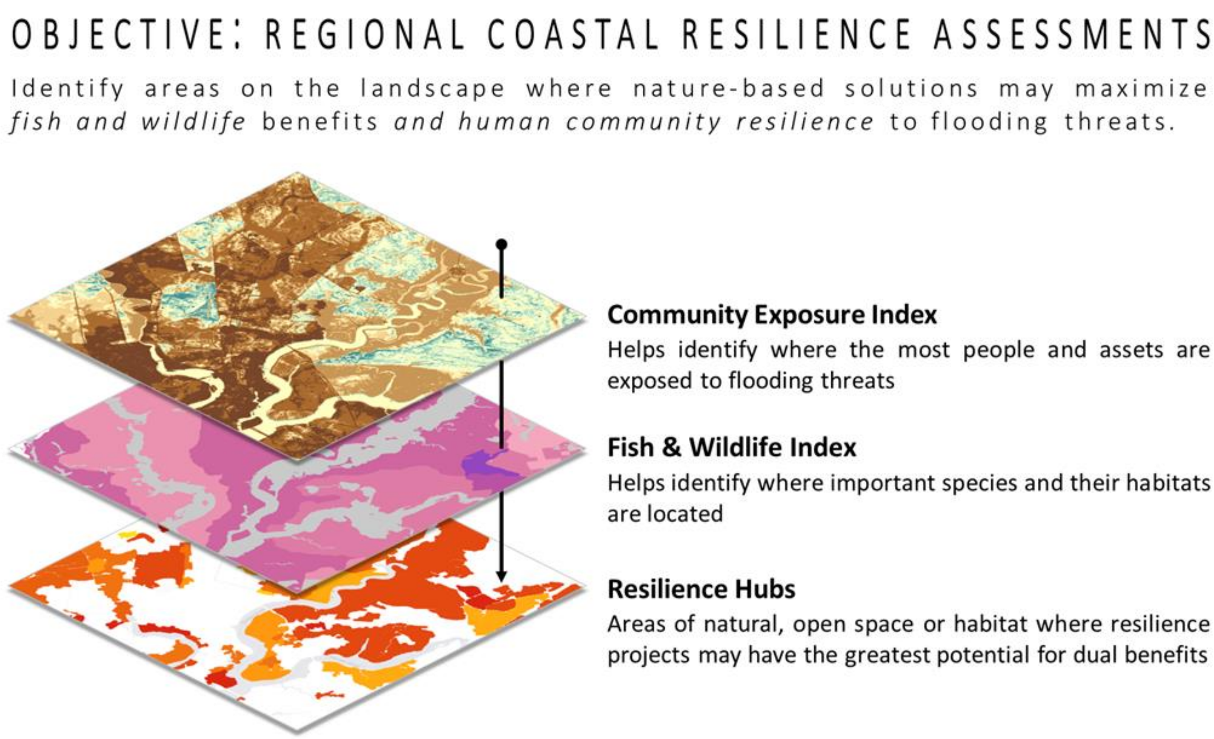
Term	Definition
Adaptive capacity	The ability of a person or system to adjust to a stressor, take advantage of new opportunities, or cope with change.
Ecosystem services	Benefits that humans receive from natural systems.
Exposure	The presence of people, assets, and ecosystems in places where they could 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, geological, 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.
Community Assets	Critical infrastructure and facilities important to the character and function of a community immediately following a major flood event, including locations with dense populations and high social vulnerability.

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. Tropical systems and heavy precipitation events have the potential to devastate both human communities and fish and wildlife habitats. As communities prepare, decision-makers need tools and resources that allow for data-driven decision support to maximize available funding opportunities and other planning needs.

The Guam Coastal Resilience Assessment aims to support effective decision-making 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.

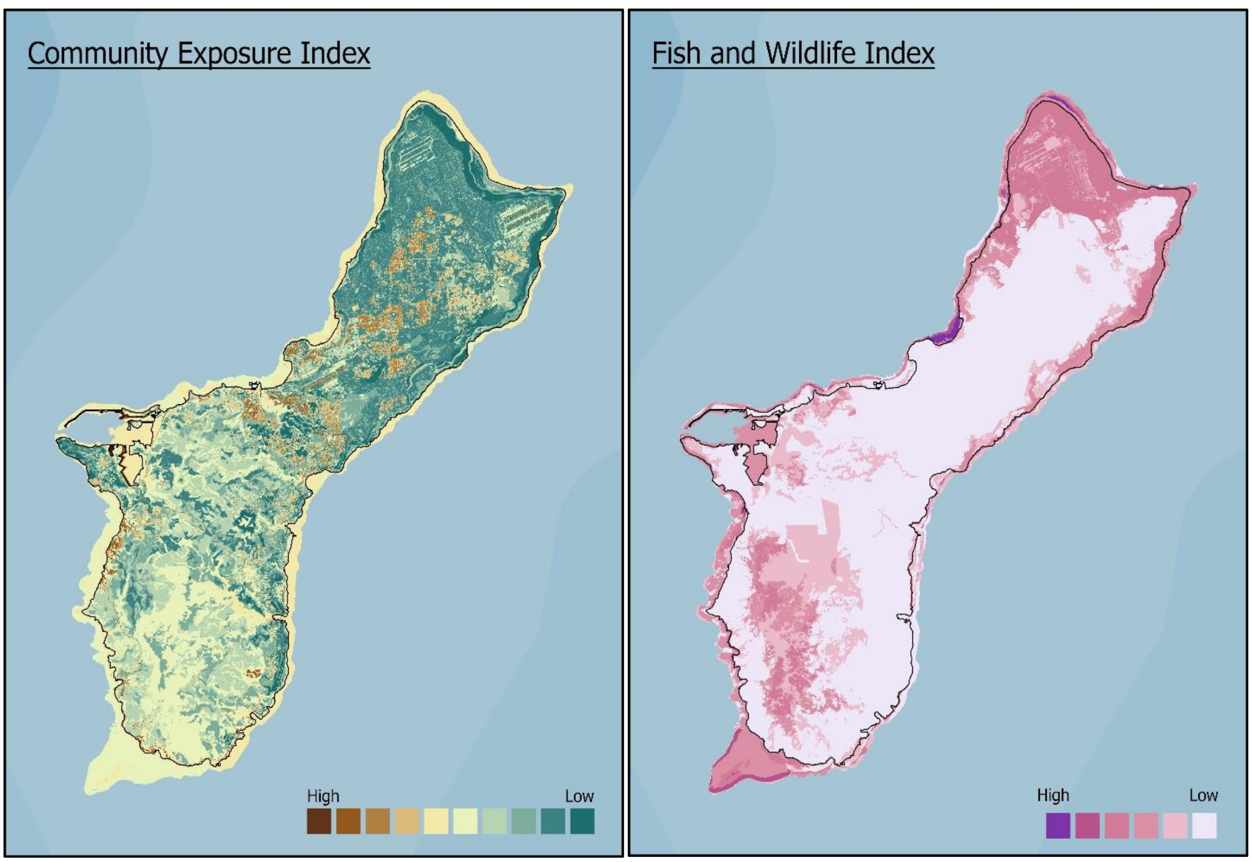
This Geographic Information System (GIS)-based Coastal Resilience Assessment combines spatial data related to land use, protected areas, human community assets, flooding threats, and fish and wildlife resources to identify and prioritize Resilience Hubs (see figure below). Resilience Hubs are large areas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



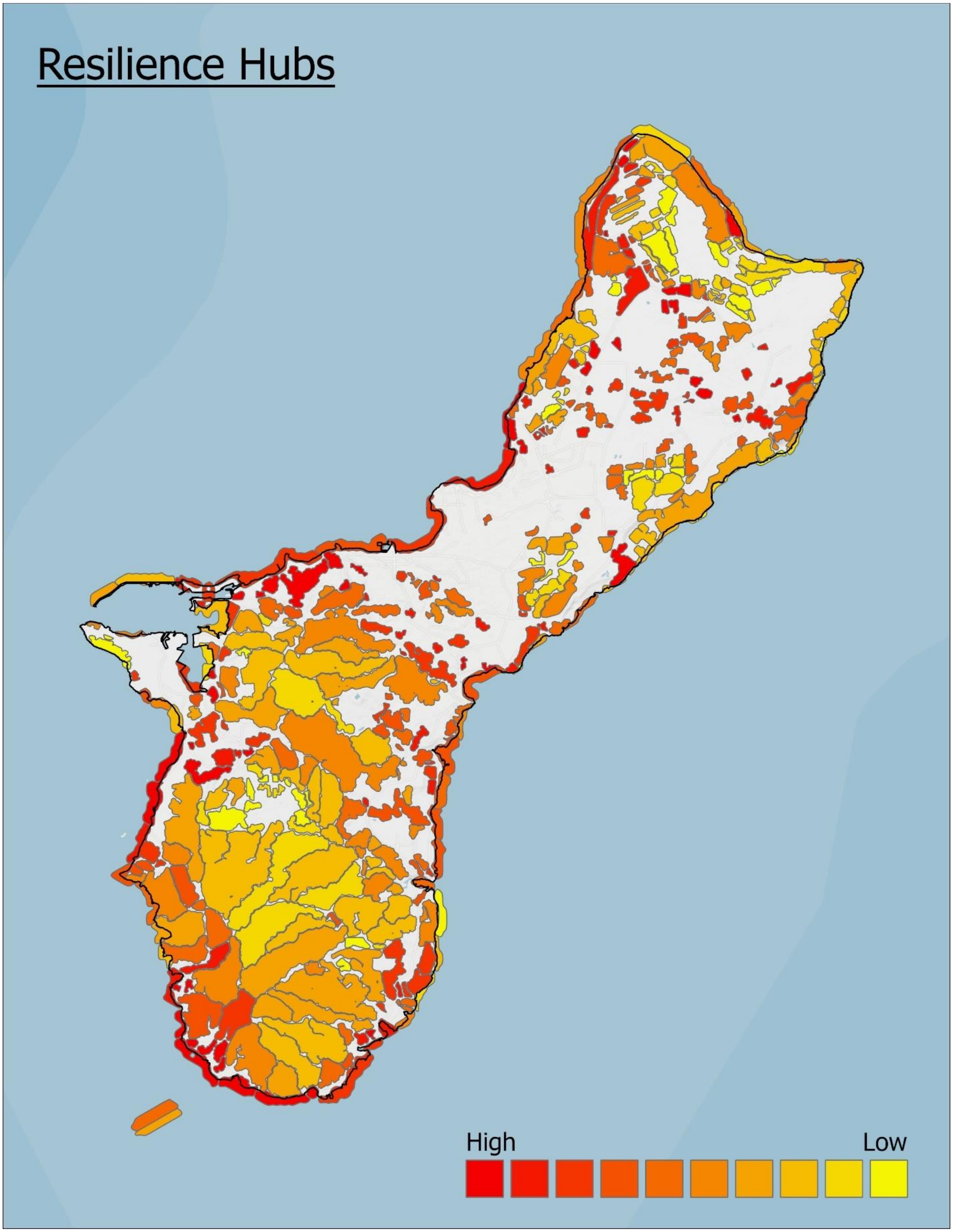
The Assessment identified areas throughout Guam that are not only exposed to a range of coastal-flood related threats, but also contain higher concentrations of community assets. In addition, through the development of habitat extent and suitability models, the analysis identified terrestrial and nearshore marine areas important for species of conservation concern. 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 Guam. The primary mapping products from the Guam Assessment are shown below.

Local community planners, conservation specialists, and others can use the outputs of the Guam Assessment to help make informed decisions about the potential of restoration, conservation, or resilience projects to support fish and wildlife while also helping to build human community resilience to flooding threats. The Assessment is intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

This Guam 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 a case study. 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 the Guam Assessment (available at resilientcoasts.org).



Community Exposure Index (left) and Fish and Wildlife Index (right) for the Guam Coastal Resilience Assessment. Higher values represent areas where higher concentrations of community assets are exposed to flooding threats (left) or areas where numerous species of conservation concern and their habitats are located (right).



Resilience Hubs for the Guam Coastal Resilience Assessment. Higher values represent areas where resilience projects may have the greatest potential to benefit both human communities and wildlife.

INTRODUCTION

1.1 Guam

Located in the tropical western Pacific, Guam is the southernmost island in the Mariana Archipelago and the largest and most populous island in Micronesia. The northern portion of the island is relatively flat, primarily composed of uplifted limestone that can rise to nearly 200 meters above sea level. The karst terrain supports unique limestone forests, sinkholes, and caves that provide important habitat for many of Guam's endemic species, including federally threatened and endangered species such as the Mariana fruit bat (*Pteropus mariannus mariannus*), Guam tree snail (*Partula radiolata*), and eight-spotted butterfly (*Hypolimnas octocula marianensis*)[1]. The southern portion is predominantly old, weathered volcanic material, with rolling hills and steeper terrain that gives rise to nearly 100 rivers and numerous fresh and estuarine wetlands (Guam FAP 2021). The island is surrounded by highly valued coral reefs that are among the most biodiverse in the United States. Guam's nearshore waters support over 5,000 marine species, including numerous threatened and endangered species such as green and hawksbill sea turtles, staghorn corals, whales, sharks, and manta ray[1].

Guam also has a rich cultural history. Known as Guåhan in the native CHamoru language, Guam has been occupied for at least 4,000 years. The long precolonial history is revealed by archaeological resources found throughout Guam. The island has been shaped by a history of colonization, war, and development that has led to the introduction of invasive species and other large-scale disturbances that have caused significant environmental degradation. Today, the island is home to nearly 168,000 people, the majority of whom reside in the island's most populated municipalities of Dededo, Yigo, Tamuning, and Mangilao. There are also several U.S. military bases that together with other federal lands, comprise approximately 30% percent of the island.

With 244 kilometers of coastline, communities throughout Guam are highly exposed to a variety of coastal-flood related threats. Guam's dynamic landscape faces numerous natural hazards ranging from major storms, earthquakes, and tsunamis to floods, drought, wildfire, and extreme heat. Located within Typhoon Alley, Guam is particularly vulnerable to tropical storms and typhoons. In the last ten years alone, Guam has been impacted by Typhoons Hagibis (2019), Wutip (2019), Yutu (2018), Mangkhut (2018), and Dolphin (2015) (FEMA 2021). The most recent severe event was Typhoon Pongsona, which struck the island with maximum winds of 173 miles per hour in 2002. It caused devastating impacts, including contaminating the freshwater system and leaving 65 percent of wells unusable, destroying 1,300 homes, leaving the island without power, and causing over one billion dollars in damages.

Climate change further threatens Guam's communities and ecosystems through coral bleaching, ocean acidification, rising sea levels, and variability in rainfall and water supply, among other impacts. Climate projections indicate that while there may be fewer tropical cyclones in the future, they are expected to increase in intensity (Wang & Zhang 2016). The impacts from severe storm-related flooding will be further exacerbated by rising sea levels (Grecni et al. 2020).

To remain vigilant in preparation for typhoons and other flooding-related threats, residents and government officials have come together to plan and adapt to climate threats, working to better understand the threats, needs, gaps, and nature-based approaches that can be applied to help build

[1] For a list of threatened and endangered species in Guam listed under the U.S. Endangered Species Act, visit the U.S. Fish and Wildlife Service Environmental Conservation Online System (https://ecos.fws.gov/ecp/) and NOAA (https://www.fisheries.noaa.gov/pacific-islands/endangered-species-conservation/marine-protected-species-mariana-islands)

local resilience. Recent efforts include research to better understand climate change impacts (Grecni et al. 2020), the vulnerability of coastal infrastructure to sea level rise (King et al. 2019), and the frequency of flooding in Guam's streams (USACE 2020). Actions taken by the Guam Government have updated setback and development guidelines to minimize the impact of coastal flooding on exposed infrastructure (BSP-GCMP 2020) and worked to identify habitat restoration and conservation priorities (GCRI 2018, DAWR 2019, Guam FAP 2021). Other ongoing efforts will continue to explore local flooding impacts and solutions such as FEMA's RiskMap Discovery project[2] and the U.S. Army Corps of Engineers Post-Disaster Watershed Assessment[3]. The Guam Coastal Resilience Assessment intends to build upon and complement these efforts.

As Guam communities take steps to lower their exposure and plan for a more resilient future, resources such as this 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. The Guam Coastal Resilience Assessment provides a framework for a holistic approach that considers both fish and wildlife habitat and resilience for human communities facing growing flooding threats.

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 projects and programs[4] that improve 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 (UNC) 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 Guam 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, Hawaiʻi, Puerto Rico, the U.S. Virgin Islands, American Samoa, and the Commonwealth of the Northern Mariana Islands. Additional Assessments are underway for Alaska and the U.S. Great Lakes (Figure 1).

[2] https://www.fema.gov/flood-maps/tools-resources/risk-map

[3] https://www.poh.usace.army.mil/Missions/Civil-Works/Project-Review-Plans/

[4] See the National Coastal Resilience Fund: https://www.nfwf.org/programs/national-coastal-resilience-fund.

Figure 1. The geographic extent of the Regional Coastal Resilience Assessments in dark gray and the Guam Assessment in orange. All Regional Assessments will be completed by 2022. 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 GIS-based approach to model landscape characteristics and their potential impacts 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 to identify and rank Resilience Hubs. Resilience Hubs are large areas of natural, open space or habitat where, if investments are made in habitat conservation or restoration, there is potential to benefit fish and wildlife species while also helping to build human community resilience to flooding threats.

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 the Regional 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 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.

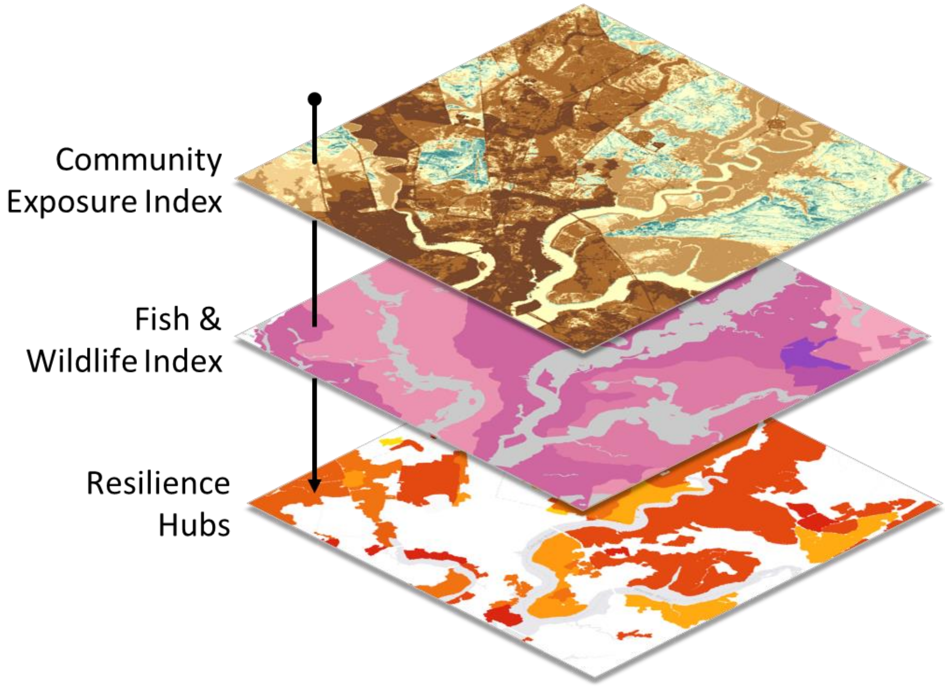


Figure 2. A conceptual model showing the separate, but interrelated components of the Regional Coastal Resilience Assessments.

