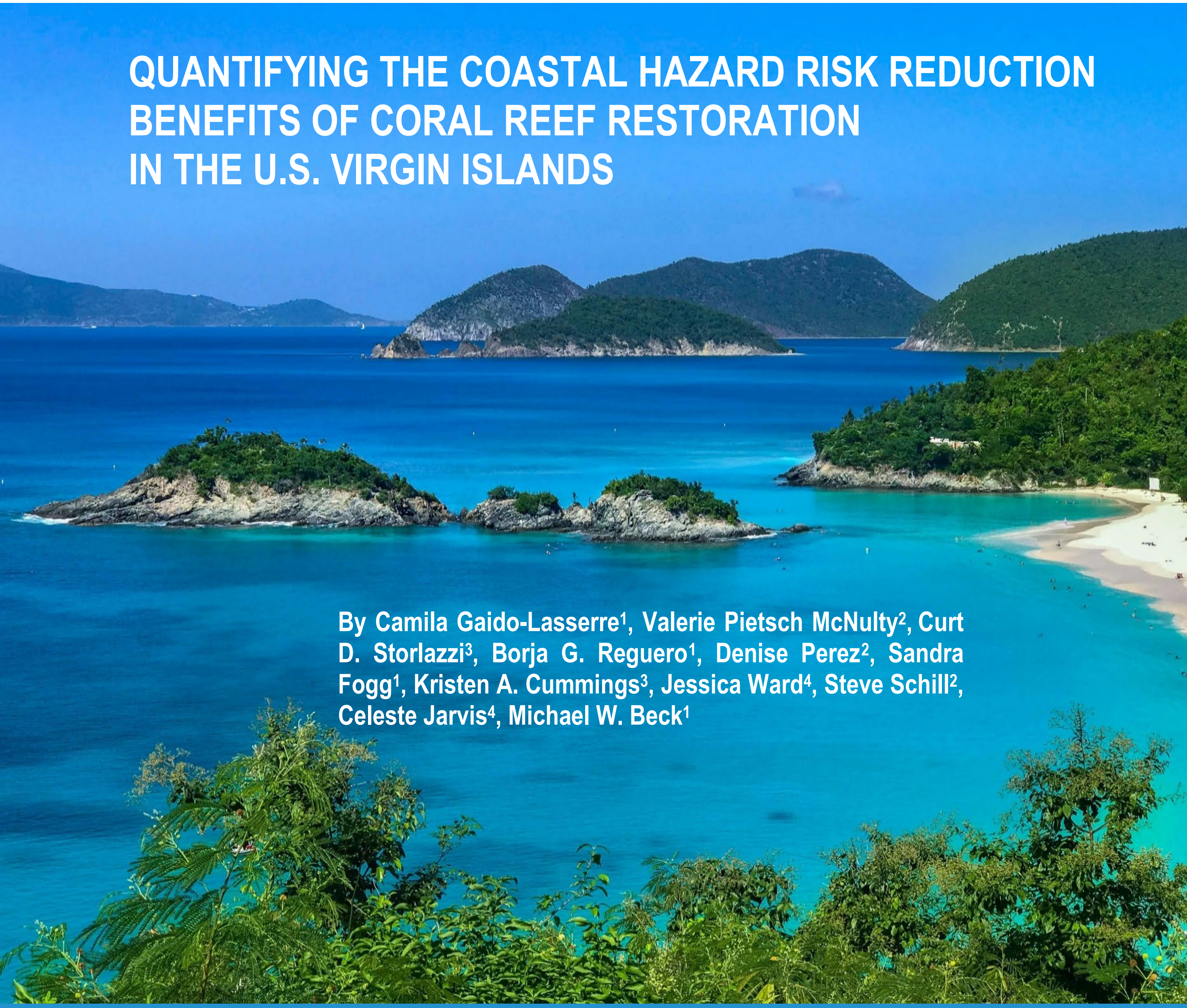

QUANTIFYING THE COASTAL HAZARD RISK REDUCTION BENEFITS OF CORAL REEF RESTORATION IN THE U.S. VIRGIN ISLANDS

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CONVERSION FACTORS

U.S. customary units to International System of Units

Multiply	By	To Obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
Area		
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)

ABBREVIATIONS

BCA	Benefit-to-Cost Analyses
BCR	Benefit-to-Cost Ratio
DSAS	Digital Shoreline Analysis System
EAB	Expected Annual Benefit
EAD	Expected Annual Damage
FEMA	Federal Emergency Management Agency
GEV	General Extreme Value
GOW	Global Ocean Wave
GDP	Gross Domestic Product
HAZUS	Federal Emergency Management Agency database
NBS	Nature-Based Solutions
NOAA	National Oceanic and Atmospheric Administration
PAEK	Polynomial Approximation with Exponential Kernel
SBC	Smoothed Baseline Cast
SWAN	Deltares 2-dimensional short wave model
UCSC	University of California at Santa Cruz
USFWS	U.S. Fish and Wildlife Service
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USVI	U.S. Virgin Islands
XBeach	Deltares 2-dimensional short and long wave and flow model

VARIABLES

c_f	Friction coefficient for currents and infragravity wave friction
f_w	Friction coefficient for incident waves

ABSTRACT

Coastal habitat restoration, especially of coral reef ecosystems, can significantly reduce the exposure of coastal communities to natural hazards and, consequently, the risk of wave-driven flooding. Likewise, reef degradation can increase coastal flood risks to people and property. In this study, the valuation of coral reefs in the United States Virgin Islands (USVI), along the coasts of St. Croix, St. John, and St. Thomas, demonstrated the social and economic benefits provided by these natural defenses. Across the territory, more than 481 people and $31.2 million of infrastructure were estimated to receive protection from coral reefs per year (2010 U.S. dollars). In 2017, Hurricanes Irma and Maria significantly damaged coral reefs throughout the archipelago. By combining engineering, ecological, geospatial, social, and economic data and tools, this study provided a rigorous valuation of where potential coral reef restoration projects could help rebuild these damaged habitats and decrease the risks from coastal hazards faced by USVI's reef-fronted communities. Multiple restoration scenarios were considered in the analysis, two of which are detailed in this report. These include (1) 'Ecological' restoration, where restoration creates a structure that is 0.25 m high and 25-m-wide reef, and (2) 'Hybrid' restoration, where restoration creates a structure that is 1.25 m high and 5 m wide. There are many ways that such structures could be developed. In the hydrodynamic analyses, there are no assumptions about how the restoration is developed. Many practitioners of both coral (and oyster reef) restoration consider that a reef height of 0.25 m might be delivered from planting corals alone and that 1.25 m might require a combination of artificial structures and coral planting. In a third scenario, the analysis investigated the reduction of protection benefits that would occur through the reduction of 1 meter of naturally occurring reef height due to reef degradation. The reduction of protection due to the loss of reefs can also be interpreted as the protection value of the existing reefs.

In all studied restoration scenarios, it was assumed that the planting of corals would enhance hydrodynamic roughness, effectively dissipating incident wave energy and reducing the potential for coastal flooding. A standardized approach was employed to strategically locate potential restoration projects along the entire linear extent of existing reefs bordering the USVI, and to identify where coral reef restoration could offer valuable benefits in flood reduction. Potential restoration projects were only located within the existing distribution of reefs across the region, even though numerous sites were positioned far offshore (2-3 km), and some were at relatively deep depths (up to 7 m). Risk-based valuation approaches were followed to delineate flood zones at a 10 m^2 resolution along the entire region's reef-lined shorelines for all the potential coral reef restoration scenarios. These were subsequently compared to flood zones without coral reef restoration.

The potential reduction in coastal flood risk provided by coral reef restoration, and the protection value of existing reefs, were quantified utilizing the latest information available at the time of analysis from the U.S. Census Bureau, Federal Emergency Management Agency (FEMA), and Bureau of Economic Analysis for return-interval storm events. The change in Expected Annual Damages (EAD), a metric indicating the annual protection gained due to coral reef restoration, was calculated based on the damages associated with each storm probability. The findings suggest that the benefits of reef restoration are spatially variable within the USVI. In some areas, the analysis showed limited benefits from reef restoration, which may be attributed to the depth or offshore distances of proposed restoration sites. However, there were a number of key areas where reef restoration could have substantial benefits for flood risk reduction.