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. The Assessment is intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

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 Guam Coastal Resilience 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. Given the geographic scale of Guam, all GIS modeling was completed at a three-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 Guam.

2.2 Study Area

The Guam Assessment includes the main island, in addition to Cabras Island and Cocos Island. Guam is the largest and southernmost island in the Marianas Archipelago. The island features a wide range of ecosystems, including limestone and ravine forests, grasslands, wetlands, and extensive coral reefs. With a total land area of 540 square kilometers (209 square miles), the island is densely populated with approximately 168,000 residents.

The Assessment covers the entire island, extending into the ocean to the 30-meter depth contour (Figure 3)[5]. The Assessment is unique in that it not only considers the immediate coastline, but it also focuses on inland areas that can often directly contribute to coastal flood-related issues. For instance, intense rainfall and riverine flooding that drains directly to the coast can exacerbate coastal flooding events. In all regions, the boundary of the Assessments follows the coastal watersheds designated by the U.S. Environmental Protection Agency (EPA), which are watersheds that drain directly to the ocean and are represented at a hydrologic unit code eight scale (HUC-8)[6]. For Guam, the HUC-8 watersheds, and thus the study area, covers the entire island (Figure 3).

[5] A 30-meter depth contour was used for the Fish and Wildlife Index to allow for the inclusion of marine habitats with potential to host significant biodiversity. In contrast, 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.

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

Figure 3. The Guam Coastal Resilience Assessment study area. The 30-meter depth contour 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 sea level rise data from NOAA and floodplain data from the Federal Emergency Management Agency (FEMA). In addition to reviewing publicly available data sources, the Guam 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 10 members representing NOAA's Office for Coastal Management, NOAA Fisheries, the Guam Coastal Management Program, Guam Division of Aquatic and Wildlife Resources, Guam Department of Land Management, Guam Department of Homeland Security, Guam Waterworks Authority, the University of Guam, and the U.S. Fish and Wildlife Service. 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 Guam 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 virtual workshop to allow local stakeholders to review and provide input on preliminary Assessment products. The Virtual Stakeholder Workshop was held over the week of March 15, 2021. The Project Team hosted three sessions to introduce the assessment and discuss preliminary results. All participants had access to written materials and an online GIS viewer to facilitate the review of draft models and provide comments during and after the workshop. The comment period remained open for several weeks following the virtual workshop.

Across the three sessions, 18 people attended the workshop, representing state, federal, municipal, non-government, and academic organizations. For a complete list of all organizations invited to the workshop, see Appendix G. Workshop participants helped 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 Guam.

Participants reviewed draft maps and data sources, providing important feedback and recommendations to improve the analyses. In addition, participants considered measures that local communities can take to enhance resilience, including management strategies, activities, and projects that restore habitats and install natural and nature-based features that reduce flood-related threats.

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 data to incorporate into revised products. NEMAC then followed up individually with Committee members and other key stakeholders to further discuss data and methods as needed. Results of the Guam 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 Guam Assessment. A complete list of datasets included can be found in Appendix A. See Appendix D for a description of the methodology used to calculate the Community Exposure Index.

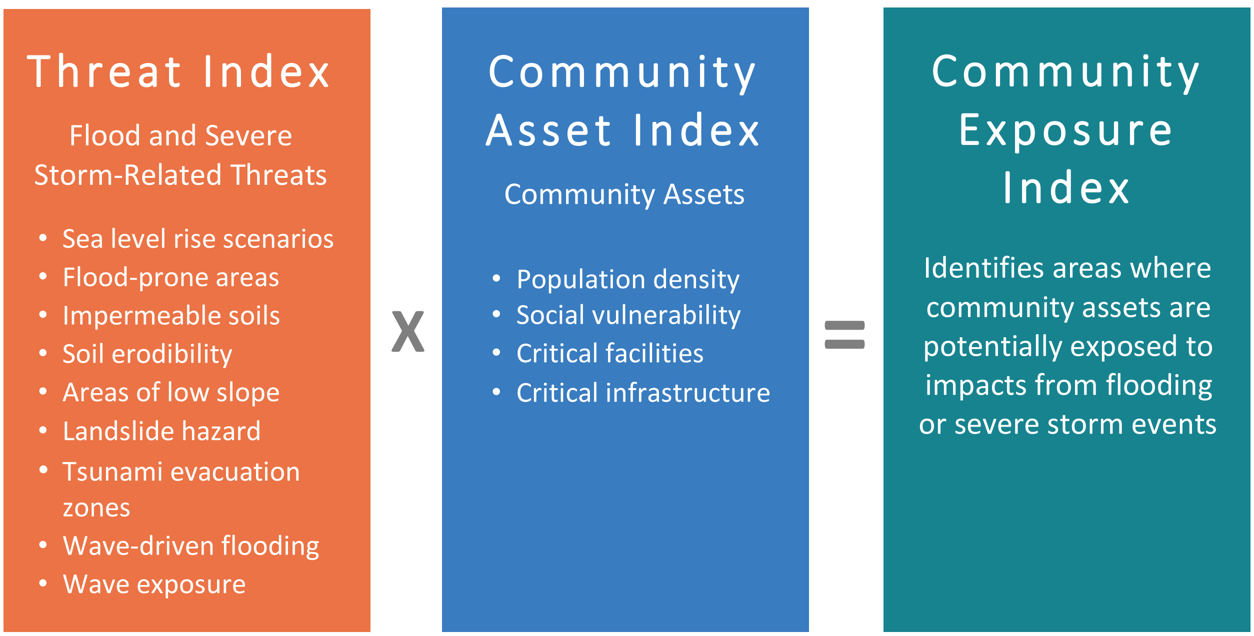


Figure 4. Elements of the Threat and Community Asset Indices used to create the Community Exposure Index.

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 Guam 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 Guam analysis included data related to sea level rise, flood-prone areas, soil erodibility, impermeable soils, areas of low slope, landslide susceptibility, and tsunami evacuation areas, each of which are described in detail in the Methodology and Data Report (Dobson et al. 2020). Storm surge, which is typically a Threat Index input used in other Regional Assessments, was unavailable for Guam at the time of modeling. An additional input—wave-driven flooding—was included to serve as a proxy for storm surge (see Appendix B.1 for details). For this input, the analysis utilized data from Storlazzi et al. (2019). These models used significant wave heights associated with the 10-, 50-, 100-, and 500-year storm return periods and inundation was modeled based on the presence or absence of coral reefs. For the purposes of this analysis, inundation models in the presence of coral reefs were used. Specific to Guam, wave energy exposure was also included in the Threat Index. Additional details on those data used to create the Threat Index for Guam can be found in Appendix A.1 and Appendix B.

2.4.2 Community Asset Index

The Community Asset Index includes data related to 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 Guam, 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). Unlike previous assessments, where critical infrastructure locations received a lower rank than critical facilities, in Guam these two categories of community assets were counted with equal weight. Based on feedback from the stakeholder workshop and Advisory Committee, critical infrastructure was given an equal rank to critical facilities since all assets are important in response to storm and flood events on remote islands. This approach is consistent with other existing methodologies to identify community assets that support recovery during an emergency, such as the FEMA Community Lifelines framework[7]. It was of utmost importance to include locally available data whenever possible. Therefore, based on feedback from the stakeholder workshop and Advisory Committee, some local datasets from the Digital Atlas of Guam and Guam Environmental Protection Agency were incorporated. In addition, the analysis included cultural and historic sites within the study area. Although these sites may not directly assist in responding to flood events, their importance to local communities, as well as any economic value they may hold, were considered justification for including them as a type of critical infrastructure. The following types of critical infrastructure were included in the Guam Assessment:

- Primary roads
- Airports
- Ports
- Power plants and substations
- Petroleum terminals and refineries
- Hazardous sites
- Wastewater treatment facilities
- Dams
- Cultural and historic resources

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 Guam Assessment can be found in Appendix A.2. See Appendix C for a description of methods used to create the Community Asset Index.

[7] FEMA Community Lifeline: https://www.fema.gov/emergency-managers/practitioners/lifelines

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 habitats 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 of conservation concern and their habitats are located. For the Guam Assessment, only those species of concern with federal- or territory-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 is available in the Methodology and Data Report (Dobson et al. 2020). Regional considerations for Guam 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.

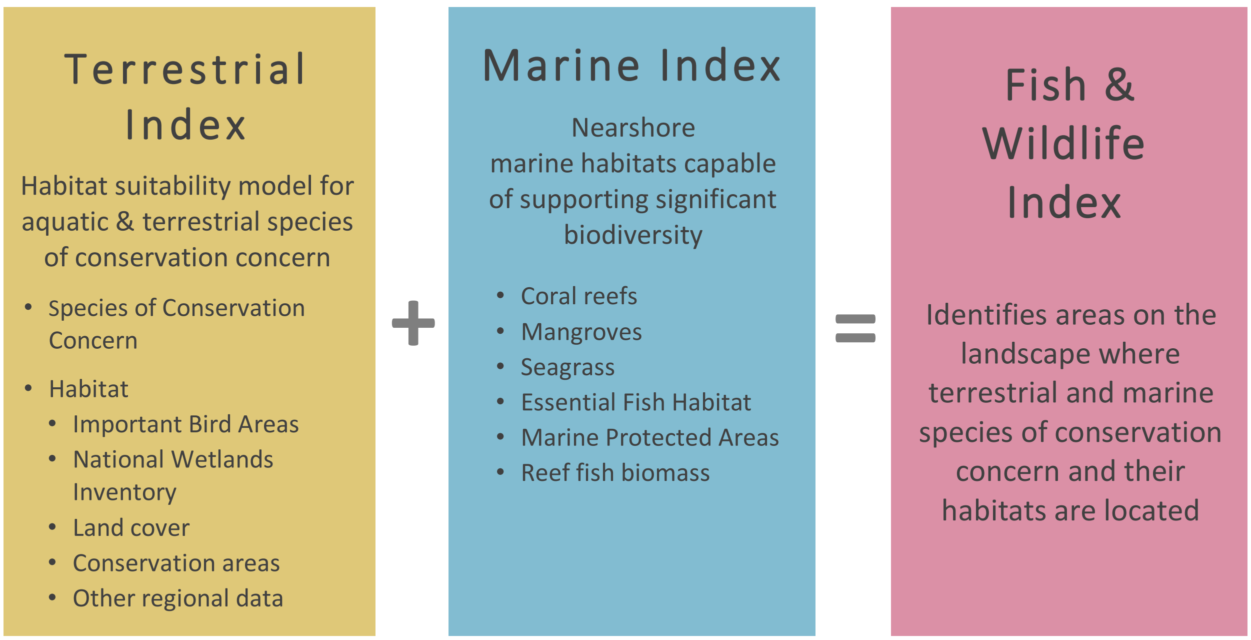


Figure 5. Elements of the Terrestrial and Marine Indices used to create the Fish and Wildlife Index.

2.5.1 Terrestrial Index

The Terrestrial Index aims to identify suitable habitats for major species 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 Guam Wildlife Action Plan (DAWR 2019) and species listed as threatened or endangered under the U.S. Endangered Species Act. The assessment includes habitat preferences for some species that are locally extirpated and only exist in captivity since habitat restoration and conservation activities may support species reintroductions in the future. Broad taxonomic and species groupings were used to model habitat preferences throughout the region, including:

- Birds
- Terrestrial mammals
- Reptiles
- Fishes

Based on habitat preferences associated with each species 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 and species group) included in the Guam Assessment is available in Appendix E.1.

In addition to using the NOAA Coastal Change Analysis Program land cover data, U.S. Fish and Wildlife Service's National Wetlands Inventory, and USGS National Hydrography Dataset to identify habitat types, the analysis utilized 2014 vegetation maps from the U.S. Forest Service (methods described in Liu & Fischer 2006). BirdLife International Important Bird Areas (IBAs) were also included, as well as other areas prioritized by local agencies for protection or management such as Overlay Refuge Areas and priority areas and potential recovery habitat for the Guam Micronesian kingfisher. A complete list of datasets and methods used to create the Guam 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 can support significant biodiversity, such as coral reefs, mangroves, and seagrass beds. While other marine habitat types may support significant biodiversity, the Guam Assessment focused on those habitat types where restoration and resilience projects may offer the multiple benefits of species richness, ecosystem enhancement, and coastal protection.

Benthic habitat maps, extending to a 30-meter depth bathymetry boundary around the island, were used to define the spatial extent of seagrass habitat. Mangrove extent was defined using C-CAP land cover and field survey data. The spatial extent of coral reef habitat was estimated from live coral cover records using NOAA's National Coral Reef Monitoring Program, which regularly implements stratified random sample surveys throughout the islands. Based on surveys from 2017, areas with higher coral cover—and thus more likely to support higher numbers of reef associated species (Komyakova et al. 2013)—were ranked higher. Due to ecosystem changes since the benthic habitats were mapped in 2007, it was recommended that the survey data be used at the sector-level broken into three depth categories, known as the strata-level, using bathymetry (Tom Oliver, NOAA, personal communication). The coral cover data were pooled for each strata and then ranked across the islands. The three depth levels are as follows: shallow (0-6 meters), mid-depth (>6-18 meters), and deep (>18-30 meters).

In addition to the spatial extent and condition of these habitat types, the Marine Index calls upon a number of additional datasets including Essential Fish Habitat, Marine Protected Areas, and reef fish biomass data from NOAA. A complete list of datasets and methods used to create the Guam 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 to create two outputs: Green Habitat Cores (inland) and Blue Habitat Cores (marine)(Figure 6).

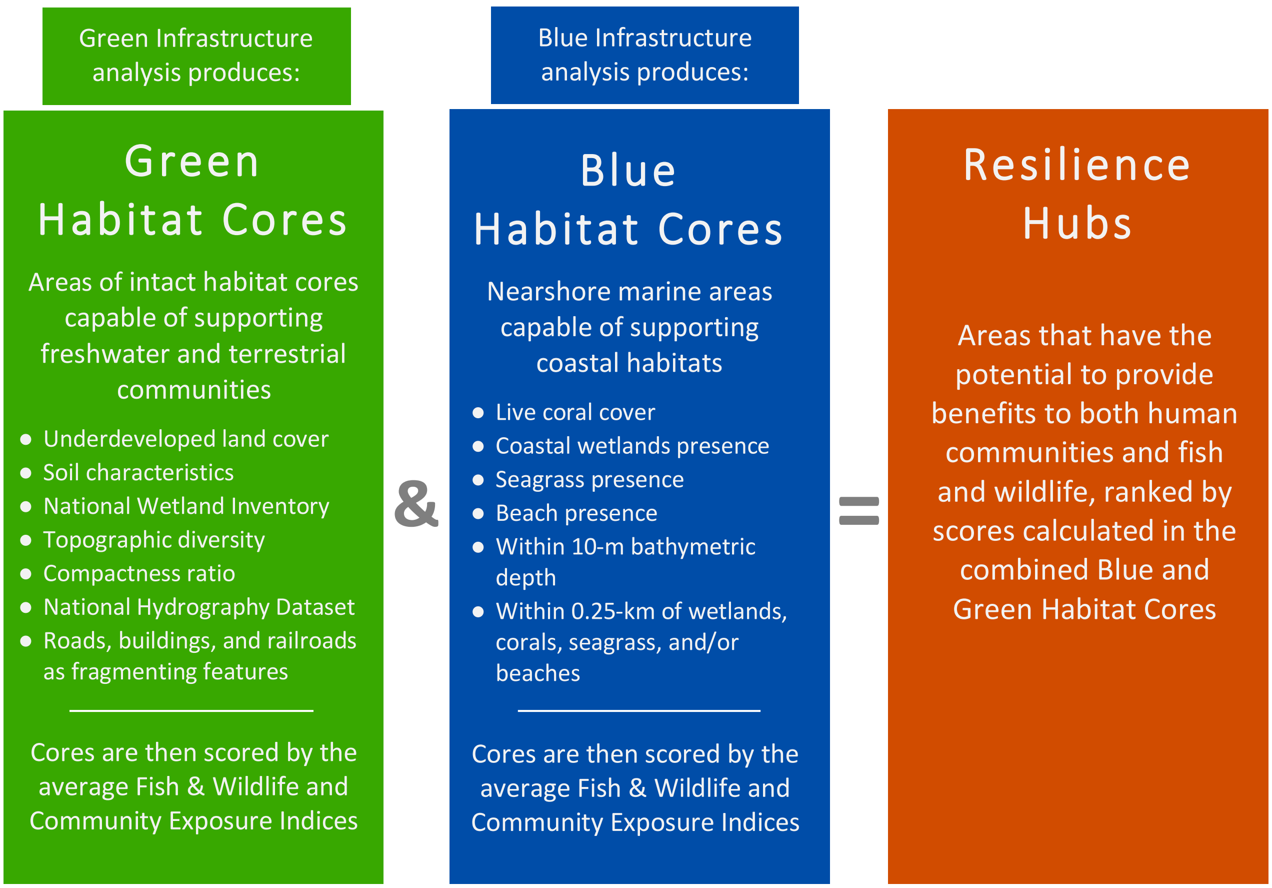


Figure 6. Elements of the Green and Blue Habitat Core outputs used to create the Resilience Hubs.

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 Appendix F and 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 to facilitate local decision-making commensurate with the size of potential nature-based projects and solutions.

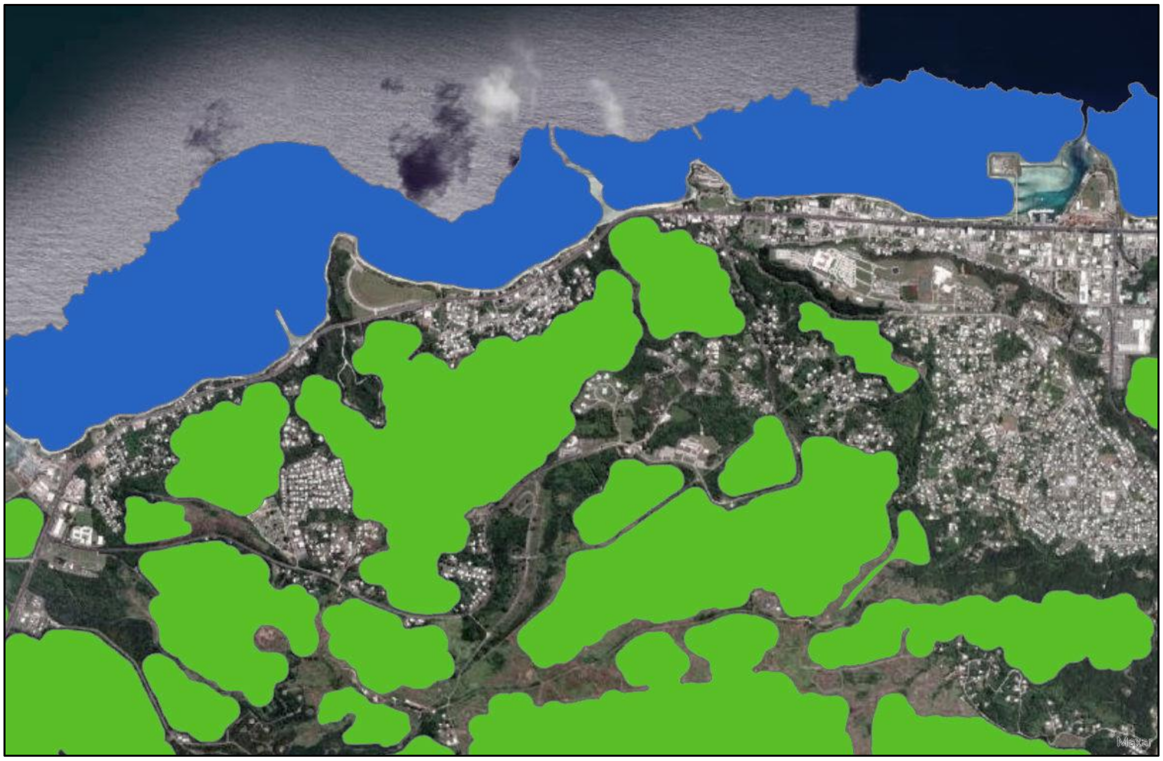


Figure 7. An initial step in creating the Green and Blue Habitat Cores. Note the Green Habitat Cores include both terrestrial and freshwater aquatic areas. The Blue Habitat data include coral cover, beaches, coastal wetlands, seagrass beds, and nearshore marine areas less than 10 meters in depth but have not yet been grouped into Cores.

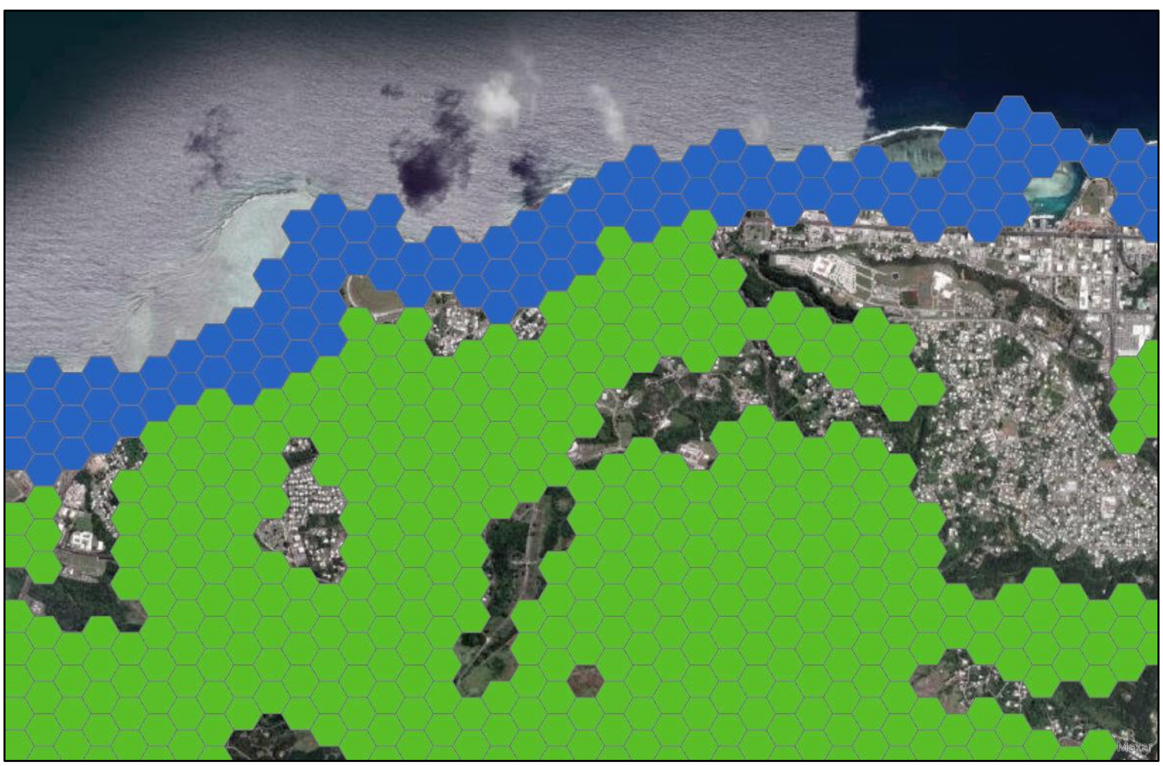


Figure 8. Green and Blue Habitat Cores converted to 4-hectare (10-acre) hexagons. As with each Habitat Core, each hexagon is later ranked to show variation within Resilience Hubs.

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

2.6.1 Green Infrastructure

The Green Infrastructure[8] 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 Guam, NEMAC replicated the analysis to create this important layer for the Guam Assessment. The analysis identifies “intact habitat cores,” or every natural area 4 hectares (10 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 considers fragmenting features that may disrupt the movement of wildlife species.

Applying these methods to Guam, the Green Infrastructure analysis resulted in the creation of Green Habitat Cores, or inland habitat cores encompassing both terrestrial and freshwater 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 Appendix F and Dobson et al. (2020).

In addition to scoring the Green Habitat Cores with the Community Exposure and Fish and Wildlife Indices, consideration was given to cores that are nearest to the community assets identified within the

[8] 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.

Community Asset Index. This ensures that priority Green Habitat Cores are identified based on their potential to benefit the largest number of community assets that are nearest to each core.

In summary, the Green Infrastructure approach—in determining both Green Habitat Cores and their subsequent hexagons—identifies contiguous natural landscapes composed of similar landscape characteristics that are nearest to community assets. 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 Guam, the Assessment developed a Blue Infrastructure[9] analysis. Marine and coastal habitats, such as coral reefs, mangroves, seagrass beds, and beaches not only support significant biodiversity but are also important natural features that can protect human communities and infrastructure from flooding-related threats. 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 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 the Guam bathymetric basins 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 fish and 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.

[9] 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 Guam 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 as stormwater management, urban flooding, and heat islands while benefiting biodiversity and human well-being. Implementing nature-based solutions, such as wetland or coral reef restoration, can provide tremendous co-benefits to people and wildlife as described in the case study outlined below (see Section 4).

3.1 Community Exposure Index

The Community Exposure Index shows that numerous communities throughout Guam are exposed to flooding threats. Areas with the highest exposure values, indicated by the darkest browns (Figure 10), are associated with areas of dense population and/or those areas with low-lying coastal infrastructure. This is particularly evident in the densely populated villages of Hagåtña and Tamuning and around Apra Harbor, which features a major port, wastewater treatment facilities, petroleum terminals, and other forms of critical infrastructure. Throughout the southern portion of the island, higher exposure values are seen along the low-elevation coastlines, where many of Guam's communities and major roads are subject to numerous flooding threats. In contrast, karst terrain with very well-drained soils dominates the northern plateau of Guam, where uplifted limestone cliffs minimize the impact of coastal flooding threats. However, there are still some areas of high exposure in northern Guam, largely concentrated around the inland areas of the Dededo and Yigo municipalities where significant development contributes to poorly drained, impermeable surfaces with low slope.

The Threat Index reveals that flood-related threats affect nearly all coastlines throughout Guam. The highest Threat values on the island are seen in coastal lagoons and low-lying areas on the western side of the island, such as Sasa Bay and Tumon Bay (Figure 11). These areas are prone to flooding, vulnerable to sea level rise, lie inside the tsunami evacuation zone, and have high concentrations of impermeable soils and impervious surfaces. In combination, the flood-related hazards create very high Threat Index values. Other portions of the coastline showing high threat values include the island's eastern margin, which is highly exposed to wave energy. In the island's interior, moderately high threat values appear throughout the south where soils show high erodibility and landslide risk is high. The Ugam, Ylig, and Pago Rivers on the southeastern coast also contribute to visibly high threat values that extend far inland due to a combination of low elevation, soil characteristics, and tsunami inundation risk.

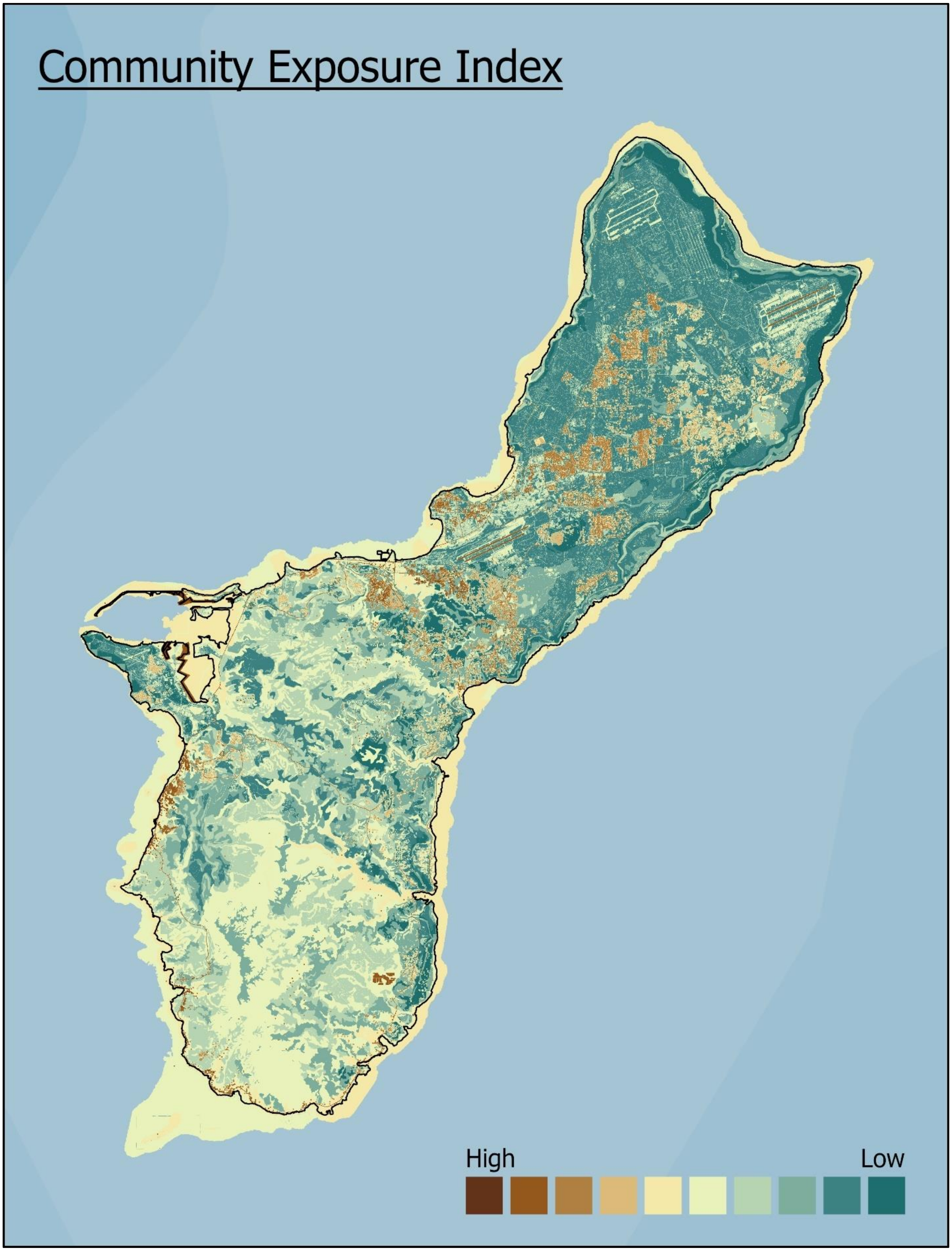


Figure 10. Community Exposure Index for Guam. The Threat and Community Asset Indices are multiplied to produce the Community Exposure Index, which shows areas where assets overlap flood threats. For detail, view results in CREST.

While flooding threats are evident throughout the island, the Community Asset Index reveals that important community assets on Guam are concentrated mainly in populated and developed areas (Figure 11); however, important community assets can be seen throughout the island, including roads, dams, communication infrastructure, ports, and airports, all of which are critical for effective emergency response in the event of major flooding. The highest concentrations of community assets are found within the island's more densely populated village of Dededo. Around the island's capital of Hagåtña, major roads, socially vulnerable communities, and the Antonio B. Won Pat International Airport are evident. On the southern portion of the island, assets are largely restricted to the immediate coastline where important roads connect the population centers of Humåtak (formerly Umatac), Malesso (formerly Merizo), and Inalåhan (formerly Inarajan). On the northern portion of the island, the Anderson Air Force Base and Guam National Wildlife Refuge contain relatively few critical assets as defined by this assessment.

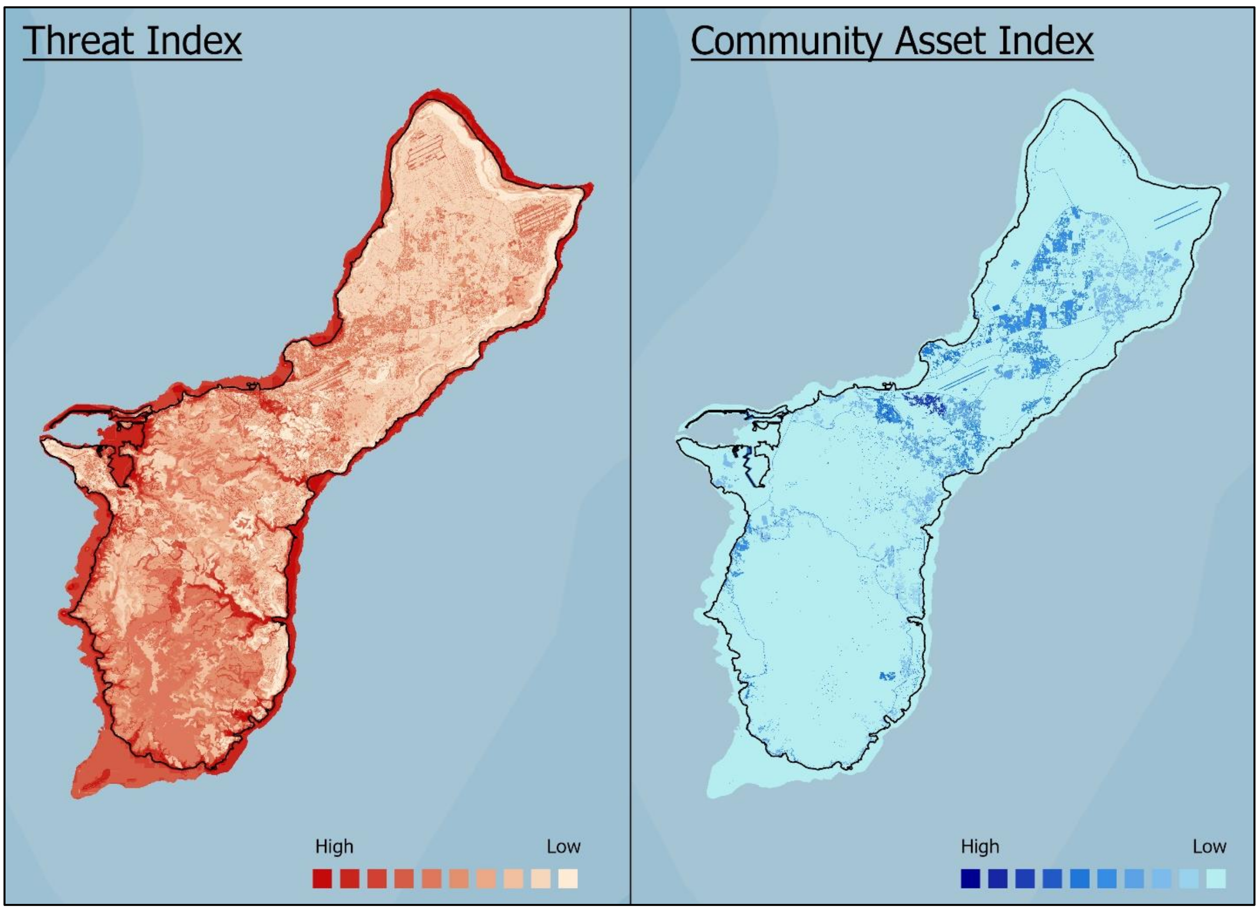


Figure 11. Threat Index (left) and Community Asset Index (right) for Guam. For detail, view results in CREST.

While the whole-island results are helpful to identify areas with high exposure values, the fine resolution of the Guam Assessment allows results to be viewed at a community scale to inform more localized decision making. For instance, the densely populated municipalities of Hagåtña, Mongmong-Toto-Maite, Tamuning, and Barrigada all featured high Community Exposure values (Figure 12). The Assessment results reveal very high Threat Index scores along the Hagåtña River and Agana Swamp. This area features flood-prone and low-lying areas in addition to impermeable soils capable of retaining water. The presence of impervious surfaces in the communities surrounding Agana Swamp further contributes to the high Threat Index values. However, despite high Threat Index scores, since the wetland area does not contain many community assets, this area does not have a very high Community Exposure Index value. Instead, the villages surrounding Agana Swamp show areas of high exposure due to the confluence of dense community assets influenced by population density and social vulnerability and moderate to high flood threats driven by sea level rise, low lying areas, and the prevalence of impervious surfaces. 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 below.