The annual flood risk reduction attributed to potential 'ecological' coral reef restoration in the USVI was 99 people and $6.1 million (2010 U.S. dollars). The Benefit-to-Cost Ratio (BCR) for this restoration approach was found to be larger than 1 (i.e., cost-effective) along 11% of the St. Croix coastline, 4.9% of the St. John coastline, and 8.7% of the St. Thomas coastline. This analysis offers stakeholders and decision-makers a spatially explicit and rigorous

evaluation that illustrates how, where, and when potential coral reef restoration efforts in St. Croix, St. John, and St. Thomas could be instrumental to reducing coastal storm-induced flooding. Understanding areas where reef management, recovery, and restoration could effectively reduce climate hazard-related risks is crucial to protect and enhance the resilience of coastal communities in USVI.

INTRODUCTION

Thousands of vulnerable coastal communities around the world are impacted by coastal flooding and erosion resulting from extreme weather events. Forecasts indicate that the severity of coastal flooding is only expected to increase in this century, exacerbated by the combined effects of population growth and climate change (Hallegatte et al., 2013; Hinkel et al., 2014; Reguero et al., 2015, 2018; Storlazzi et al., 2018). Coral reefs can substantially diminish coastal flooding and erosion by dissipating up to 97% of incident wave energy (Ferrario et al., 2014). Reefs function like low-crested structures, such as breakwaters, with hydrodynamic behavior well characterized by coastal engineering models (Hoeke et al., 2011; Taebi and Pattiaratchi, 2014; Reguero et al., 2018). In a previous study, a process-based, high-resolution, non-linear model that estimated the coastal protection benefits provided by coral reefs was established for all populated U.S. reef-lined coasts (Reguero et al. 2021). The model mapped the natural defense benefits of reefs at a resolution relevant to management scales, offering a framework to thoroughly assess the valuation of people and property protected by coral reefs under various current and future climate scenarios (Storlazzi et al., 2019, Reguero et al., 2021). This approach was then applied at a finer scale to Puerto Rico and Florida, and it provided the framework for this current study (Storlazzi et al., 2021).

Due to the hazard risk reduction benefits provided by coral reefs, there is growing interest in restoring reefs and other natural infrastructure as a tool to reduce flood risks and enhance the resilience of tropical coastal communities (Beck and Lange, 2016). Coral reef restoration aims to recover habitats and/or coral populations that have suffered losses or damage due to storms or human activities, and it can also fortify resilience against future disturbances. Hurricane Irma struck the U.S. Virgin Islands (USVI) as a Category 5 storm in 2017, leaving widespread damage and loss of lives. The impact was particularly severe on the islands of St. Thomas and St. John, where coastal communities bore the brunt of the destructive force. St. Croix faced substantial damage as well, with 70% of homes and structures affected by the storm (Cangialosi et al., 2018). The damages intensified when Hurricane Maria followed 10 days later, compounding the impacts with additional fatalities and extensive flooding and mudslides. Storm surges in the region ranged from 2 to 3 m. The combined aftermath of these hurricanes throughout the eastern Atlantic resulted in thousands of casualties and inflicted over $90 billion in damages across the Caribbean, casting an enduring impact on the communities of the U.S. Virgin Islands (Pasch et al., 2018). In regions like these, where storms such as Hurricane Irma and Maria caused extensive damage to reef ecosystems and property, habitat restoration is imperative to rebuild ecosystems, strengthen natural resilience, and protect coastal communities from future climate hazards.

Acknowledgment of the role of coral reefs in natural resilience is becoming more prevalent in coastal areas worldwide and has led to an increase in funding for such initiatives. In June of 2023, FEMA provided the first-ever hazard mitigation funding for coral reef restoration to Puerto Rico. Approximately $38.6 million was issued under the Hazard Mitigation Grant Program (HMGP) to rebuild coral ecosystems damaged by Hurricanes Irma and Maria (FEMA, 2023b). Later in the year, the USVI paved the way toward more funding opportunities through the official governmental recognition of the significance of reefs as natural infrastructure. Infrastructure eligible for FEMA recovery funding has historically only included gray infrastructure. However, on 26 October 2023, the U.S. Coral Reef Task Force (USCRTF) and the Office of the Governor of the USVI passed a resolution declaring coral reefs within U.S. states and territories as part of the national infrastructure. With this new distinction, federal funding can now more easily be granted to post-disaster recovery efforts that prioritize reef restoration to safeguard communities and assets, mitigate hazards, and build resilience against future events. This shift in policies and allocations of funding recognizes the importance of NBS and illustrates the momentum toward adopting NBS for climate resilience (Executive Order 533, 2023).

In addition to the protection benefits, reef restoration, whether fully ecological or hybrid in nature, can also be cost-effective for flood reduction. In a recent study of over 20 Caribbean countries, the BCR was greater than 1 (i.e., cost-effective) for reef restoration projects, meaning that the economic benefits of restoration outweigh the costs (based on flood reduction benefits alone) and indicating the value of NBS for risk reduction. Over the course of project lifetimes, it is estimated that restored natural infrastructure can provide $100,000s per hectare in flood protection benefits (Beck et al. 2022). This cost-efficient restoration can be implemented with a fully ecological approach (coral planting) or through a hybrid strategy that employs both an engineered structure and live corals to improve the reef morphology.

Extant reefs offer solid benthic substrate and vertical structure, enabling ecological (green) restoration through the planting of corals to increase the density or abundance of live corals (Shaver and Silliman, 2017; Boström-Einarsson et al., 2020). This form of restoration typically requires the collection and rehabilitation of naturally fragmented corals, colony propagation, or the relocation of live individuals (Bayraktarov et al., 2019). The general goal of ecological restoration is to repopulate corals in areas where populations have been diminished or lost in a manner that allows self-perpetuation and attraction of the species that are essential to ecological processes on reefs (Lirman and Schopmeyer. 2016; Ladd et al., 2018). Structural or "gray" restoration generally involves the development of artificial reefs using existing rocks/dead coral heads or the deployment of constructed metal or concrete forms. The goal is to increase the amount of reef structure and habitat available for the corals and other reef organisms to grow on. Structural restoration is required in areas where the reef has been lost due to long-term bioerosion of the reef or physical damage such as vessel grounding. These structures can then either be 'seeded' through natural coral recruitment or, more commonly, planted with corals or coral fragments to facilitate and speed development, which is a "gray-green" hybrid form of restoration.

As part of the federal government's recovery and restoration efforts following Hurricanes Irma and Maria, several key partners convened to understand if damaged reefs could be restored to (re)deliver hazard mitigation benefits. These partners included the National Oceanic and Atmospheric Administration's (NOAA), Coral Restoration Center, the Department of the Interior (USFWS, USGS), FEMA, The Nature Conservancy (TNC), and the University of California Santa Cruz. FEMA, which is required to conduct Benefit-to-Cost analyses (BCAs) to justify post-disaster funding, would need such BCAs to release funding for coral reef restoration aimed at coastal hazard risk reduction. To address this need, the U.S. Geological Survey (USGS), the University of California Santa Cruz (UCSC), and NOAA worked together to assess and quantify, in social and economic terms, how the potential restoration of ecological or hybrid coral reefs of the coasts of USVI could reduce the threats to, and increase the resiliency of, their coastal communities under the 2017 Hurricane and Wildfire Supplemental.

METHODOLOGY

Using a risk quantification valuation framework to understand the annual risk reduction and socioeconomic benefits that coral reefs provide, this effort aims to understand exactly where, when, and how coral reef restoration can maximize social and economic benefits to coastal communities (Storlazzi et al., 2019, 2021, Viehman et al. 2023). Oceanographic, coastal engineering, ecological, geospatial, social, and economic data and tools were utilized to quantify the increase in coastal protection benefits resulting from potential coral reef restoration. This study expands previous research conducted by the USGS, UCSC, and NOAA, furthering the comprehensive evaluation of the effectiveness of coral reef restoration in reducing coastal hazard risks to the USVI coastline (Figure 1). Through high-resolution flood modeling and damage calculations, methods similar to those used by FEMA and U.S. Army Corps of Engineers (USACE), the risk reduction benefits provided by potential reef restoration in St. John, St. Thomas, and St. Croix were estimated. The stepwise methodology is taken from Reguero et al. (2021) and Storlazzi et al. (2021), based on previous analyses developed for assessing coastal risk and the role of natural infrastructure; this approach integrates physics-based hydrodynamic modeling, quantitative geospatial analysis, and assessments of the social and economic impacts to quantify the hazard. It evaluates the effect of coral reef restoration in reducing coastal flooding hazards and analyzes the resulting economic and social implications (Figure 2).

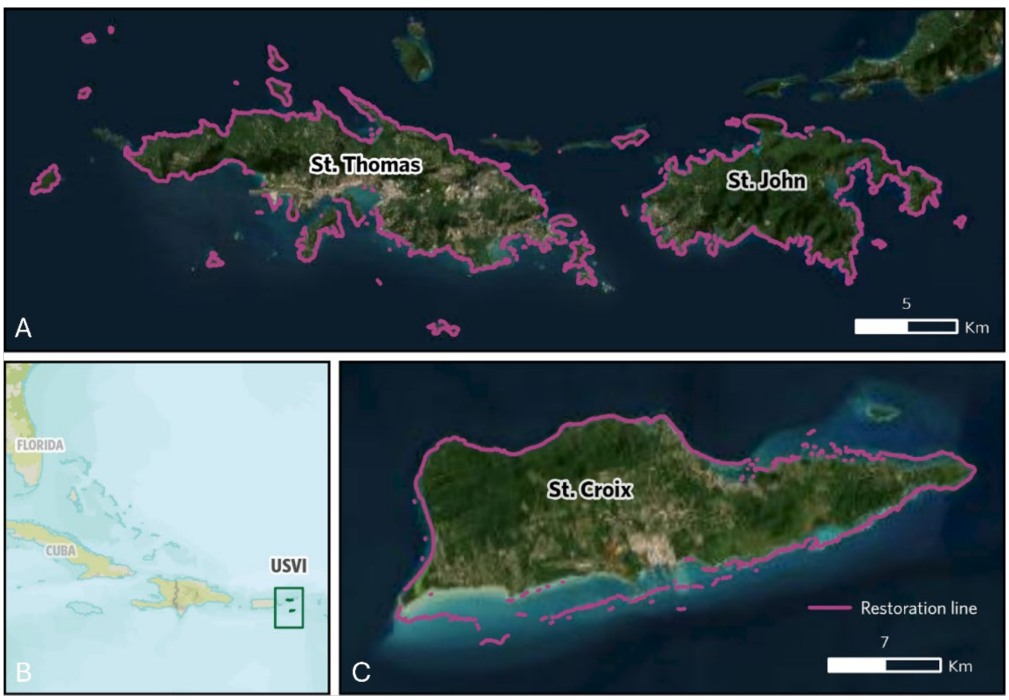

Figure 1. Map indicating the location of the study areas in the U.S. Virgin Islands (B): St. Thomas and St. John (A), and St. Croix (*C*) and the spatial location of the restorations (restoration line). Satellite image extracted from Esri, Maxar, Earthstar Geographics, and the GIS User Community.

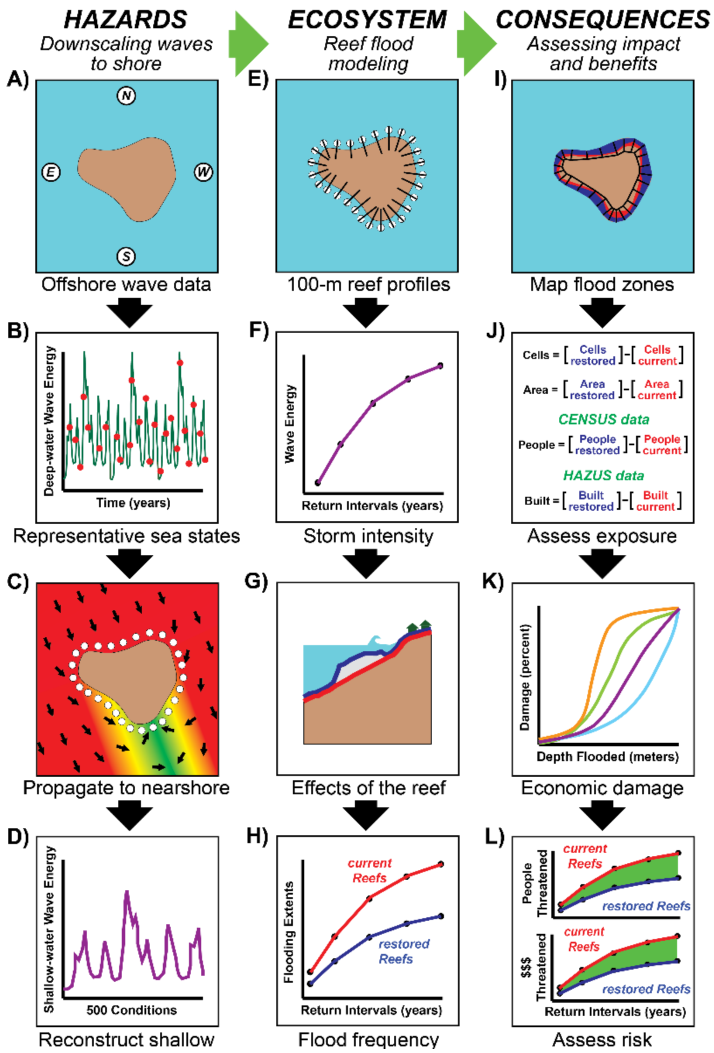

Figure 2. Schematic diagram demonstrating the methodology used to evaluate the decrease in coastal flooding hazard risk due to coral reef restoration from Storlazzi et al. (2021). Each step is described in more detail in the methodology section.

Projecting the Coastal Hazards

Sixty-one years (1948–2008) of validated long-term, hourly hindcast deep-water wave data were extracted from the Global Ocean Wave (GOW) database (Reguero et al., 2012) for the area of USVI. Following the methodology of Camus et al. (2011), more than half a million hourly data points on wave climate parameters were propagated to the nearshore shore using a hybrid downscaling approach. The offshore wave climate data were synthesized into 500 combinations of sea states (wave height, wave periods, and wave directions) that best represented the range of conditions from the GOW database. These selected sea states were then propagated to the coast using the physics-based Simulating Waves in the Nearshore (SWAN) spectral wave model (Booij et al., 1999; Ris et al., 1999; Delft University of Technology, 2016), which simulates wave transformations nearshore by solving the spectral action balance equation (Figure 2.C). Wave propagation around reef-lined islands has been accurately simulated using SWAN (Hoeke et al., 2011; Taebi and Pattiaratchi, 2014; Storlazzi et al., 2015). Standard SWAN settings were used (for example, Hoeke et al., 2011; Storlazzi et al., 2015), except that the directional spectrum was refined to 5-degree bins (72 total) to better simulate refraction and diffraction in and amongst islands (Appendix 1).

To accurately model from the scale of the island groups or large sections of coastline (order of 10s of km) down to management scales (order of 100s of m), a series of two dynamically downscaled nested, rectilinear grids were used. The coarse (1-km resolution) SWAN grids provided spatially varying boundary conditions for finer-scale (200-m resolution) SWAN grids (Figure 3). The bathymetry for the SWAN grids was generated by grid-cell averaging of various topobathymetric digital elevation (DEM) models (Appendix 2). The propagated 500 shallow-water wave conditions from the finest SWAN grids were extracted at 100-m intervals along the coastline, at a water depth of 30 m, and then reconstructed into hourly time series using multidimensional interpolation techniques (Camus et al., 2011).