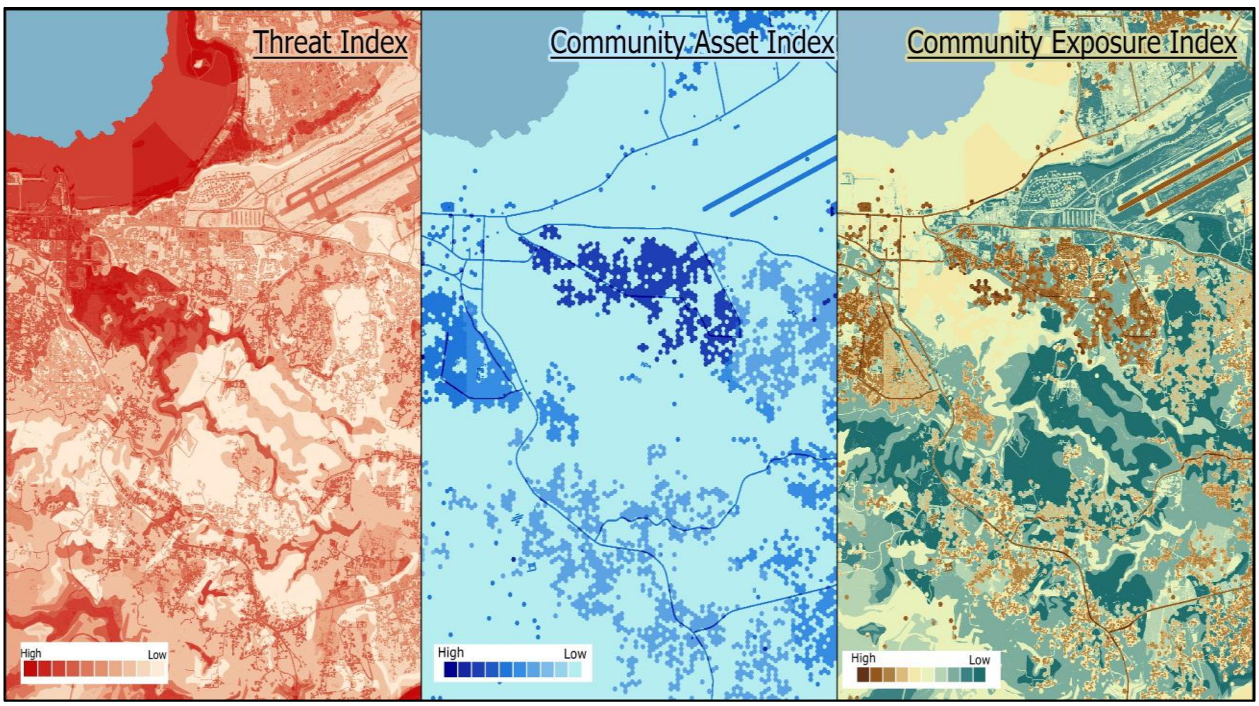


Figure 12. The community of Mongmong-Toto-Maite on the western coast of Guam shows higher values of exposure, resulting from the combination of flood threats and community assets.

3.2 Fish and Wildlife Index

The combined Fish and Wildlife Index shows the highest values along coral reefs, in the relatively intact limestone forests in the north and along the Mount Lamlam-Alifan ridge, and wetlands and remnant ravine forests to the south (Figure 13). Due to the additive nature of the Fish and Wildlife Index, the highest values are all observed in coastal waters where healthy marine habitats coincide with coastal habitats utilized by species captured in the Terrestrial Index, such as sea birds and sea turtles. In some instances, high values are driven by overlapping features, such as areas that are designated for protection or conservation. Guam Conservation Areas and Marine Preserves under local and federal management serve as priority areas for restoration efforts to assist in the recovery of many of Guam's species of greatest conservation concern (DAWR 2019). Tumon Bay Marine Reserve, Ritidian Point within the Guam National Wildlife Refuge, Bolanos Conservation Area, and the U.S. Air Force Overlay Refuge, among other conservation areas, are all evident in the Fish and Wildlife Index. While much of Guam's native species are threatened by invasive species, development, and climate change, there are ample opportunities to implement habitat conservation and restoration projects throughout Guam.

As noted in the Methods section, the Terrestrial Index evaluated habitat suitability across four broad species groups. Many of the species included in the Guam Wildlife Action Plan (DAWR 2019) rely on habitat types that are heavily impacted by invasive plant and animal species that hinder native species recovery. While many species of conservation concern included in the Wildlife Action Plan are locally extirpated, they are included in the Terrestrial Index to highlight areas that if restored, could serve as important habitat to help reestablish native populations (Figure 14). For instance, the Guam National Wildlife Refuge units are managed for the conservation of threatened and endangered species, including priority recovery habitat for the Guam Micronesian kingfisher (*Todiramphus cinnamominus*), Mariana crow (*Corvus kubaryi*), Mariana fruit bat (*Pteropus mariannus mariannus*), Mariana eight-spot butterfly (*Hypolimnas octocula marianensis*), and other species. In southern Guam, the Terrestrial Index identifies high values in the freshwater wetlands around Sasa Bay, Fena Lake, Masso Reservoir, Namo River, and Atantano Bay, which serve as important habitat for the Mariana common moorhen (*Gallinula chloropus guami*) and other wetland species. For a complete list of species referenced for this analysis, see Appendix E.1.

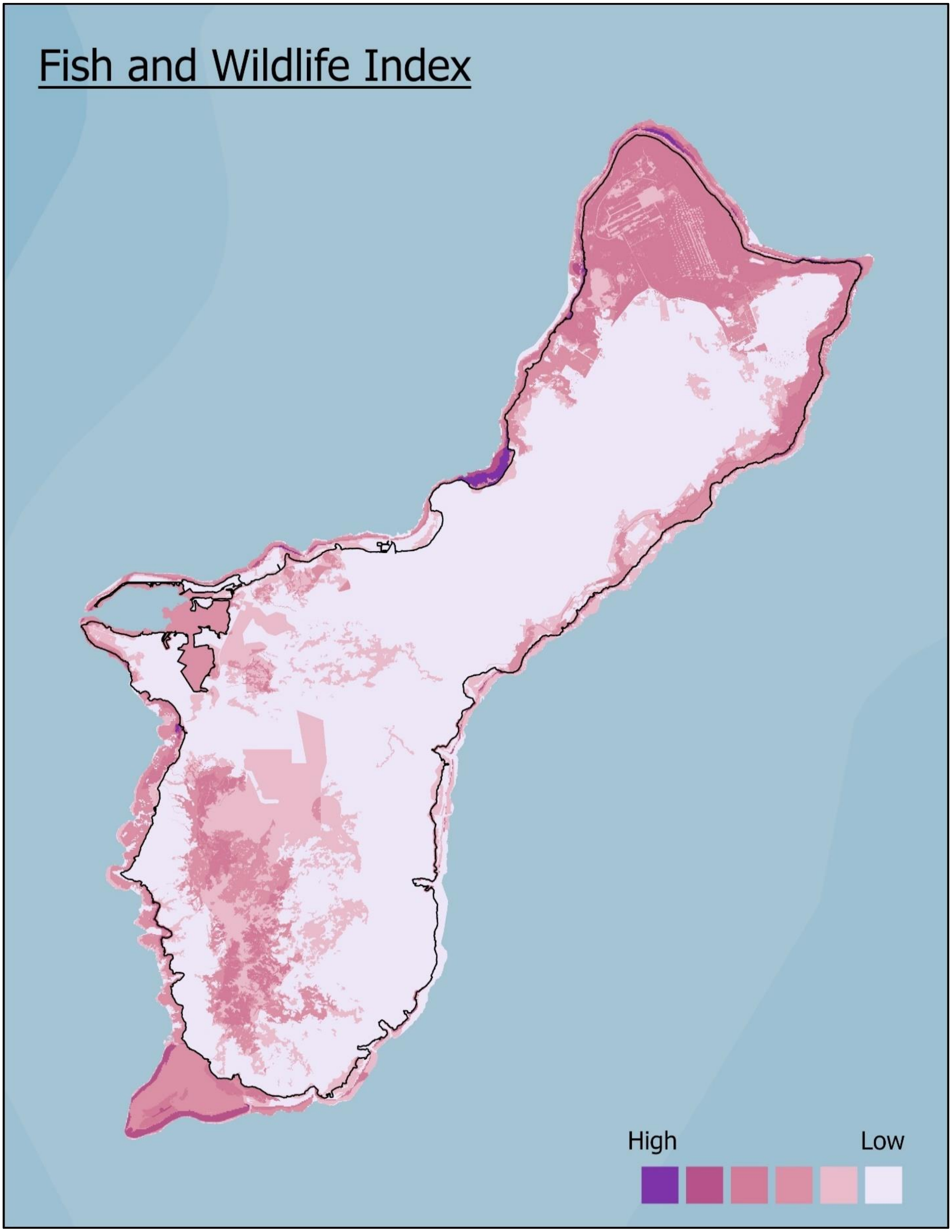


Figure 13. Fish and Wildlife Index for Guam. Terrestrial and Marine Indices are added to produce the Fish and Wildlife Index, which shows concentrations of fish and wildlife species of conservation concern and their habitats. For detail, view results in CREST.

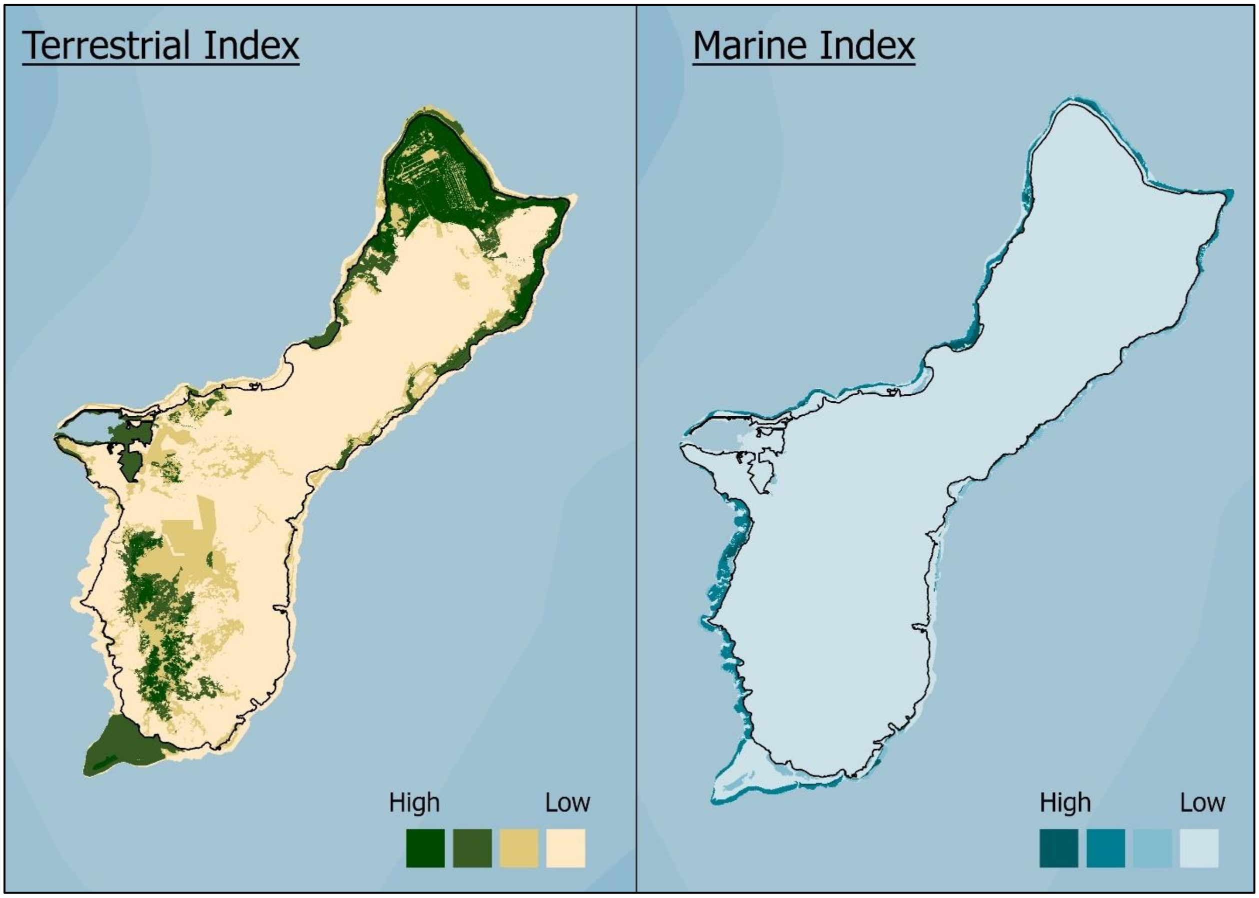


Figure 14. Terrestrial Index (left) and Marine Index (right) for Guam. For detail, view results in CREST.

The Marine Index reveals very high values around much of the island, largely driven by the prevalence of coral reef ecosystems (Figure 14). While mangroves and seagrass beds are present throughout the island, they are not widely distributed, leaving live coral cover, reef fish biomass, Essential Fish Habitat (EFH), and the presence of Marine Preserves to predominantly influence the Marine Index values. Despite successive widespread bleaching events (Raymundo et al. 2019), many coral reefs surrounding Guam have relatively high coral cover and are prominent in the Marine Index, particularly along the western coastline and the margins of Cocos Lagoon. As expected, areas with high live coral cover also feature high reef fish biomass, further contributing to high values observed in these areas. Reef fish biomass was particularly high inside Tumon Bay Marine Reserve, a protected area managed by the Guam Department of Agriculture that is important for humphead wrasse (*Cheilinus undulatus*) and other species of conservation concern. While not as prevalent, relatively large mangrove stands near Apra Harbor, Malesso, and Inalåhan also received higher values in the Marine Index since they provide important nursery habitat for numerous reef fish identified in the Guam Wildlife Action Plan including snappers (*Lutjanidae*), groupers (*Serranidae*), and jacks (*Carangidae*). Similarly, seagrass beds and staghorn coral thickets in the reef flats around Apra and Cocos Lagoons also provide important habitat for juvenile reef fishes. Together, these features all highlight the significant marine biodiversity found in Guam.

Some of the highest Marine, Terrestrial, and combined Fish and Wildlife values identified are found in and around the Cocos Lagoon on the southern tip of Guam. By examining the lagoon, Cocos Island, and Malasso more closely (Figure 15), several factors contribute to the high values observed in this area. In the lagoon itself, high coral cover and moderately high reef fish biomass are visible along the reef crest surrounding the shallow reef flat. Dense seagrass beds provide important foraging habitat for green sea turtles and the Achang Reef Flat Marine Preserve and NOAA Manell-Geus Habitat Focus Area[10] highlight the importance of this region for conservation and restoration efforts. Cocos Island supports several species no longer found on the main island, including the Micronesian starling (*Aplonsis opaca guami*) and several skink species. Also designated as an Important Bird Area, the beaches and strand forest of Cocos Island provide high-quality habitat that is represented by high scores in the Terrestrial Index. On the main island, mangroves line the coast around Malesso revealing high Marine Index values. Further inland, high Terrestrial Index values are evident around the Bolanos Conservation Area, an area which provides recovery habitat for the Guam Mironesian kingfisher and secondary habitat for many of Guam's terrestrial species. In combination, the numerous diverse habitat types highlight the importance of this area for Guam's species of conservation concern. 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](#) below.

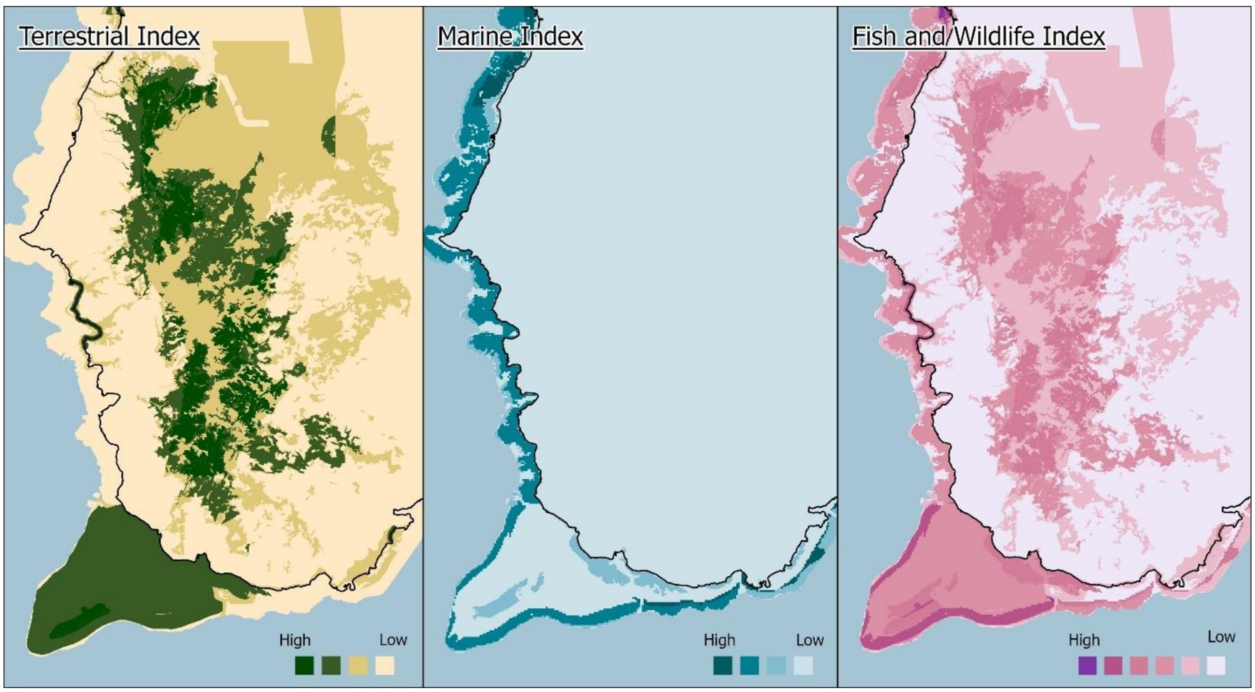


Figure 15. The southern coast of Guam, including Cocos Lagoon and Cocos Island, shows higher values in both the Terrestrial and Marine indices, resulting in medium to high values in the Fish and Wildlife Index. For detail, view results in CREST.

[10] For details about the NOAA's Habitat Blueprint and Manell-Geus Habitat Focus Area, see: https://www.habitatblueprint.noaa.gov/habitat-focus-areas/manell-geus-guam/.

3.3 Resilience Hub Analysis

The Guam Assessment identified many Resilience Hubs across the island. While the southern half of the island features numerous large Resilience Hubs, the highest-ranking Hubs are distributed throughout Guam revealing ample opportunities to implement nature-based solutions that help build human community resilience while also benefiting fish and wildlife habitat and the species and ecosystem services they support.