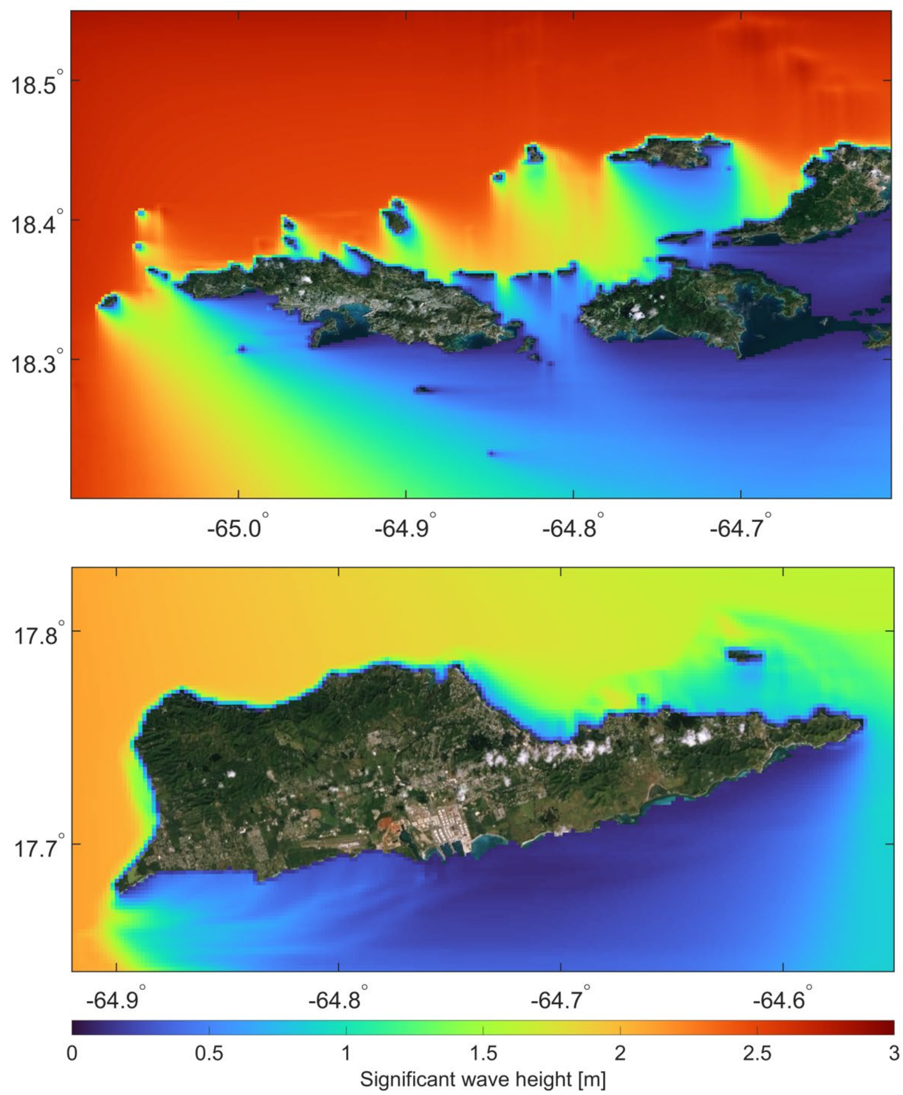

Figure 3. Maps showing an output example of the SWAN model and how one of the 500 wave conditions was dynamically downscaled to the 200-meter (m) grid-scale offshore of St. Thomas, St. John (upper panel), and St. Croix (lower panel). Colors indicate significant wave height in meters. Satellite image extracted from Microsoft Bing Maps.

Evaluating the Role of Coral Reefs in Coastal Protection

Benthic habitat maps defining coral reef spatial extent and coral cover percentage (Appendix 3) were used to delineate the location of nearshore coral reefs and their relative coral abundance along the reef-lined shorelines (Figure 4. Cross-shore transects were created every 100 m alongshore (Appendix 4) using the Digital Shoreline Analysis System (DSAS) software version 4.3 in ArcGIS version 10.3 (Thieler et al., 2009). Transects were cast in both landward (topography) and seaward (bathymetry) directions using the smoothed baseline cast method with a 500-m smoothing distance, perpendicular to a baseline that was generated from coastlines digitized from USGS 1:24,000 quadrangle maps and smoothed in ArcGIS using the polynomial approximation with exponential kernel algorithm and a 5,000 m smoothing tolerance (Figure 2.E). Transects varied in absolute length to ensure each intersected the −30 m and +20 m elevation contours. The bathymetric (Appendix 5) and coral coverage (Appendix 3) data were extracted along these shore-normal transects at a grid-cell cross-shore resolution of 1 m.

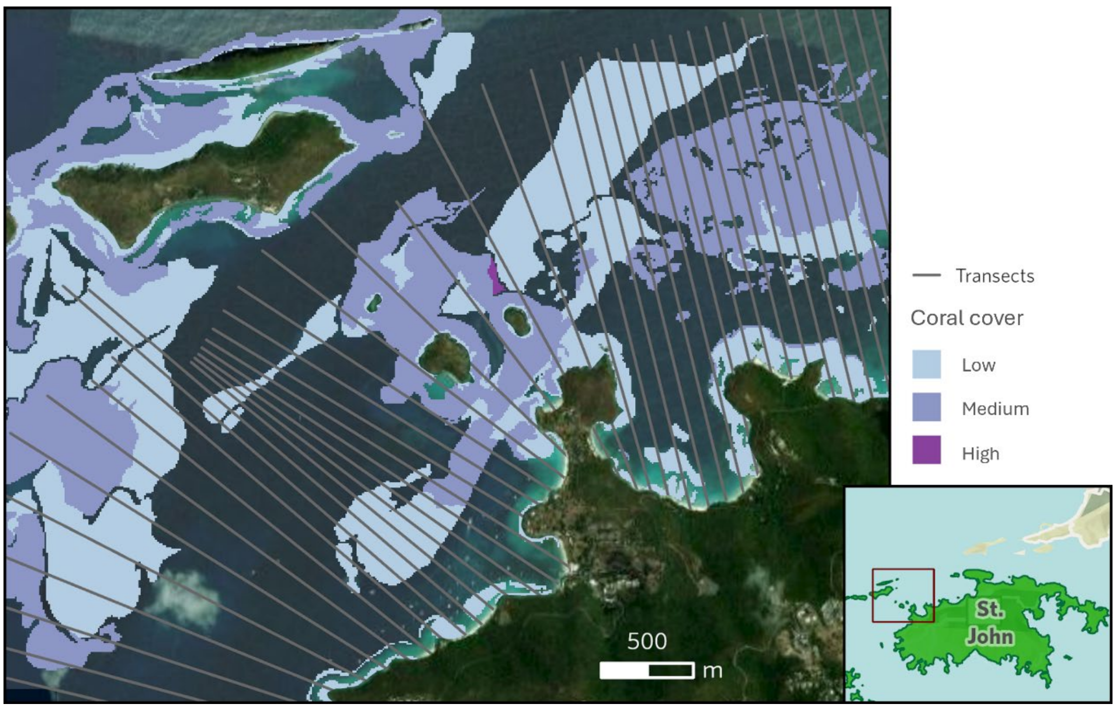

Figure 4. Example map showing live coral cover offshore of St. John, U.S. Virgin Islands. Colors patches indicate the coral coverage classification; gray lines show cross-beach transects at 100-meter (m) intervals. Satellite image extracted from Esri, Maxar, Earthstar Geographics, and the GIS User Community.

The nearshore wave time series (hourly data from 1948 to 2008) were fit to a General Extreme Value (GEV) distribution (Méndez et al., 2006; Menéndez and Woodworth, 2010) to obtain the significant wave heights associated with the 10-, 50-, 100-, and 500-year storm return periods (Figure 2.F). The corresponding 10-, 50-, 100-, and 500-year storm return period extreme water levels for a given location were taken from the nearest NOAA tidal station (NOAA, 2017), which includes the effects of historical tropical cyclones.

The significant wave heights and peak periods associated with each storm return period and with the corresponding return-value sea levels were then associated with the corresponding 100-m spaced shore-normal transects and propagated over the coral reefs (Appendix 4) using the numerical model XBeach (Roelvink et al., 2009;

Deltares, 2016), as demonstrated in Figure 2.G and Figure 4. XBeach solves for water-level variations up to the scale of long (infragravity) waves using the depth-averaged, non-linear shallow-water equations. The forcing is provided by a coupled wave action balance in which the spatial and temporal variations of wave energy due to the incident-period wave groups are solved. The radiation stress gradients derived from these variations result in a wave force that is included in the non-linear shallow-water equations and generates long waves and water level setup within the model. Although XBeach was originally derived for mild-sloping sandy beaches, with some additional formulations, it has been applied in reef environments and proved to accurately predict key reef hydrodynamics (Pomeroy et al., 2012; van Dongeren et al., 2013; Quataert et al., 2015; Storlazzi et al., 2018).

XBeach was run for 3,600 s in one-dimensional hydrostatic mode along the cross-shore transects at a varying resolution ranging from 10 m in seaward locations to 1 m in more landward locations (resolution varies depending on depth); the runs generally stabilized after 100–150 s and thus generated good statistics on waves and wave-driven water levels for more than 50 minutes (Appendix 6). The application of a one-dimensional model neglects some of the two-dimensional dynamics that occur on natural reefs, such as lateral flow. However, it does represent a conservative estimate for infragravity wave generation and wave runup, as the forcing is shore normal and expected to be an overestimation. As stated above, the choice is warranted in this case because the observations show near-normally offshore waves (such as wave propagation modeled with SWAN).

The additional formulations that incorporate the effect of higher bottom roughness on incident wave decay through the incident wave friction coefficient (f_w) and the current and infragravity wave friction coefficient (c_f), as outlined by van Dongeren et al. (2013), were applied. The friction induced by corals was parameterized per Storlazzi et al. (2019) based on the spatially varying coral coverage data and results from a meta-analysis of wave-breaking studies over various reef configurations and friction coefficients for the different coral coverages (for example, van Dongeren et al., 2013; Quataert et al., 2015). Coral coverage classes, as established by the benthic habitat maps, were assigned f_w and c_f (Table 1) over the spatial extent of the reef along the profile (Appendix 3). Profiles of total water levels (setup plus runup) at each grid cell over the profiles were then extracted to define the wave-driven flooding along each of the profiles.

Table 1. Wave and current friction coefficients for different coral coverage classification as determined from benthic habitat maps.

Coral Coverage classification	**Wave Friction Coefficient (f_w)**	**Current and Infragravity Wave Friction Coefficient (c_f)**
None (sand)	0.10	0.01
Low	0.15	0.07
Medium	0.30	0.10
High	0.45	0.13

<u>Reef Scenarios</u>

In collaboration with stakeholders, scientists, and decision-makers, two generalized restoration scenarios and one degradation scenario were developed and compared with the ‘current state’ of the reefs (‘baseline’), per Storlazzi et al. (2021). The scenarios modeled included:

1. **‘Ecological’ Restoration**. The restoration of a reef structure that is 0.25 m high and 25 m wide. It is assumed by many practitioners that such a structure could be achieved solely by planting corals on preexisting underwater terrain over a distance of 25 m in the cross-shore direction (horizontal

width of restoration), represented by +0.25 m increase in height and 0.45 and 0.13 increases in friction coefficients for f_w and c_f, respectively (Table 1), owing to the presence of the corals over the 25-m-wide extent. To predict project costs, it was assumed that this scenario would require coral planting only.

2. **'Hybrid' Restoration.** The restoration of a reef structure that is 1.25 m high and 5 m wide. It is assumed by many practitioners that such a structure would require a mix of artificial structure and coral planting. Increases in friction coefficients of 0.45 and 0.13 for f_w and c_f (Table 1), respectively, were assumed, owing to the presence of the corals over the 5-m-wide extent. To predict project costs, it was assumed that this scenario would require coral planting, the emplacement of a 1-m-high solid structure, and coral planting on top of the structure.
3. **Reef Degradation ('No Reef')**. The reduction of the reef elevation by 1 m (increasing the water depth) across the reef extension. Friction coefficients were decreased to the none coral coverage classification from Table 1.
4. **Current State ('Baseline')**. Friction coefficients were derived from live coral coverage data (Appendix 3) based on Table 1, and elevation was based on bathymetry datasets (Appendix 5).

The development of the reef restoration scenarios considered (i) the likelihood of delivering flood reduction benefits, (ii) existing coral restoration practices, and (iii) permitting factors such as depth for potential navigational hazards. An algorithm, subject to the following conditions, was developed and utilized to place restoration scenarios along the length of the reef. Restoration line placements (along and across the shore) were determined based on the presence of continuous coral/hardbottom habitat exceeding 100 m alongshore and proximity to the 3-m depth contour. The ArcGIS simplify line tool was employed to generate a general 3-m depth contour, which was then clipped to the existing coral/hardbottom extent from benthic habitat maps. A 25-m buffer was applied and manually edited to ensure that the restoration areas were entirely within the coral/hardbottom footprint. Operational considerations dictated that restoration locations were not established shallower than the 2-m contour or deeper than the 7-m contour. Additionally, restoration locations were positioned as close to the shore as possible on continuous coral/hardbottom habitat. Restoration sites were not designated in areas with a length alongshore less than 100 m (spanning two cross-shore profiles) or in the absence of coral or hardbottom along a cross-shore profile.

Evaluating the Role of Potential Coral Reef Restoration and Degradation in Coastal Protection

The wave and sea level conditions were then propagated using XBeach over the same 100-m spaced shore-normal transects modified to account for the identified coral reef scenarios (Figure 2.G).

Profiles of total water levels (setup plus runup) at each grid cell over the profiles were then extracted to define the wave-driven flooding along these cross-shore profiles with the influence of the different coral reef scenarios (Figure 5).

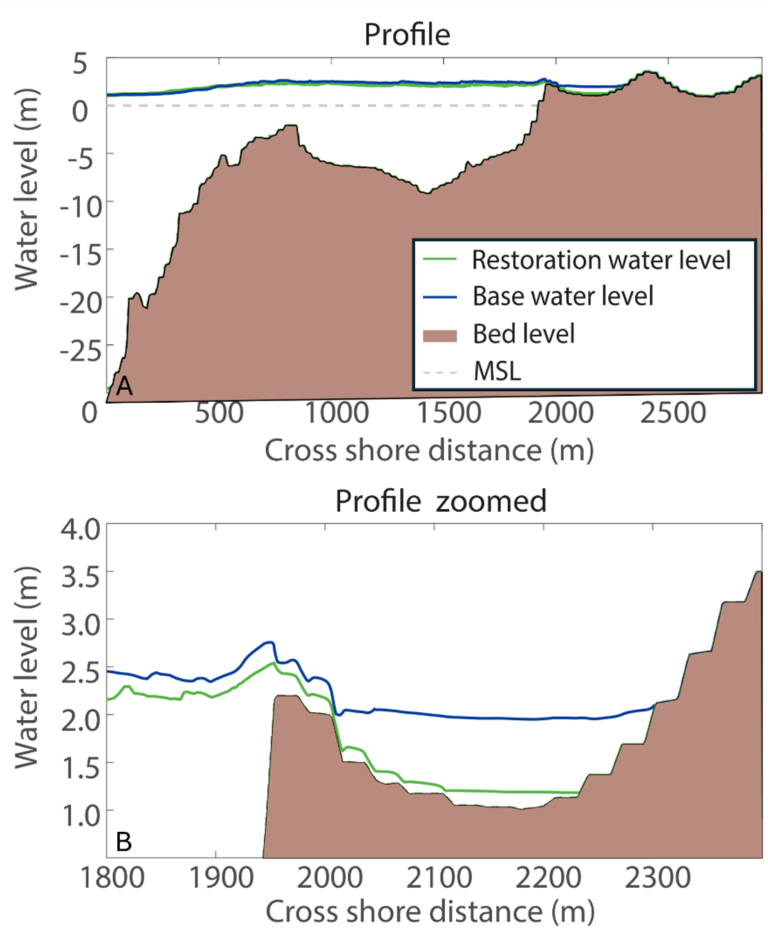

Figure 5. Plots of example topographic-bathymetric cross-sections and XBeach model wave-driven total water levels, in meters (m), during the 100-year storm for current reefs (base) and with restored reefs. *A*, Cross-shore profile with computed 'ecological' restoration and 'baseline' water levels. *B*, Zoomed-in view of A closer to shore. The black line denotes topography and bathymetry, the blue line the total water level (setup plus runup) with current coral reefs, and the green line the total water level with restored coral reefs. Note the high vertical exaggeration and the differences between the water levels of both scenarios (restoration benefits).