The final Resilience Hub rankings are the product of the Community Exposure and Fish and Wildlife Indices. As described in the Methods section above, the boundaries of the Resilience Hubs are formed through the Green and Blue Infrastructure analyses, which identify Green and Blue Habitat Cores at least 4 hectares (10 acres) in size. The habitat cores represent areas of contiguous open space that are of a sufficient size to implement a nature-based solution with maximum potential to provide fish and wildlife and flood risk reduction benefits. Once the boundaries of the Blue and Green Habitat Cores are determined, they are ranked based on the product of the Community Exposure and Fish and Wildlife Index values (Figures 16). Using zonal statistics, a single average rank is then applied to each habitat core to create the combined Resilience Hubs (Figures 17). To see the variation in ranking within a given Resilience Hub, results are also viewed as a hexagon grid (Figure 18). Each 4-hectare (10-acre) hexagon also receives a rank based on the Community Exposure and Fish and Wildlife Index values. The hexagons clearly show higher rankings around the coast and adjacent to dense community assets, while more interior and remote locations receive lower ranks.

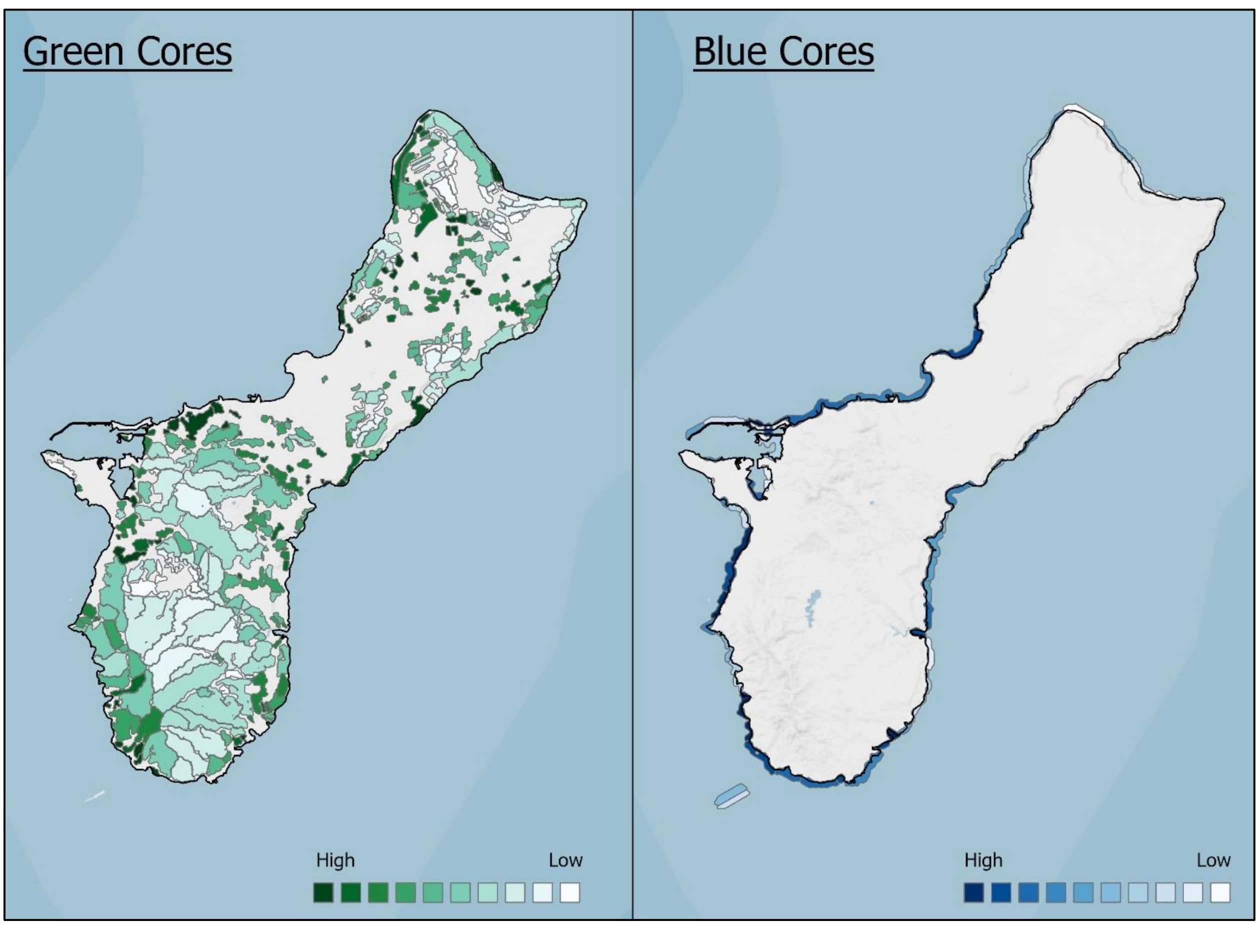


Figure 16. Green Habitat Cores (left) and Blue Habitat Cores (right) for Guam.

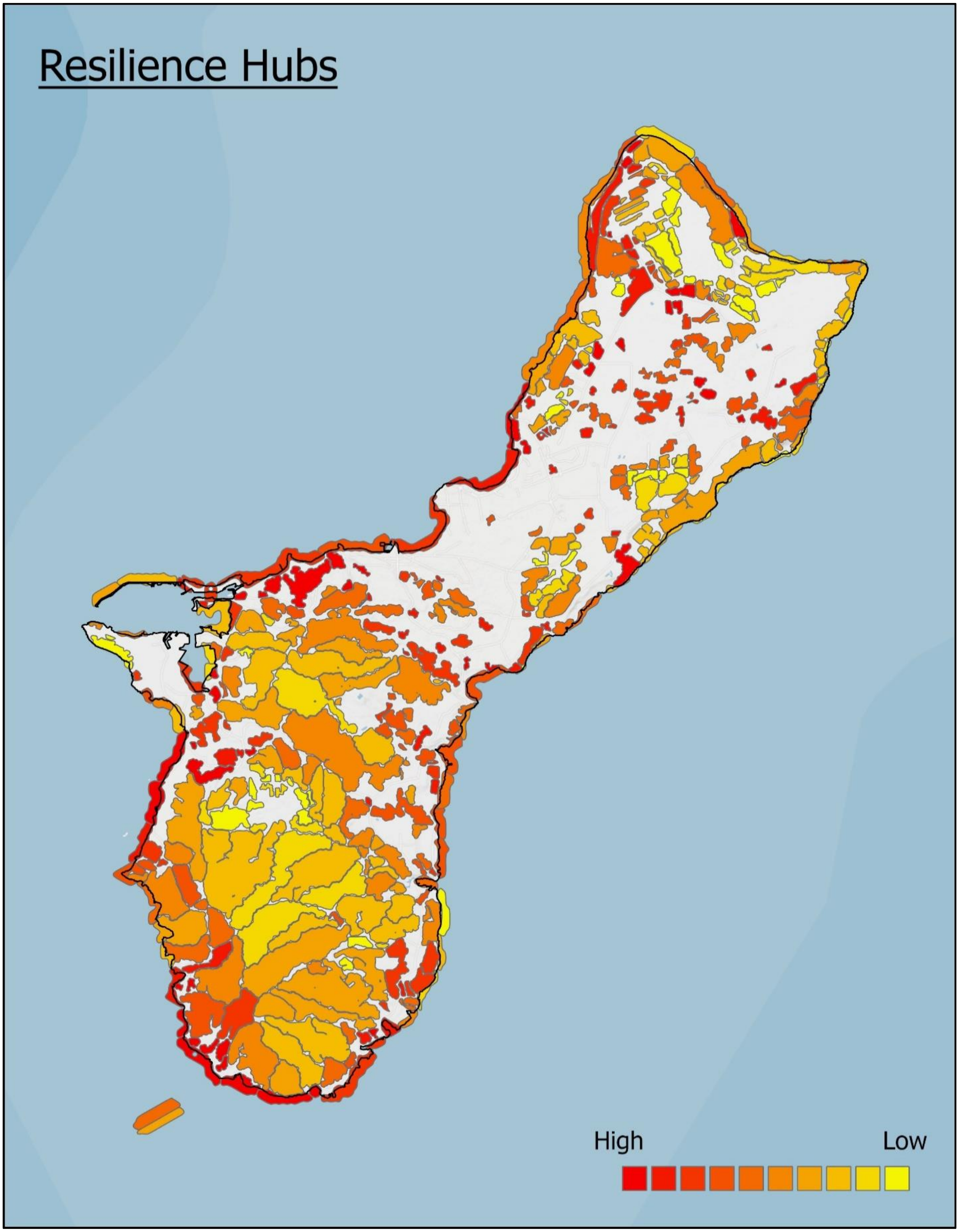


Figure 17. Ranked Resilience Hubs for Guam. Resilience Hubs identify areas of habitat at least 4 hectares (10 acres) in size. High ranking hubs (darker reds) represent areas well suited for the implementation of nature-based solutions that may benefit both species of conservation concern and human community resilience to flooding threats. For detail, view results in CREST.

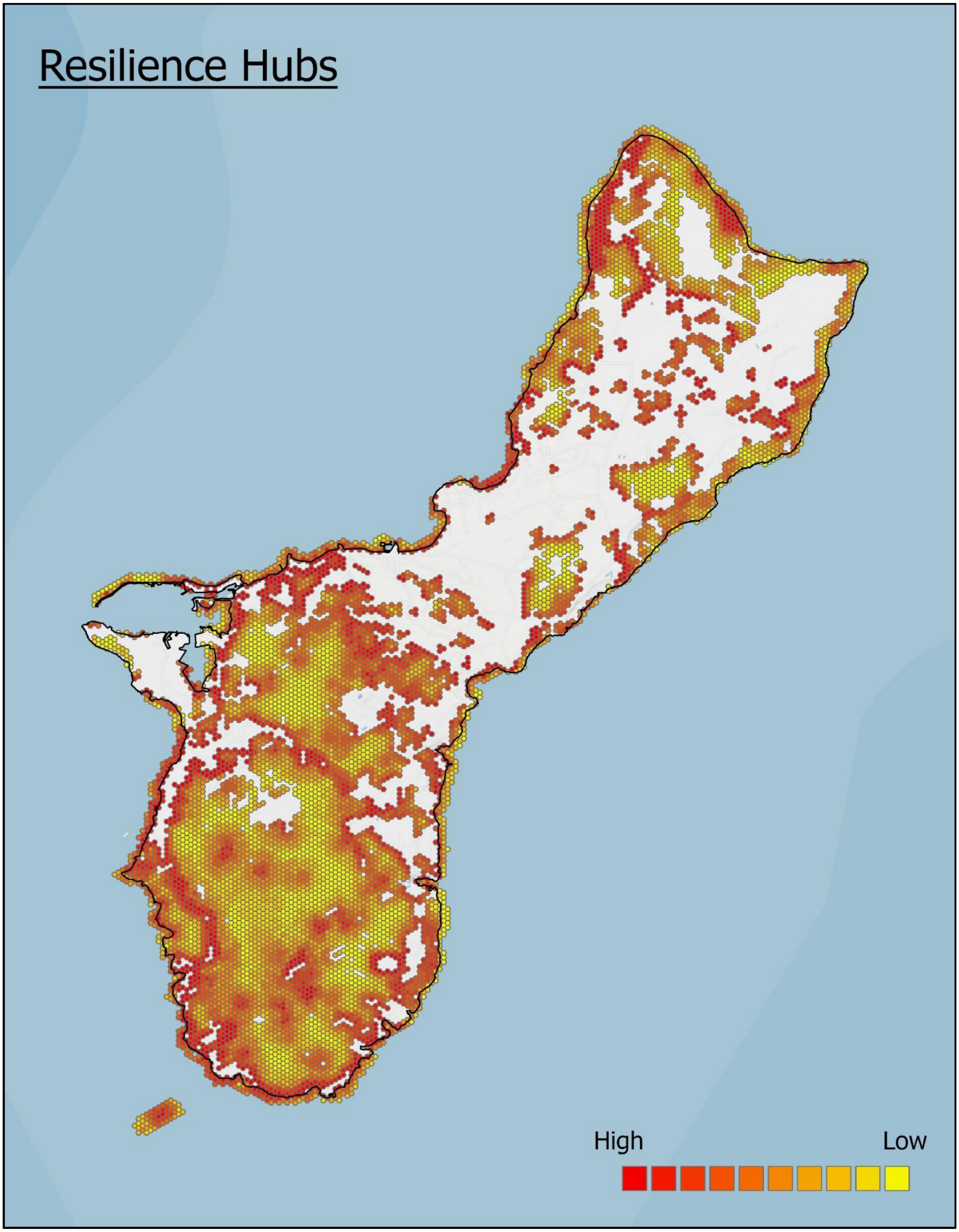


Figure 18. Ranked 4-hectare (10-acre) hexagons to view variation in Resilience Hub rankings. Highest-ranking hexagons (darker reds) represent areas well suited for the implementation of nature-based solutions that may benefit both species of conservation concern and human community resilience to flooding threats. For detail, view results in CREST.

The analysis identified many large Resilience Hubs, particularly in the southern portion of the island where there are large tracts of natural land cover with few fragmenting features (Figure 17). The nearshore waters also feature large Hubs due to the presence of extensive coral reefs around most of the island. However, only the highest-ranking Hubs represent areas with the greatest potential to implement nature-based solutions capable of achieving benefits for fish and wildlife while also reducing flooding risk to important human community assets. In contrast, the less populated areas in the southern interior and on the northern coast feature few high-ranking Hubs, which suggest that while there are significant opportunities for ecological benefits, projects in these areas are less likely to build human community resilience to flooding.

Throughout Guam there are numerous roads, buildings, or other infrastructure that fragment the landscape and produce small Hubs scattered across the island. This is particularly evident in the central region where there are relatively few Green Habitat Cores and thus few Resilience Hubs (Figures 17 and 18). This relatively flat area is highly developed and therefore features high Community Exposure values; however, there are few patches of contiguous intact habitat that meet the criteria used to identify habitat cores. Therefore, there are few Hubs indicating that while projects in this area may support important community benefits, there may be limited contiguous terrestrial habitat to support nature-based solutions that can also benefit terrestrial species of conservation concern. Despite limited open space, in those areas that do feature contiguous habitat there are several high-ranking Resilience Hubs, such as those around Agana Swamp. In contrast, there are several higher-ranking blue habitat cores in and around the Tumon Bay, Agana Bay, and Pago Bay, suggesting there may be more opportunities to implement nature-based solutions in coastal and nearshore marine habitats such as coral reef conservation and restoration, mangrove restoration, living shorelines, and other techniques that help slow coastal erosion and reduce flooding to nearby communities.

The analysis revealed a large network of Blue Habitat Cores encompassing nearly the entire nearshore marine boundary (<10-meter depth)(Figure 16). Blue Habitat Cores found in nearshore areas also received a higher score if multiple habitat types, such as coral reefs, mangroves, or sandy beaches are present in the same areas (within 0.25 kilometers). Areas with multiple habitat types in close proximity may offer opportunities to implement a suite of coordinated nature-based solutions to maximize the potential to protect surrounding coastal communities from storm and flood events. This is particularly evident in Cocos Lagoon, where the presence of coral reefs, seagrass beds, and mangroves contribute to high-ranking Resilience Hubs adjacent to the village of Malesso (Figures 17 and 18).

Even in more rural locations, such as around Talo'fo'fo (fomerly Talofofo) village, there are numerous resilience-building opportunities highlighted by high-ranking Resilience Hubs (Figure 19). For instance, the Talo'fo'fo River Valley boasts forested wetland habitat important to numerous species of conservation concern. However, the large river valley also experiences numerous flooding threats leaving many community assets exposed. The high ranking terrestrial and nearshore marine Resilience Hubs highlight multiple potential opportunities to conserve and restore the areas of open space surrounding the village. To explore the results of the analysis in more detail for any area of interest throughout Guam, visit the Coastal Resilience Evaluation and Siting Tool (CREST) at resilientcoasts.org. For more details about CREST, please refer to Section 3.4 below.

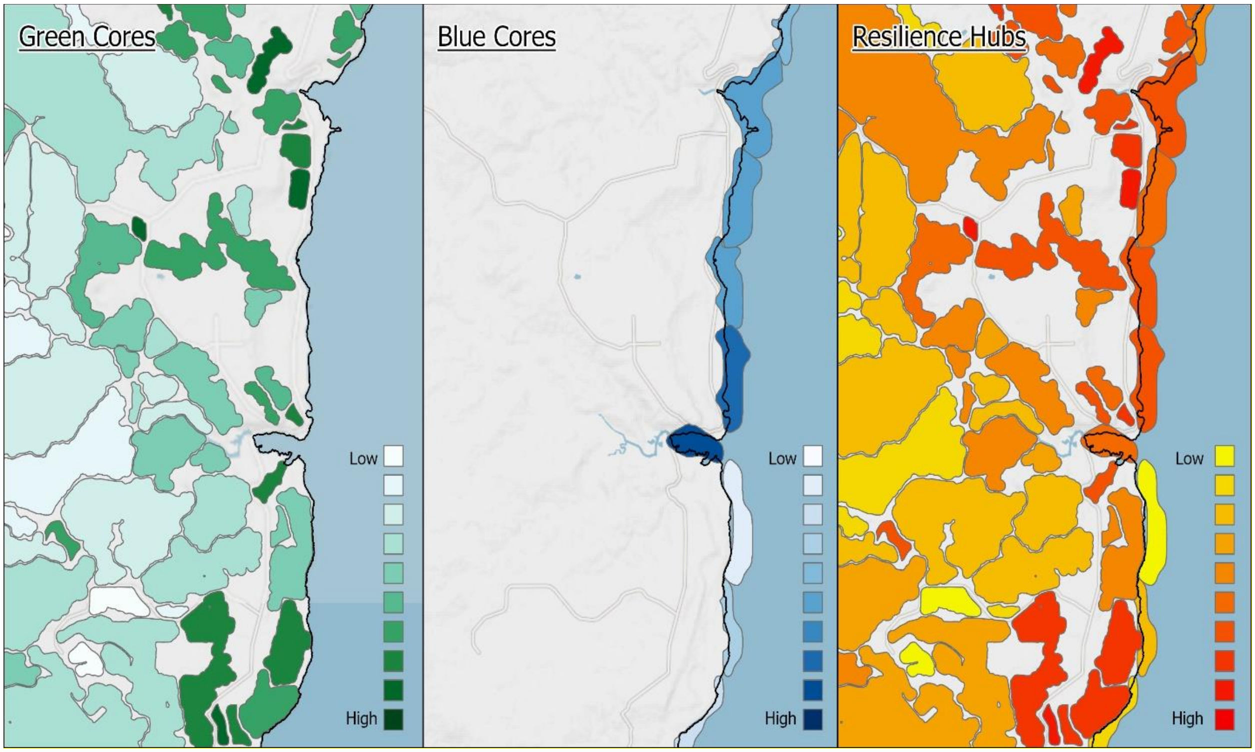


Figure 19. The mouth of the Talo'fo'fo River shows a range of ranked Resilience Hub scores.