Quantifying the Social and Economic Benefits/Losses of Potential Coral Reef Restoration/Degradation

Wave-driven total water level depths and extents were then interpolated between adjacent shore-normal transects for the four return intervals (Figure 2.H) to develop flood mask layers for the total water levels for the four reef scenarios (Figure 2.I). The flood masks were derived by creating an interpolated flood surface raster with values representing absolute water level (flood depth + elevation) and then taking the difference between that surface and the elevation to calculate the corresponding water depth. The extent of the water depth raster defined the flood mask (Figure 6). Any pixels with a positive value were retained as flood-water depth (Figure 7).

The flood surface used to derive the flood masks was computed as the product of a natural neighbor interpolation of XBeach model flood points (points in space, with information on flood water depth and elevation along each transect spaced 100 m) and a distance-weighted multiplier between 0 and 1, calculated as an exponential function of distance from the flood extent along each transect. Within 50 m of the flooded section of each transect, the multiplier is equal to 1 (in application, retaining 100 percent of the interpolated flood value) and exponentially decreases to zero at a distance of 500 m (no flooding regardless of interpolated flood value). This method allowed for a more realistic flood zone to be created between transects while honoring the known flood extents. To correct areas of disconnected backshore pooling, any pixel regions that were discontinuous with the coastline were removed. The resultant raster was then converted to a polygon feature class and clipped by a land polygon feature class derived from the DEM (where values were greater than zero). Finally, to account for the stochasticity of XBeach model runs, the flood mask output polygons were put through a series of topological rules for the flooded pixels where for each scenario: 10-year return period < 50-year return period < 100-year return period < 500-year return period.

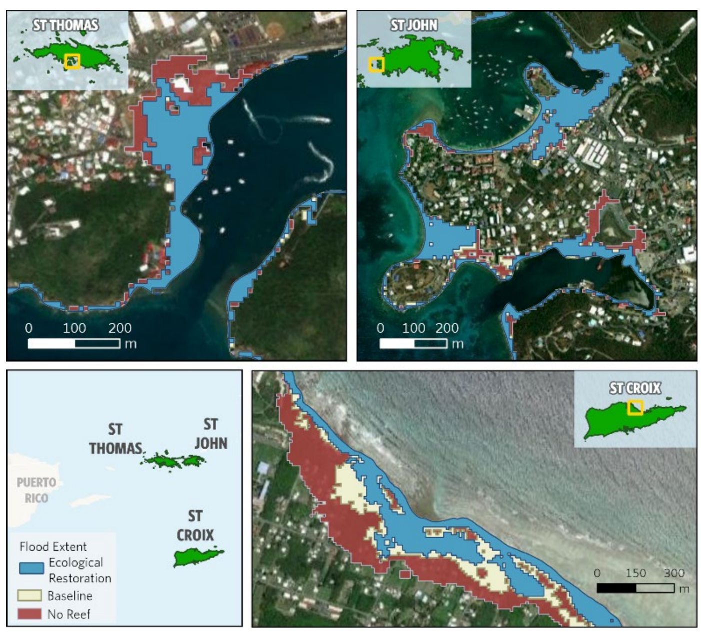

Figure 6. Map showing example 50-year floodplains under a 'No Reef,' 'baseline,' and 'ecological' restoration scenario. The regions protected by coastal flooding because of the coral reef restoration and the current reefs for the 50-year return-interval storm are therefore shown in the yellow and red bands, respectively. Satellite image extracted from NOAA, Maxar, Earthstar Geographics, and the GIS User Community, U.S. Virgin Islands GIS Division, Esri, TomTom, Garmin, Foursquare, SafeGraph, FAO, METI/NASA, USGS, NPS, USFWS.

Figure 7. Maps showing example 10-meter resolution flood depths for various storm recurrence intervals on St. Croix, U.S. Virgin Islands. *A*, 10-year storm. *B*, 50-year storm. *C*, 100-year storm. *D*, 500-year storm. Colors indicate flood-water depth, in meters, interpolated from adjacent XBeach model profile model transects spaced every 100 meters along the coast. Satellite image extracted from Esri, Maxar, Earthstar Geographics, and the GIS User Community.

The resulting number of people threatened, building damage, and indirect economic impact was then computed using the wave-driven flood depths. The number of people impacted by wave-driven flooding was determined by cross-referencing the flooded cells with the U.S. Census Bureau's (2016) TIGER database, as shown in Figure 8 (results are aggregated at the restoration line every ~100 m for easier visualization). The number of people at risk from flooding was calculated from the intersection between the flood depth raster and people per unit area. The built infrastructure impacted by wave-driven flooding was determined by cross-referencing the flooded cells with the Federal Emergency Management Agency's (2016) flood hazard exposure data in the HAZUS database (Scawthorn et al., 2006a, 2006b). The data were projected into each respective UTM Coordinate System (coordinate system from the transects belonging to that region).

For each type of HAZUS asset (e.g., different types of residential, commercial, and industrial buildings), a damage degree raster was created using the damage functions found in HAZUS (Figure 2.K) for the different categories of infrastructure following the methodology of Wood et al. (2013), as shown in Figure 9 (results are aggregated at the restoration line every ~100 m for easier visualization). These damage functions relate flood-water depth with the degree of damage (percentage of damage to each type of building). The damage degree raster was built from the flood depth raster where every cell represented the degree (or percent) of damage from flooding, with values ranging from 0.0 (no damage) to 1.0 (complete damage). Once the damage degree rasters were built, the economic value of the damage (in 2010 U.S. dollars) was calculated for each asset, in simple words, each building value per unit area was multiplied by the degree of damage. Similarly, the number and extent of flooded buildings were calculated by intersections between the flood depth raster and buildings (and specific building types) per unit area, as shown in Figure 9. Finally, building damage, number of flooded buildings, and people flooded were aggregated into summary points. The summary points were created as regularly 10-m spaced points within the union between all flood extents. Each point was assigned a transect ID and coral cover attribute based on the nearest transect.

Figure 8. Map showing the distribution of people protected from coastal flooding from the 'hybrid' coral reef restoration scenario for the 100-year storm in St. Thomas, U.S. Virgin Islands. Colors indicate the percentage of the population benefited by the reef restoration compared to the 'baseline' scenario, based on the U.S. Census Bureau's 2010 TIGER data. Satellite image extracted from Esri, Maxar, Earthstar Geographics, and the GIS User Community.

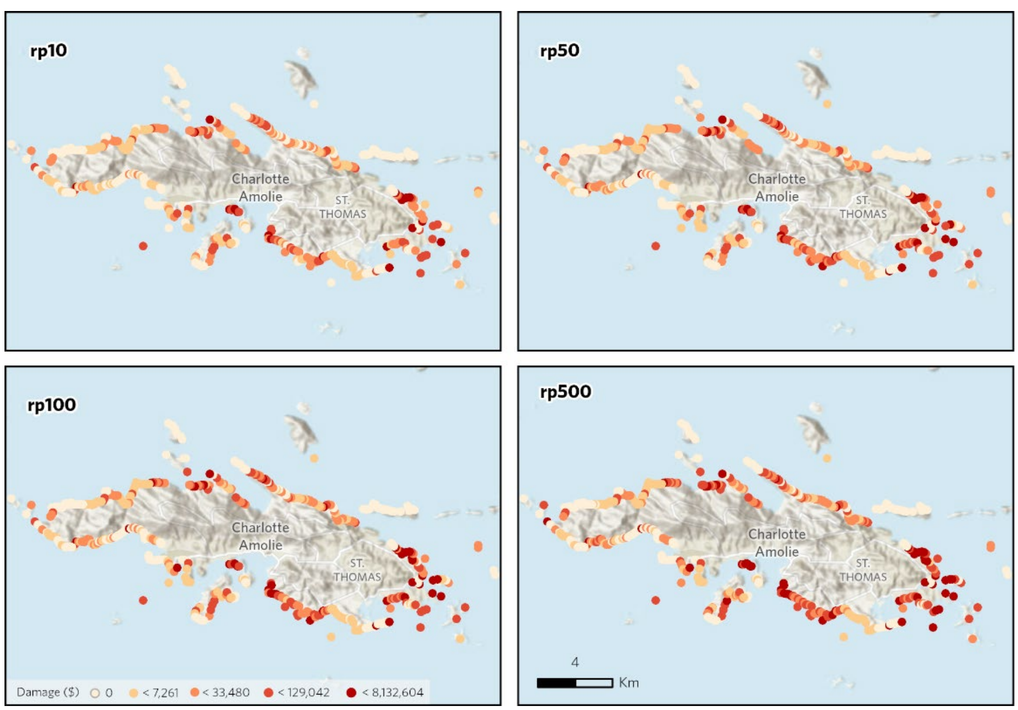

Figure 9. Map showing the value of infrastructure, in thousands of 2010 U.S. dollars, protected from coastal flooding from the 'hybrid' coral reef restoration scenario for the 100-year storm on St. Thomas, U.S. Virgin Islands. Colors indicate the total value of infrastructure, based on the Federal Emergency Management Agency's HAZUS data, in the area protected from flooding by the reef restoration. Satellite image extracted from Esri, NGA, USGS, U.S. Virgin Islands GIS Division, TomTom, Garmin, Foursquare, SafeGraph, FAO, METI/NASA, NPS, USFWS.

The value of the coral reef restoration in terms of decreased coastal hazard risk was then determined as the difference in people and infrastructure impacted by wave-driven flooding in the simulations for current coral reef conditions compared to those with the three coral reef scenarios (Figure 2.L). The calculated damages by infrastructure type were aggregated and summarized into tables (see results section) for each return period. The infrastructure was categorized into the types of general building stock that includes residential, commercial, industrial, agricultural, religious, government, and education buildings. Damage was estimated in percent and weighted by the area of flooding at a given depth for a given HAZUS census block. The entire composition of the general building stock within a given census block was assumed to be evenly distributed throughout the block.

A storm return period, t_i, also known as a recurrence interval, is the inverse of the probability of occurring and an estimate of the likelihood of such a storm event. For example, a 100-year return period of a flood represents a probability of the flood occurring in a given year of 1/100. The damages associated with the probability of occurrence characterize risk for the reef scenarios: current (no restoration) conditions and with the three coral reef restoration scenarios. The expected annual damage (EAD) is the frequency-weighted sum of damages for the full range of possible damaging flood events and is a measure of what might be expected to occur in a given year. The EAD was calculated from each damage curve (for each reef scenario, Figure 10) as:

$$EAD = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{t_i} - \frac{1}{t_{i+1}}\right)(D_i + D_{i+1}) \quad (1)$$

where:

EAD	is the frequency-weighted sum of damages for the full range of possible damaging flood events;
I	is the specific storm return period number;
n	is the total number of different storm return periods (in this case, *n* = 4);
t_i	is the storm return period, also known as the recurrence interval; and
D_i	represents the loss in the damage curve (Figure 2.L) for the probability of $1/T_i$, per Olsen et al. (2015).

The benefits were calculated as the difference in damages between the scenarios: current reefs and restored reefs (Figure 10). The expected annual benefits (EAB), a measure of the annual gain of protection provided coral reefs (or decreased exposure) owing to the projected restoration, is calculated as:

$$EAB = EAD_{restored} - EAD_{current}. \quad (2)$$

The EAB (Figure 11) was used to calculate the Present Value (PV) of the flood reduction benefits provided by each restoration. The present value was calculated over a 30-year project lifespan and at both a 2.8 and 7% discount rate. A 30-year lifespan is considered a conservative value for infrastructure projects. For example, FEMA uses a 50-year lifespan on flood infrastructure projects (FEMA, 2009).

The flood reduction benefits PV were divided by an estimated project cost to spatially calculate the Benefit-to-Cost ratio (BCR) of each restoration type (Figure 12). A cost of $1,500 USD and $3,057 USD per linear meter for the ‘ecological’ and ‘hybrid’ restoration were used, respectively. These restoration costs were estimated for two intervention types: direct outplanting of coral fragments to the substrate (i.e., ‘ecological’ restoration) and the use of artificial structures for constructing a ‘hybrid’ restoration. These costs were reported in units of USD per linear meter.

For the ‘hybrid’ reef scenario, the cost of artificial structures and the cost of deployment were included where available. However, pricing from the Ocean Rescue Alliance was only provided for the structure (Shelby Thomas, CEO from Ocean Rescue Alliance, written communication, 12 December 2022). Pricing for the SEAHIVE structure, a hexagonal concrete hybrid reef structure developed by the University of Miami, was estimated from reported manufacturing costs for six 6-m structures (Rhode-Barbarigos, 2022). For Reef Ball structures, the cost was based on the pallet module (0.8 x 1.2 m) and included deployment from prices advertised as of December 2022 (Reef Innovations, n.d.). Pricing information for artificial structures was biased to Florida, where labor and materials have a much higher cost than the rest of the Caribbean. At the time of this report, the USVI had yet to implement hybrid restoration. Therefore, comparable costs were retrieved from Grenada (Reguero et al., 2018), and four studies in the Caribbean reported for the Resilient Islands Project (TNC, 2019). More details on the restoration cost estimates can be found in Appendix 7. Due to the lack of maintenance costs for reef restoration projects, the values used only include the initial cost of the restoration project. The BCR provides a simple indication of return on investment, where a BCR > 1 is usually considered a cost-effective project.