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 full access to the Guam Assessment data so they may incorporate them 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 Guam 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.

CREST is intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans.

CASE STUDY

4.1 Coral Reef Restoration to Build Coastal Resilience*

Guam is surrounded by highly valued and biodiverse coral reefs that support over 400 species of scleractinian, or reef-building corals. In the extensive shallow reef flats found along much of the southern coasts, staghorn coral thickets and seagrass beds provide important habitat for fishes, sea turtles, and other species of conservation concern. Coral reefs not only provide ecological benefits, but also provide millions of dollars each year in tourism, fisheries benefits, and coastal protection (Spalding *et al*. 2017, Storlazzi *et al*. 2019). Healthy reefs can lessen sea level rise impacts and dissipate up to 97 percent of storm-generated wave energy (Ferrario *et al.* 2014). Within the reef flats, staghorn (*Acropora*) coral communities along with other coral species, help to buffer wave energy along the coast.

While Guam still has many relatively healthy coral reefs along the coastline, many are negatively impacted by chronic stressors from poor water quality, overfishing, and siltation. These impacts were magnified by a series of recent environmental events that caused widespread coral mortality. From 2013 to 2017, Guam's reefs suffered repeated bleaching and mortality associated with heat stress, disease outbreaks, and extreme low tides (Raymundo et al. 2017). Acroporid species were hit particularly hard (Figure 20), with an estimated 36 percent overall mortality in 2017, and many populations suffered over 90 percent mortality (Raymundo et al. 2019). Several staghorn *Acropora* species are limited to a small thicket in a single location, leaving populations at risk of extirpation.

Fortunately, researchers and federal and local government agencies are working to conserve and restore Guam's valuable reefs. As local partners restore adjoining watersheds to improve nearshore water quality, efforts are underway to actively restore staghorn *Acropora* communities. Since 2013, two coral nurseries have been built providing coral fragments that can be outplanted to surrounding reefs. While small-scale pilot efforts have been successful, large scale and innovative restoration efforts are required to combat rapidly intensifying threats.

Researchers at the University of Guam Marine Laboratory (UOGML) are leading a project to restore staghorn coral (*Acropora* spp.). With funding from the National Coastal Resilience Fund[11] and other sources, UOGML is working with partners to increase Guam's capacity to restore coral reefs while identifying genetic attributes that are associated with resilient corals able to persist in the face of bleaching and other threats. The project is being implemented through a coordinated effort among the Guam Reef Restoration and Intervention Partnership (GRRIP), which includes the University of Guam Marine Lab, Guam Bureau of Statistics and Plans, Guam Environmental Protection Agency, Guam Department of Aquatic and Wildlife Resources, NOAA, the National Parks Service, The Nature Conservancy, and Underwater World.

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* This case study presents research conducted by Dr. Laurie Raymundo at the University of Guam. Dr. Raymundo contributed to the writing of this case study.

[11] For more information about the National Fish and Wildlife Foundation and the National Coastal Resilience Fund see https://www.nfwf.org/programs/national-coastal-resilience-fund.

Figure 20. Mortality within the Acropora pulchra *community in Adelup, Guam. On the right is a zone of previous bleaching and exposure mortality, 2013-2015; on the left shows 2016 mortality from bleaching and disease. Photo credit: A. Miller, 2016.*

The following case study describes ongoing research and restoration activities at three sites in Guam, using the Guam Coastal Resilience Assessment results to demonstrate the utility of various outputs to evaluate potential locations to site similar types of resilience efforts. Through 2023, the UOGML team will restore staghorn *Acropora* communities in the Piti Bomb Holes, Achang, and the Tumon Bay Marine Preserves (Figure 21). The project will expand existing coral nurseries in Piti and Cocos Lagoon, facilitating the development of new coral-rearing techniques, genetic research, and ultimately the restoration of 1.68 hectares (4.15 acres) of restored reef.

As of early 2021, the project team completed an extensive survey to verify the presence, condition, percent coral cover, and extent of all known staghorn communities representing eight putative species. The surveys were a critical first step to develop a baseline reference condition that can be used to assess the success of future outplanting and reestablishment efforts. The team is also working to expand the existing coral nurseries in Piti and Cocos Lagoon using techniques that have proved successful in other locations around the world. Each nursery received additional coral trees (nine in Piti and 12 in Malesso (formerly Merizo)) and mid-water rope or chandelier nurseries that will greatly increase the number of coral fragments available for outplanting (Figure 22). All pilot structures are currently being tested.

Figure 21. Map showing the coral restoration project locations in red and the Tumon Marine Preserve, Piti Bomb Holes Marine Preserve, and Achang Marine Preserve in the white hatching. The blue dots show the locations of the coral nurseries.

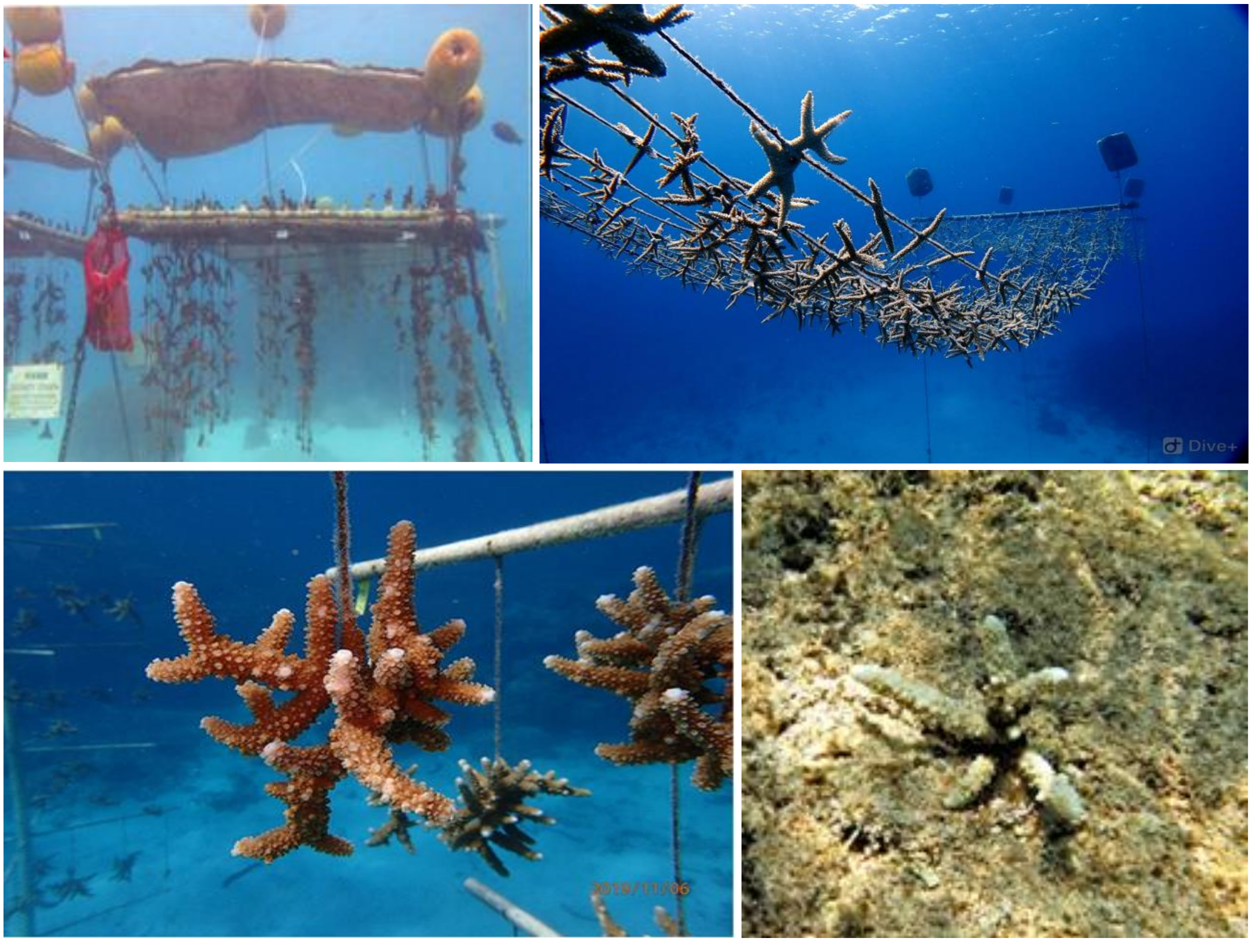

Figure 22. Various coral nursery structures including a coral table (upper left), a mid-water rope nursery for large-scale coral gardening (upper right), and a coral tree nursery (lower left). Image on the lower right shows an outplanted, nursery-grown staghorn fragment at the Piti Bomb Holes Marine Preserve. Photo credits: Laurie Raymundo, University of Guam.

The nursery-reared fragments will then be outplanted to suitable plots[12] at all three project sites. Starting with smaller-scale pilot efforts and gradually expanding to larger-scale efforts, the enhanced nursery capacity will help produce thousands of corals that can be used to restore Guam's reef flats. This is particularly important for the villages such as Piti where abundant coastal infrastructure is exposed to numerous flooding threats (Figure 23). By restoring the adjacent reef flat, *Acropora* communities can provide coastal protection benefits, potentially reducing the impacts of threats such as sea level rise (Figure 24) and wave-driven flooding (Figure 25).

[12] Plots selected using four primary environmental metrics including sufficient depth to prevent extreme low tide exposure, water circulation/flushing, absence of significant siltation, and presence of living healthy coral in proximity.

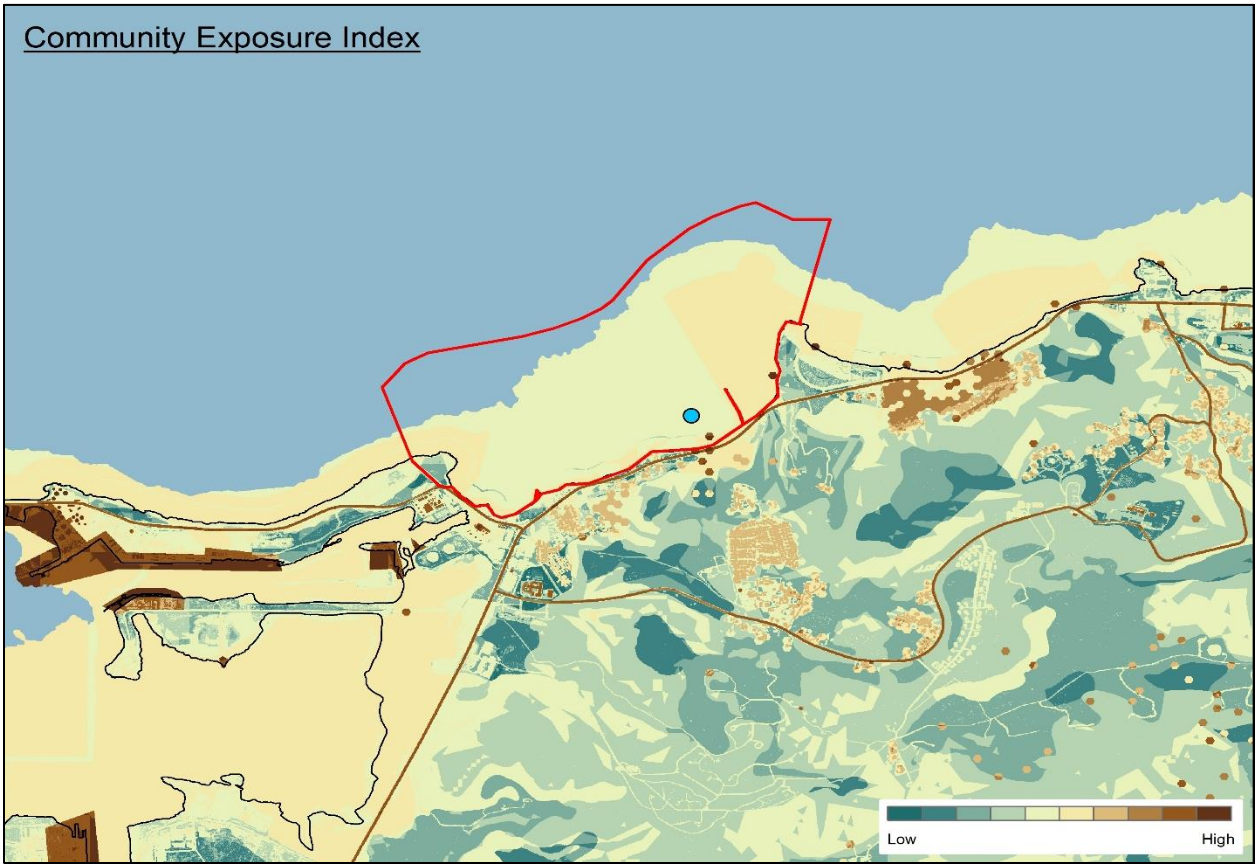

Figure 23. The Community Exposure Index results for the Piti Bomb Holes Marine Reserve site (red line) reveal many community assets exposure to flooding threats. The blue dot shows the approximate location of the coral nursery.

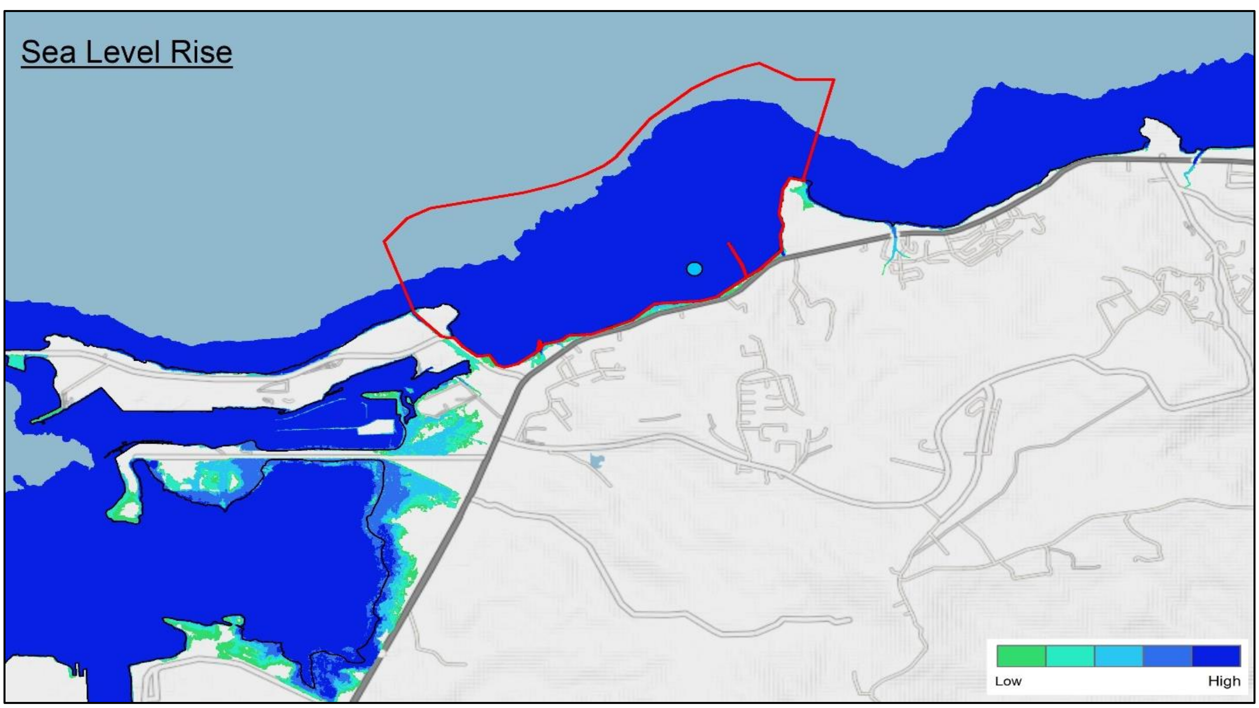

Figure 24. Healthy coral reefs help to reduce shoreline erosion and flooding associated with sea level rise. Red outlines the Piti Bomb Holes Marine Reserve; the blue dot shows the approximate location of the coral nursery.

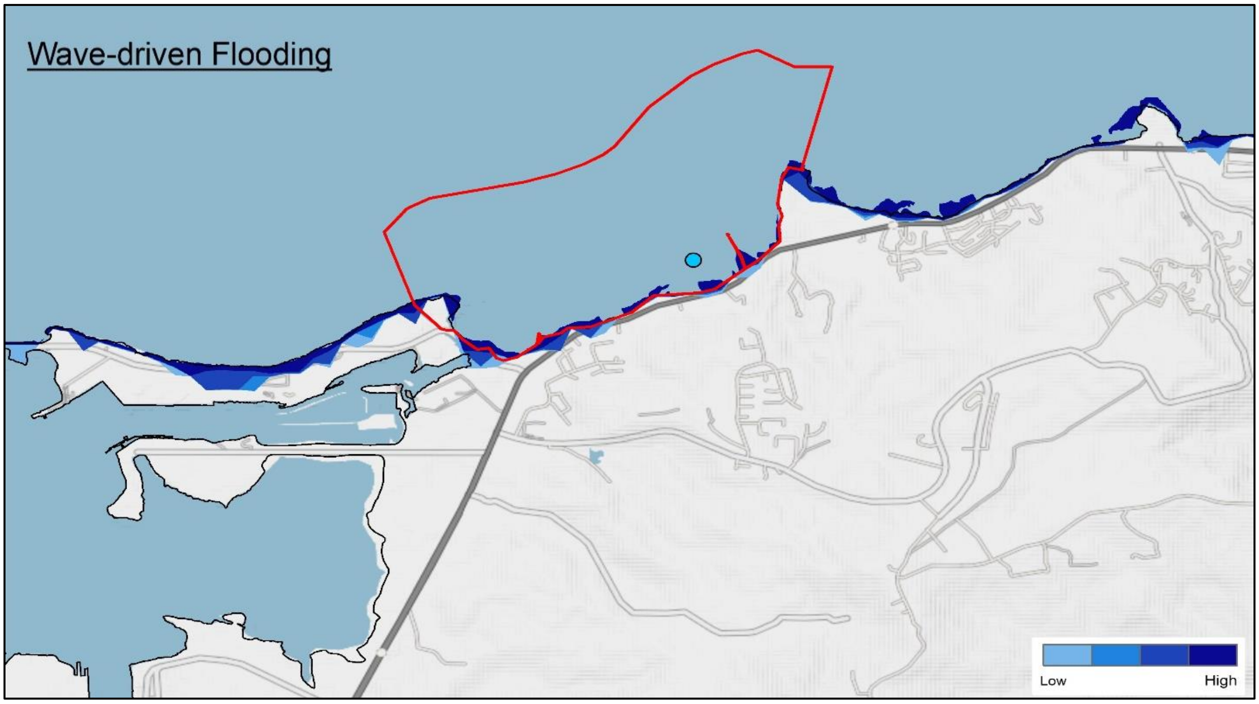

Figure 25. Healthy coral reefs help reduce shoreline erosion and flooding associated with wave-driven flooding. Red outlines the Piti Bomb Holes Marine Reserve; the blue dot shows the approximate location of the coral nursery.

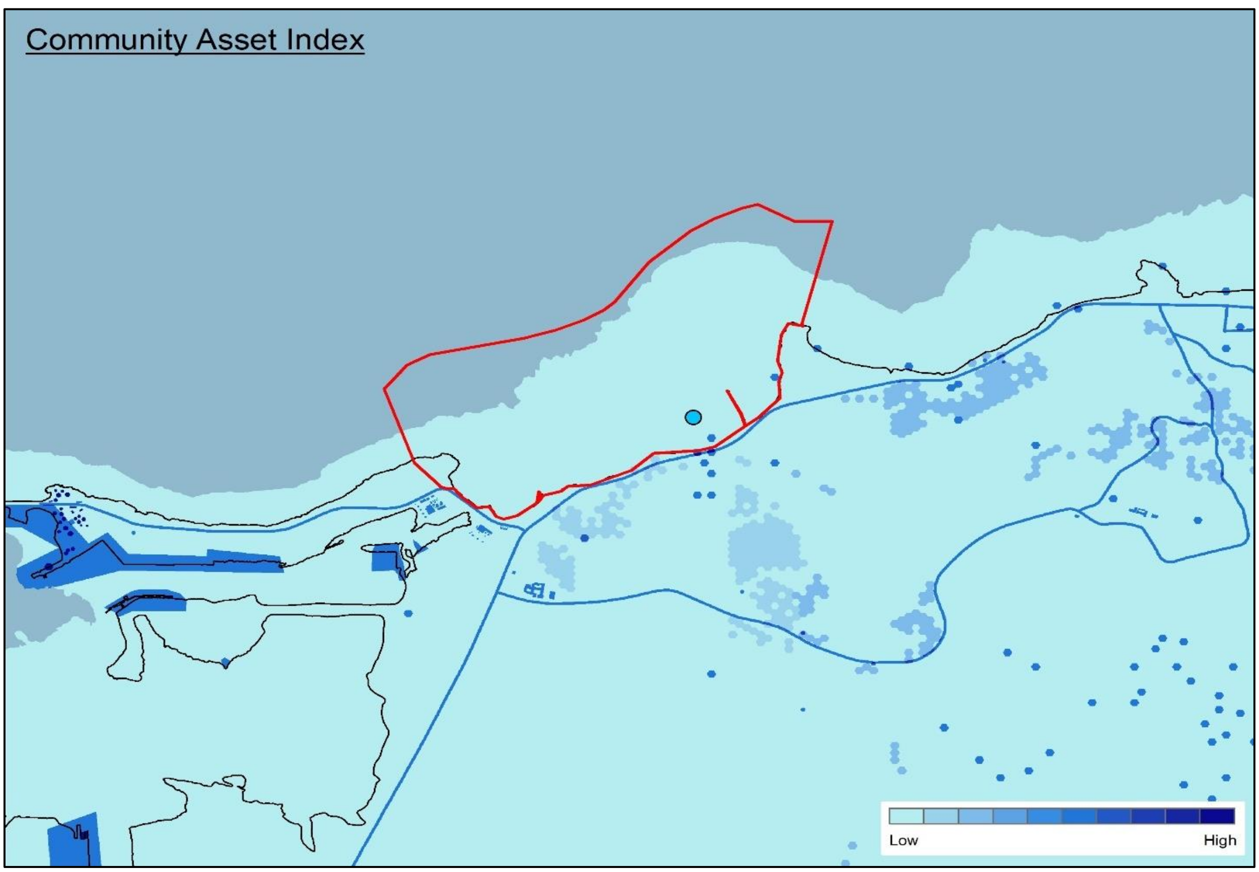

Figure 26. The Community Asset Index shows concentrations of community assets along the coastline adjacent to the Piti Bomb Holes Marine Preserve site (red line). The blue dot shows the approximate location of the coral nursery.

The results of the assessment highlight numerous community assets in proximity to the Piti Bomb Holes Marine Reserve (Figure 26). The Preserve is not only close to populated areas, but the reef also helps protect adjacent critical facilities and infrastructure including a major coastal road, fire stations, and a school and hospital. The site also has a nearby port and communication infrastructure. In addition, the area is important for Guam's economy as a popular tourist attraction for diving, snorkeling, and other ecotourism opportunities. While a restored reef may not protect all these assets from severe coastal flooding threats, it is expected to help reduce wave energy and shoreline erosion.

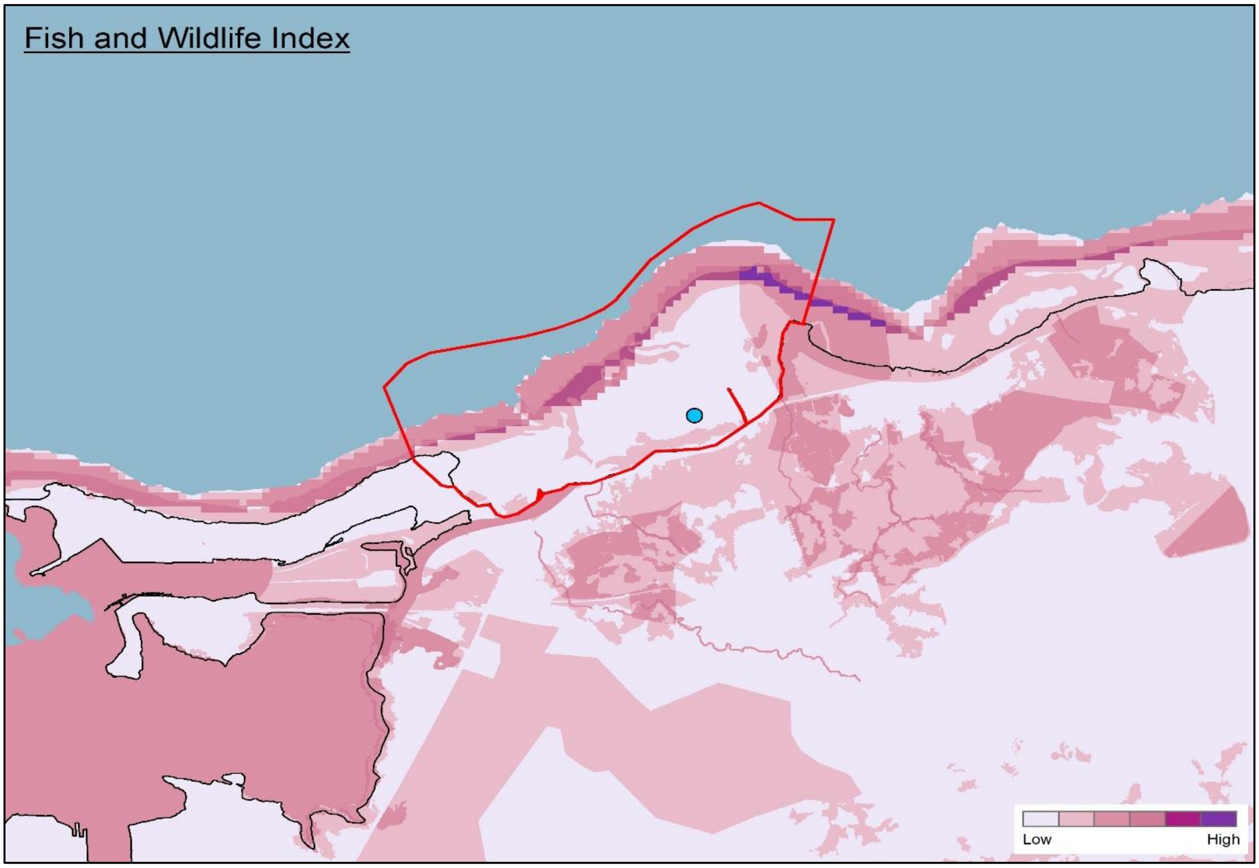

Figure 27. Fish and Wildlife Index results in the Piti Bomb Holes Marine Reserve site (red line). Note the high values along the outer reef crest where coral cover and reef fish biomass are high. The blue dot shows the approximate location of the coral nursery.

Piti Bomb Holes Preserve is also significant for ecosystem resilience, as it harbors the most diverse habitat types among Guam's Marine Preserves including important seagrass and diverse coral reef habitat (NOAA 2009). By restoring staghorn *Acropora* communities specifically, the flats will provide invertebrate and juvenile reef fish habitat for numerous ecologically and economically important species. The Guam Assessment highlights the significant fish and wildlife resources that utilize both the nearshore and terrestrial habitat surrounding the bay (Figure 27). However, as climate impacts become more severe, the myriad ecological benefits corals provide may be diminished. Therefore, the UOGML team is also working with researchers from Colombia and the United Kingdom to develop restoration techniques that will allow outplanted corals to thrive and reproduce into the future. By identifying genetic traits that confer resilience to temperature stress and disease, researchers hope to cross resistant colonies with at-risk populations to grow corals that are more likely to survive the effects of climate change and maintain a healthy, biodiverse coral reef ecosystem. Researchers also aim to maximize remaining genetic diversity of all outplanted populations to optimize successful spawning and recruitment of restored populations in the future.

With the presence of considerable flooding threats, concentrations of coastal community assets, and wildlife habitat, coral restoration efforts in Piti Bomb Holes demonstrate 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. Within and surrounding the Piti Bomb Holes (Figure 28), Achang, and the Tumon Bay Marine Preserves, a range of high-ranking Hubs are visible. 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 the island, can help support the prioritization of habitats for other restoration projects in Guam.

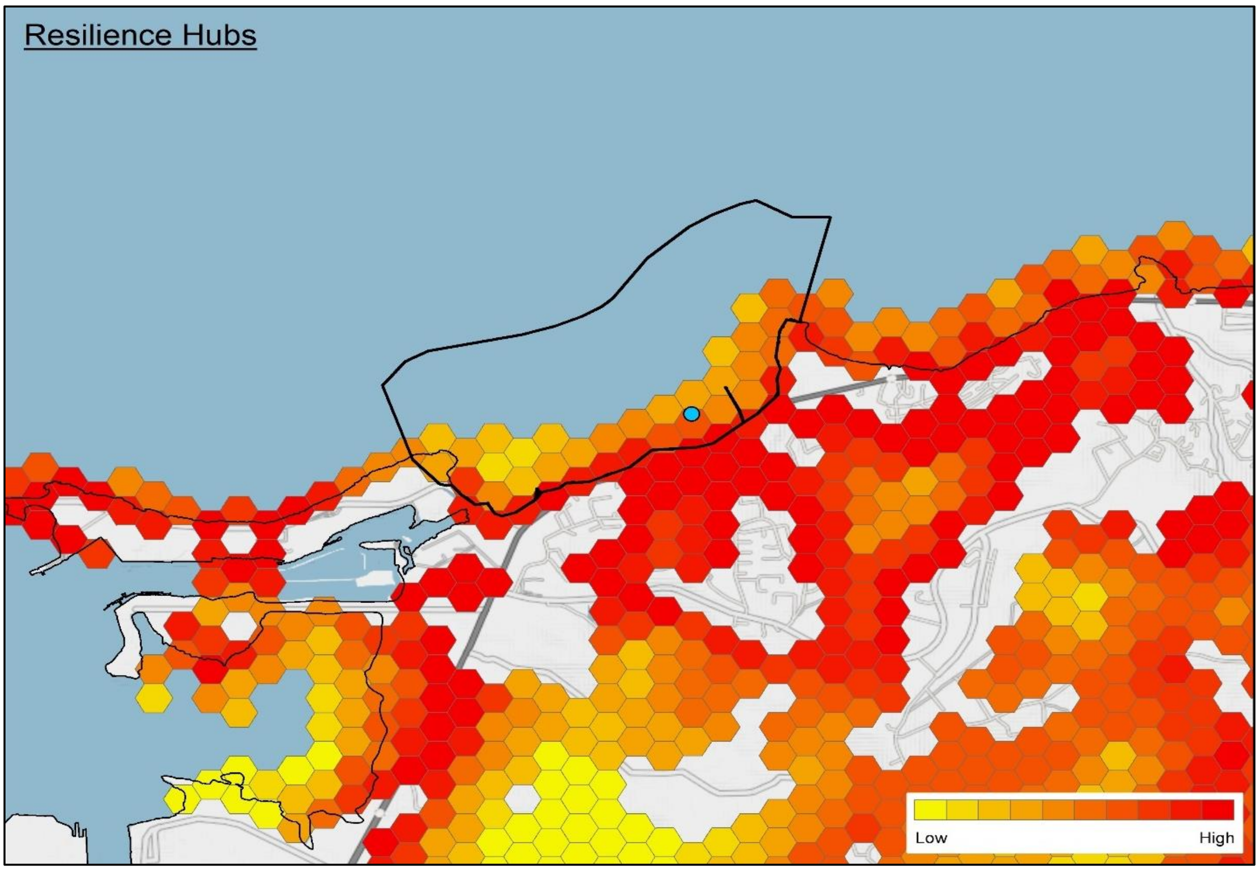

Figure 28. Resilience Hub hexagon results in the Piti Bomb Holes Marine Reserve site (black line). The blue dot shows the approximate location of the coral nursery.

The increased capacity afforded by the coral nurseries will provide opportunities for future restoration efforts in Guam. To help ensure the lessons learned through this project and others are shared more broadly, the UOGML will also host a regional workshop to bring together coral reef managers from throughout Micronesia. The team will also work to engage local residents to assist in coral reef monitoring and maintenance. By engaging citizen scientists, sharing and applying lessons learned, and through rigorous long-term monitoring, this project will develop essential capacity and best practices to help protect Guam’s vital coral reef resources into the future.

CONCLUSION

5.1 Summary and Key Takeaways

As communities across Guam deal with current and future flooding threats from natural events, tools such as this Coastal Resilience 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 nearly 177 kilometers of coastline, Guam is exposed to a variety of coastal-flood related hazards. The effects of flood-related hazards are compounded in areas with higher populations and assets, such as in Hagåtña, Tamuning, Sinajana, and Mongmong-Toto-Maite. Inland villages are not immune to flood-related threats, especially as they relate to heavy precipitation events and flash flooding. Furthermore, the effects of coastal flooding are exacerbated when combined with heavy inland precipitation, suggesting efforts to build resilience should consider the benefits of a holistic, watershed-wide approach.

Guam is ecologically diverse, with an abundance of wildlife assets, both in the terrestrial and marine environments. Combining the information in the Fish and Wildlife Index with the Community Exposure Index, the Assessment identified numerous Resilience Hubs, or areas where resilience-building projects may benefit both human and wildlife communities. As with all GIS analyses, site-level assessments are required to validate results and develop detailed design and engineering plans. The Regional Assessments are intended to be used as a screening-level tool designed to help identify areas that may be well suited for nature-based solutions. The results are limited by those data available at the time of analysis and by the underlying accuracy and precision of the original data sources; therefore, the assessment may not capture all flood-related threats, community assets, fish and wildlife resources, or areas of open space. Resilience Hubs are not intended to identify all potential opportunities for nature-based solutions, but rather are meant to help assess potential projects based on dual benefits for habitats and human 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 Guam 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 Guam Assessment was completed at a 3-meter resolution, using the projection *NAD 1983 Stateplane Guam FIPS 5400* (WKID 65161).

A. Data Summary

A.1 Threat Index

The following is a comprehensive list of datasets used to create the Threat Index for the Guam Coastal Resilience Assessment. **Bolded layer names indicate the source data were specific to the Guam 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 of Coastal Management Sea Level Rise Inundation Database (2015 or later)
Wave Driven Flooding	Floodmasks; USGS (Storlazzi et al. 2019)
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 (2016)
Tsunami Evacuation Zone	Tsunami Aware, NOAA Office for Coastal Management
Landslide Hazard	NOAA Office for Coastal Management
Wave Exposure	Digital Atlas of Southern Guam

A.2 Community Asset Index

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

Layer Name	Dataset and Source
Population Density	Digital Atlas of Southern Guam (U.S. Census Bureau 2010 Decennial Census)
Social Vulnerability	Thomas A. Oliver, Danika Kleiber, Justin Hospital, Jeffrey Maynard, Dieter Tracey. Coral Reef Resilience and Social Vulnerability to Climate Change: Main Hawaiian Islands. Pacific Islands Fisheries Science Center, PIFSC Special Publication, SP-20-002a. 6 p. doi:10.25923/5xhp-5k12
Critical Facilities	Schools: USGS National Structures Dataset, Guam EPA; Hospitals: HIFLD, Guam EPA; Fire Stations & Police Stations: digitized with Google Maps search
Building Footprints	Open Street Maps, digitized by NEMAC team as-needed
Critical Infrastructure *(Various Inputs, see below)*	
Primary roads	*Digital Atlas of Northern Guam*
Airport runways	*HIFLD Airport Runways*
Ports	*HIFLD Port Facilities*
Marinas	*Guam EPA (personal communication)*
Power Plants/Substations	*Pacific Islands Data Portal - Coastal and Marine Spatial Planning; EPA FRS (2019)*
Wastewater treatment facilities	*EPA Facility Registry Service (FRS): Wastewater Treatment Plants*
Communication Towers	*HIFLD: FM Transmission towers, Microwave Service Towers*
Major dams	*Digital Atlas of Southern Guam/USACE Dam Lines*
Petroleum terminals	*Digitized by NEMAC team from US EIA*
Hazardous Sites	*EPA FRS (2019)*
Cultural/Historic Sites	*Guam EPA (personal communication)*

A.3 Terrestrial Index

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

Dataset Name	Source and Year
C-CAP Land cover	NOAA Office for Coastal Management (2016)
National Wetlands Inventory	U.S. Fish & Wildlife (most recent available)
National Hydrography Dataset	USGS (most recent available)
GAP Land cover	NOAA C-CAP 2016 High Res Land Cover (2016)
Important Bird Areas & Key Biodiversity Areas	BirdLife International (2020)
Environmental Sensitivity Index Species Habitat	NOAA Office of Response and Restoration (2005)
Critical Habitat Designations	U.S. FWS (most recent available)
Wildlife Action Plan species list	Guam Division of Aquatic and Wildlife Resources (2019)
Habitat Classification Scheme	IUCN Red List of Threatened Species (Version 3.1)
Protected Areas Database of the U.S. (PADUS)	USGS (Version 2.0)
Vegetation Maps	USFS, 2011-2014
Ecological Reserve Areas	Digital Atlas of Southern Guam
Conservation Areas	Digital Atlas of Southern Guam
Overlay Refuge Areas	U.S. Department of Defense (personal communication)
Guam Micronesian Kingfisher MOA Priority Areas	U.S. Department of Defense (personal communication)
Guam Micronesian Kingfisher Potential Recovery Habitat	U.S. Department of Defense (personal communication)
Green Sea Turtle Nesting Locations	SWOT, State of The World's Sea Turtles

A.4 Marine Index

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

Dataset Name	Source and Year
Critical Habitat Designations	U.S. FWS (most recent available)
Essential Fish Habitat	NOAA Fisheries
Benthic Habitat Maps	NOAA National Centers for Coastal Ocean Science (2005)
Coral Cover Surveys	NOAA National Coral Reef Monitoring Program, strata-level data (2017)
Mangrove Presence	NOAA C-CAP 2016, Estuarine Wetland classes; University of Guam Marine Lab (personal communication)
Seagrass Cover	NOAA National Centers for Coastal Ocean Science (2005)
Marine Protected Areas	USGS Protected Areas Database of the U.S. (PADUS), Version 2.0
Bathymetry	Pacific Islands Benthic Habitat Mapping Center 5m grid
Reef Fish Biomass	NOAA National Coral Reef Monitoring Program: Reef Fish Monitoring sector-level data (2017)

A.5 Resilience Hubs

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

Dataset Name	Source and Year
C-CAP Land Cover Atlas	NOAA Office for Coastal Management 2016
National Wetlands Inventory	U.S. Fish & Wildlife (most recent data available)
National Hydrography Dataset	U.S. Geological Survey (USGS) 1:24,000
Bathymetric Data	NOAA NCEI Coastal Relief Model
Coral Cover Surveys	NOAA National Coral Reef Monitoring Program, strata-level data (2019)
Benthic Habitat Maps	NOAA National Centers for Coastal Ocean Science (2007)
National Elevation Dataset	U.S. Geological Survey (USGS), EROS Data Center
SSURGO Soils Survey	USDA-NRCS SSURGO (2.2 or later)
Roads polyline	OpenStreetMap (latest data available)

B. Detailed Methodology: Threat Index

The Threat Index for Guam was created by following the methodology outlined in the Methodology and Data Report (Dobson et al. 2020). Any changes to the inputs used in this region, and their sources, are listed in Appendix A.1.

B.1 Wave Driven Flooding

Wave driven flooding was ranked according to probability of occurrence, where a 10-year return period is given a higher rank than a 500-year return period. The following rank value was applied to each return period:

Wave Driven Flooding	Rank Value
0	0
500-year return period	1
100-year return period	2
50-year return period	3
10-year return period	4

A. Import each floodmask vector and add a rank field according to the table above.
    a. Right click layer in Contents > Attribute Table > +Add
        i. Name: Rank; Type: Short Integer
        ii. Save the changes and return to the attribute table
    b. Right click Rank field > Calculate Field > Rank = *see above*
B. Merge floodmasks with regional boundary
C. Rasterize the merged floodmasks and regional boundary
    a. Tool: Polygon to Raster
        i. Input feature: merged floodmasks and boundary
        ii. Value field: Rank
        iii. Cell assignment: Maximum Area
        iv. Priority Field: Rank
        v. Cellsize: 3

B.2 Tsunami Evacuation Zones

The data available for tsunami inundation in Guam describe the extent of evacuation zones only. Therefore, all areas falling inside the tsunami evacuation zone extent were assigned a uniform value of 3.

A. Add a rank field to the tsunami evacuation zone vector features.
    a. Right click layer in Contents > Attribute Table > +Add
        i. Name: Rank; Type: Short Integer
        ii. Save the changes and return to the attribute table
    b. Right click Rank field > Calculate Field > Rank = 3
B. Merge inundation extent with regional boundary

C. Rasterize the merged inundation extent and regional boundary
    a. Tool: Polygon to Raster
        i. Input feature: merged inundation extent and boundary
        ii. Value field: Rank
        iii. Cell assignment: Maximum Area
        iv. Priority Field: Rank
        v. Cellsize: 3

B.3 Landslide Hazard

Landslide Hazard was ranked according to qualitative hazard levels given in the source dataset. The following rank value was applied to each hazard level:

Landslide Hazard	Rank Value
Low	1
Medium	2
High	3
Very High	4

A. Import each landslide hazard vector and add a rank field according to the table above.
    a. Right click layer in Contents > Attribute Table > +Add
        i. Name: Rank; Type: Short Integer
        ii. Save the changes and return to the attribute table
    b. Right click Rank field > Calculate Field > Rank = *see above*

B. Merge landslide hazards with regional boundary

C. Rasterize the merged landslide hazards and regional boundary
    a. Tool: Polygon to Raster
        i. Input feature: merged landslide hazards and boundary
        ii. Value field: Rank
        iii. Cell assignment: Maximum Area
        iv. Priority Field: Rank
        v. Cellsize: 3

B.4 Wave Exposure

Wave energy exposure was ranked according to the distribution of daily wave energy values found along the coast of Guam, using a quantile distribution. The following rank value was applied to each range of wave energy values:

Wave Exposure (J/m)	Rank Value
0 - 125	1
126 - 178	2
179 - 1544	3
1545 - 1754	4
1755 - 1912	5

B.5 Calculating the Threat Index

The Threat Index was classified into 10 classes to multiply with the Asset Index and ultimately create the Community Exposure Index. Below is the classification that was used for the Guam Threat Index.

Guam Threat Index Distribution

Threat Index Break Value	0 - 2	3	4 - 5	6	7	8	9 - 10	11 - 13	14 - 16	17 - 35
Final Rank Value	1	2	3	4	5	6	7	8	9	10

C. Detailed Methodology: Community Asset Index

The Community Asset Index for Guam was created by following the methodology outlined in the Methodology and Data Report (Dobson et al. 2020). Any changes to the inputs used in this region, and their sources, are listed in Appendix A.2.

C.1 Population Density

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 Guam.

Population Density Distribution for Guam	Rank Value
0	0
≤ 143.3	1
≤ 397.7	2
≤ 518.4	3
≤ 1276.2	4
≤ 1446.8	5

C.2 Social Vulnerability

To evaluate social vulnerability in Guam, data from the U.S. Census, aggregated by the NOAA Coral Reef Conservation Program, was utilized. The metrics include personal disruption, population composition, poverty, labor force structure, and housing characteristics[13]. The methodology for building the input was used, as outlined in the Data and Methodology Report (Dobson et al. 2020), with the only exception being the distribution and ranking. The rank values assigned by the original creators were used directly.

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

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

Infrastructure and facility data inputs were included in the analysis generally following the methodologies found in the Methodology and Data Report (Dobson et al. 2020). An exception to this was that parcel and footprint boundaries of critical infrastructure features were assigned a rank value of three and five, respectively; these rank values match the values that were assigned to parcel and footprint boundaries for features in the critical facilities input.

Cultural and historic sites were included in the Critical Infrastructure component of the Community Asset Index using 2,500 square meter sized hexagons. The spatial arrangement of these hexagons was the same as those that were used to create the Population Density and Social Vulnerability inputs

[13] https://repository.library.noaa.gov/view/noaa/24814

(Dobson et al. 2020). Any hexagon containing >0 historic site locations was assigned a rank value of five, to be included in the Critical Infrastructure input.

C.4 Calculating the Community Asset Index

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

Guam Community Asset Index Distribution

Asset Index Break Value	0	1	2	3	4	5	6	7	8 - 9	10 - 15
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 were 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 was further classified to make it easier to work with and understand the results. The distribution used for the Community Exposure Index in Guam is shown below.

Guam Community Exposure Index Distribution

Exposure Index Break Value	1	2	3	4 - 5	6 - 8	9 - 13	14 - 21	22 - 35	36 - 59	60 - 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 Guam 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 groupings are based on the species of concern included in the Guam Wildlife Action Plan and species listed under the U.S. Endangered Species Act. Habitat preferences for those 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 Guam.

Forest Birds

Mariana swiftlet (yayaguak) (*Aerodramus vanikorensis bartschi*)
Micronesian starling (såli) (*Aplonis opaca guami*)
Mariana crow (åga) (*Corvus kubaryi*)
Guam rail (ko'ko') (*Gallirallus owstonii*)
Micronesian honeyeater (egigi) (*Myzomela rubratta saffordi*)
White-throated ground-dove (paluman apaka/fache') (*Gallicolumba xanthonura*)
Mariana fruit-dove (totot) (*Ptilinopus roseicapilla*)
Guam Micronesian kingfisher (sihek) (*Todiramphus cinnamominus cinnamominus*)

Wetland Birds

Mariana common moorhen (pulattat) (*Gallinula chloropus guami*)
Nightingale reed warbler (ga' kaliso/ga' karriso) (*Acrocephalus luscinia luscina*)

Seabirds

Brown booby (lu'ao) (*Sula leucogaster*)
Pacific reef heron (chuchuko') (*Egretta sacra*)
White-tailed tropicbird (utak or fakpe) (*Phaethon lepturus*)

Terrestrial Mammals

Mariana fruit bat (fanihi) (*Pteropus mariannus mariannus*)
Pacific sheath-tailed bat (finihi) (*Emballonura semicaudata rotensis*)

Reptiles

Snake-eyed skink (guali'ek halom tano') (*Cryptoblepharus peocilopleurus*)
Slevin's skink (guali'ek halom tano') (*Emoia slevini*)
Micronesian gecko (guali'ek halom tano') (*Perochirus ateles*)
Green sea turtle (haggan) (*Chelonia mydas*)
Hawksbill sea turtle (haggan karai) (*Eretmochelys imbricata*)

Freshwater Fishes

Giant marbled eel (hasule) (*Anguilla marmorata*)
Flagtail (umatan) (*Kuhlia rupestris*)

Invertebrates

Fragile tree snail (akaleha') (*Samoana fragilis*)
Humped tree snail (akaleha') (*Parula gibba*)
Guam tree snail (akaleha') (*Partula radiolata*)
Mariana eight spot butterfly (*Hypolimnas octocula mariannensis*)
Marianas rusty (*Vagrans egistina*)

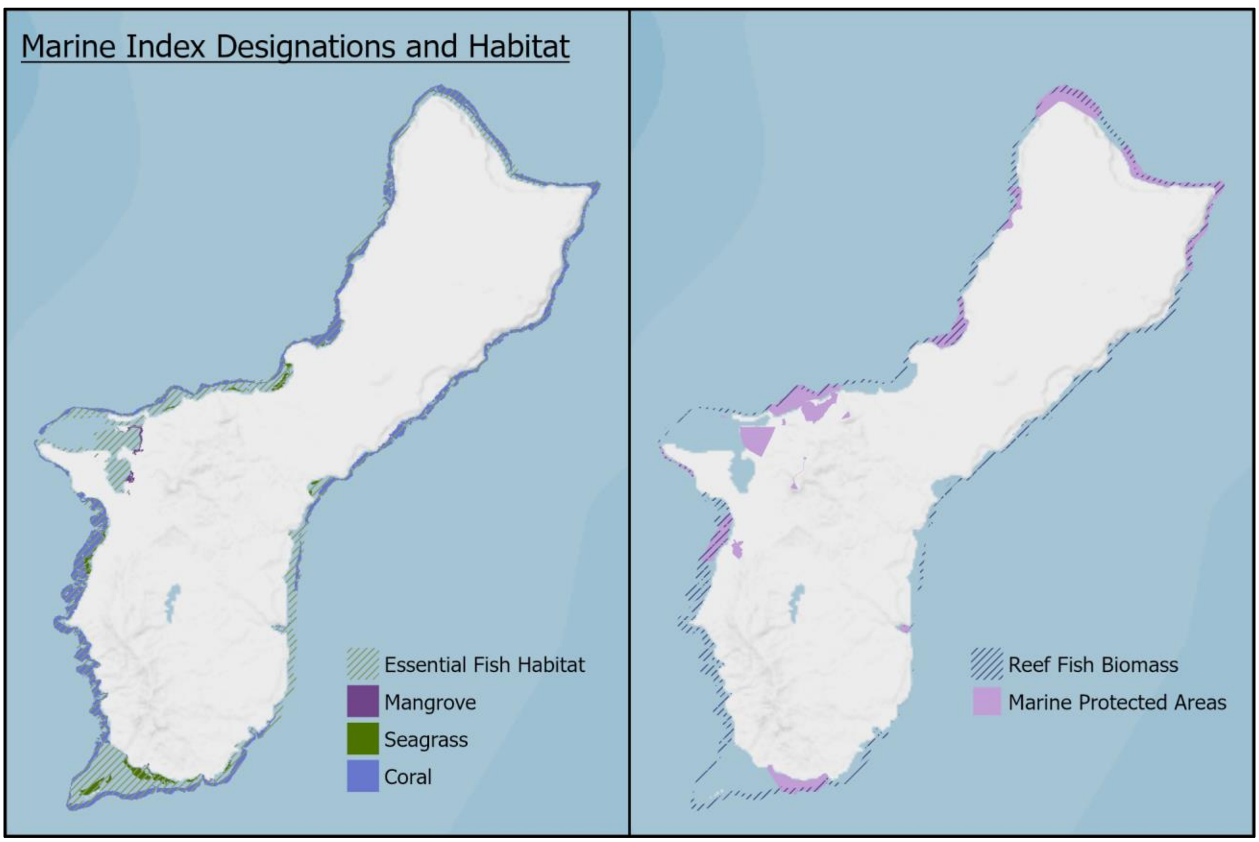
The distribution for the Guam Terrestrial Index is displayed below. The final rank value was determined using a quantile distribution and was then combined with the Marine Index to create the Fish and Wildlife Index.

Guam Terrestrial Index Distribution

Terrestrial Index Break Values	0	1 - 2	3 - 5	6 - 12
Final Rank Value	1	2	3	4

E.2 Calculating the Marine Index

In general, the same overarching methods were applied in Guam as outlined in the Methodology and Data Report (Dobson et al. 2020). However, due to differences in data availability, some modifications to the methods used for Guam were necessary. These are discussed in the following sections. See Appendix A.4 for details on datasets used in this analysis. The spatial extent and distribution of coral reefs, seagrasses, and mangroves are shown in the map below and described in the following text.



Coral Cover

To incorporate coral cover data from NOAA's National Coral Reef Monitoring Program, each strata-level (depth bin) surveyed was ranked according to the percent coral cover and then rasterized to be included in the Marine Index (Tom Oliver, NOAA, personal communication). The strata-level depth bins were created according to guidance from NOAA using bathymetry as follows:

Strata	Depth
Shallow	0 - 6m
Mid-depth	>6 - 18m
Deep	>18 - 30m

The percent coral cover was ranked across the islands using a quantile distribution and five classes. The following ranking scheme was used to rank coral cover by strata-level in Guam. The rank value of '0' shown below is the land area of each island.

Percent Coral Cover in Guam	Rank Value
0	0
≤ 8.4	1
≤ 10.4	2
≤ 10.5	3
≤ 17.7	4
≤19.4	5

Seagrass Cover

Despite the potential unreliability of the benthic habitat maps, seagrass cover was still incorporated into the analysis since no other options were available during the time of modeling. The following ranking scheme was used to rank seagrass cover in Guam.

Seagrass Cover in Guam	Rank Value
0	0
Patchy, 10 - <50%	3
Patchy, 50 - <90%	4
Continuous, 90 - 100%	5

Reef Fish Biomass

Reef Fish Biomass was used to further identify areas of high biodiversity. Biomass was ranked at the sector level using a quantile distribution of the mean total fish biomass and then ranked and rasterized into three classes to be included in the Index. The ranking scheme for Guam is shown below. The rank value of '0' is the land area of the island.

Reef Fish Biomass in Guam	Rank Value
0	0
≤ 12.5	3
≤ 13.8	4
≤ 68.9	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.

Guam Marine Index Distribution

Marine Index Break Values	0 - 3	4 - 8	9 - 10	11 - 18
Final Rank Value	1	2	3	4

E.3 Calculating the Fish and Wildlife Index

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

Guam Fish and Wildlife Index Distribution

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

Using a quantile distribution, the Fish and Wildlife Index was reclassified into 6 classes 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 generally followed to model Resilience Hubs in Guam; however, regionally-specific modifications were applied as follows. Due to the relatively small size of Guam, a smaller area threshold of approximately 4 hectares (10 acres) was used to generate habitat cores in Guam. Additionally, a 0.25-km buffer was applied when calculating the average Community Exposure Index values for each Blue and Green Habitat Core as opposed to the 1-km buffer used in other regions.

To rank the Green Habitat Cores a distance factor was applied to each Green Habitat Core, which prioritized those open, natural landscapes nearest to community assets. To accomplish this, Euclidean distance was calculated to determine the distance between each Green Habitat Core and surrounding community assets. In addition to determining the proximity of Green Habitat Cores to assets, the average density of nearby community assets was also calculated. The average calculated density and distance of nearby community assets to each habitat core was then considered in combination with the average scores from the Fish and Wildlife and Community Exposure Indices to calculate the rank for each Green Habitat Core.

This approach was not taken with the Blue Habitat Cores, which are already scored using presence of and proximity to valuable marine habitats including live coral cover, seagrass beds, beaches, and tidally influenced coastal wetlands including mangroves.

G. Stakeholder Engagement

To allow local stakeholders to review and provide input on preliminary Assessment products, the Project Team hosted a virtual stakeholder workshop including a series of three meetings held over the week of March 15, 2021. All invited stakeholders had access to written materials and an online GIS viewer to review draft models and provide comments during and after the workshop. The following list includes all organizations invited to participate in the stakeholder workshop.

East-West Center
Guam Bureau of Statistics and Plans, Coastal Management Program
Guam Bureau of Statistics and Plans, Coral Reef Initiative
Guam Department of Agriculture, Biosecurity Division
Guam Department of Agriculture, Division of Aquatic and Wildlife Resources
Guam Department of Agriculture, Forestry & Soil Resources Division
Guam Department of Land Management
Guam Department of Park and Recreation, Historic Resources Division
Guam Environmental Protection Agency
Guam Homeland Security, Office of Civil Defense
Guam Preservation Trust
Guam Waterworks Authority
National Oceanic and Atmospheric Administration
Pacific Islands Ocean Observing System
Port Authority of Guam
U.S. Army Corps of Engineers
U.S. Department of Agriculture
U.S. Environmental Protection Agency
U.S. Federal Emergency Management Agency
U.S. Fish and Wildlife Service
U.S. Geological Survey
University of Guam