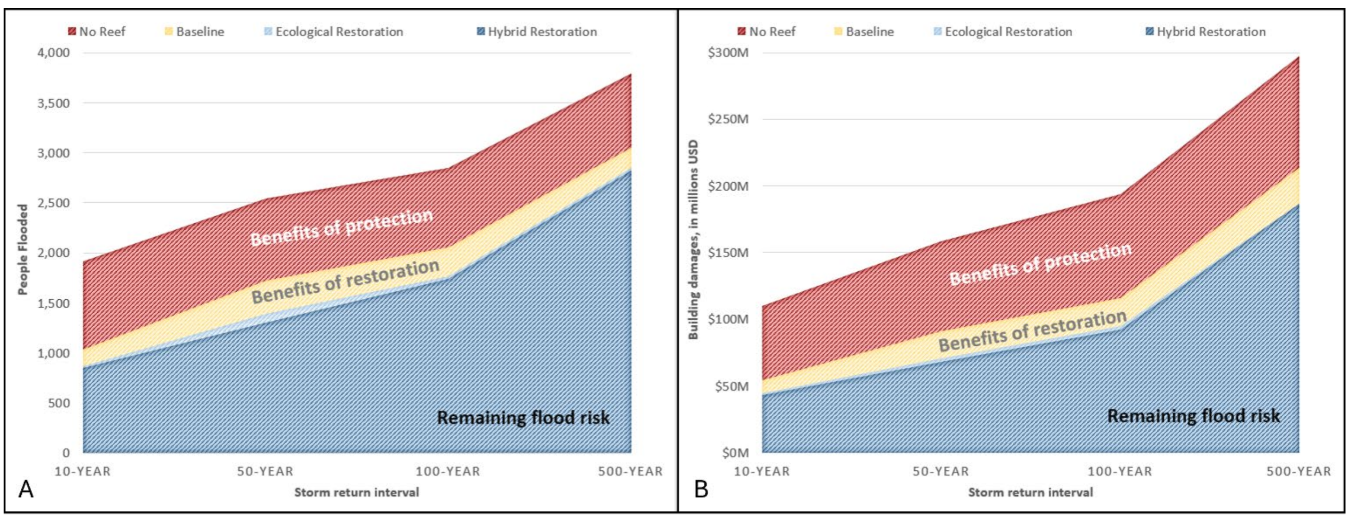

Figure 10. Example plots showing damage curves both with and without the coral reef restoration scenarios in the U.S. Virgin Islands. *A*, Number of people displaced by loss of housing from coastal flooding for the ‘ecological’ and ‘hybrid’ restoration scenarios. *B*, Values of damage to building by coastal flooding for the ‘ecological’ and ‘hybrid’ restoration scenarios. The differences between the scenarios denote the increased protection from coastal flooding owing to coral reef restoration and protection.

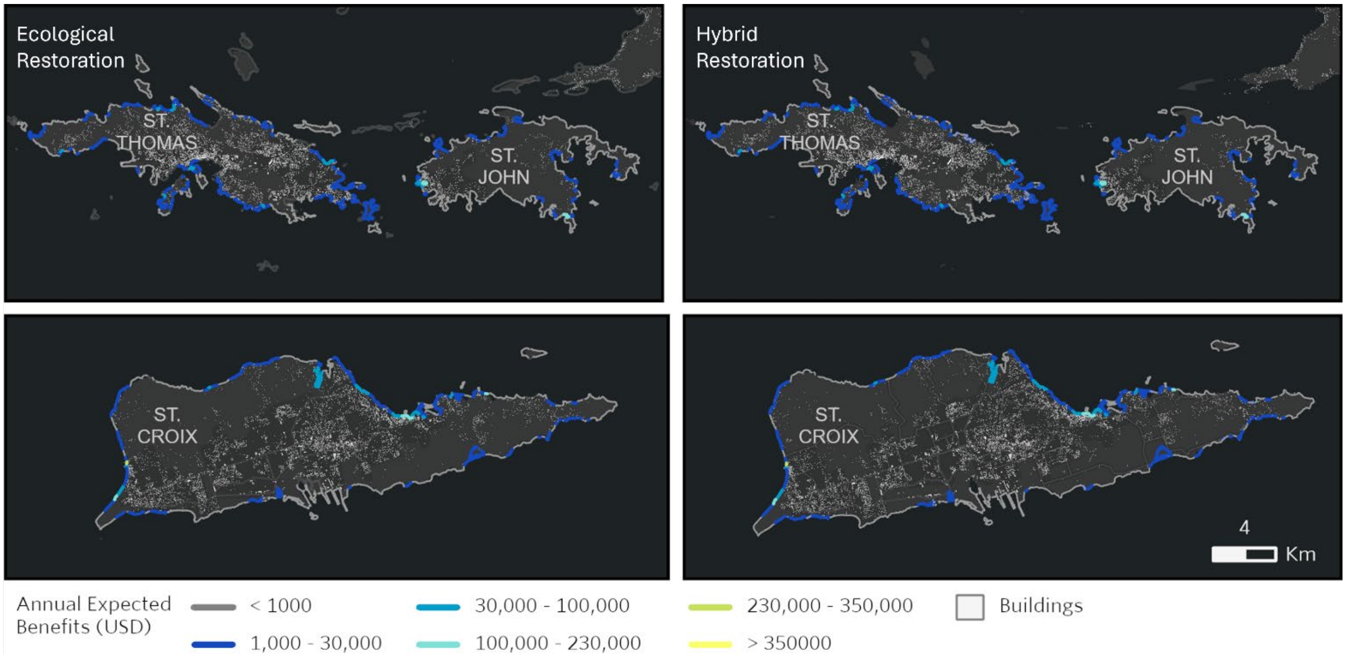

Figure 11. Spatial Expected Annual Benefits (EAB) for both the 'ecological' and 'hybrid' restoration scenarios. Satellite image extracted from U.S. Virgin Islands GIS Division, Esri, TomTom, Garmin, Foursquare, SafeGraph, FAO, METI/NASA, USGS, NPS, USFWS, Kadaster Netherlands.

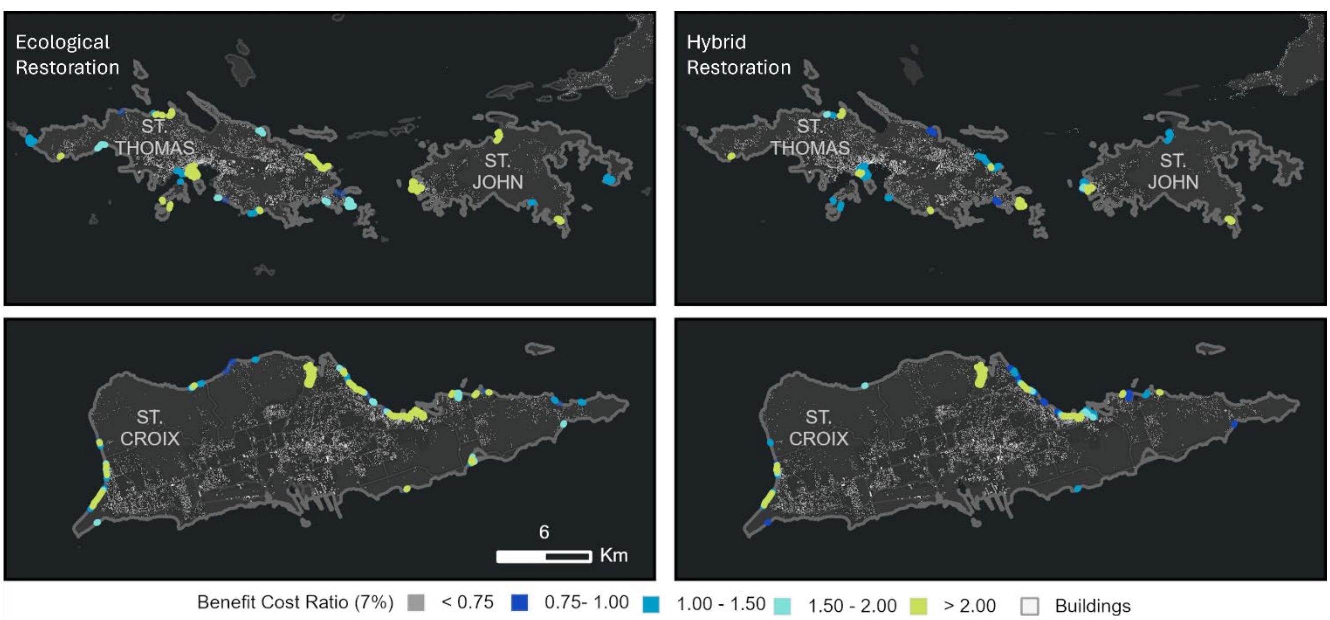

Figure 12. Spatial Benefit-to-Cost Ratio (BCR) for both the 'ecological' and 'hybrid' restoration scenarios with a 7% interest rate. Satellite image extracted from U.S. Virgin Islands GIS Division, Esri, TomTom, Garmin, Foursquare, SafeGraph, FAO, METI/NASA, USGS, NPS, USFWS, Kadaster Netherlands.

Uncertainties, Limitations, and Assumptions

Numerical flood modeling errors were estimated to be ±0.5 m. This value is greater than the root-mean-square and absolute errors computed between model results and measurements (van Dongeren et al., 2013; Quataert et al., 2015) but was used in an effort to mitigate the fact that the number of storms tested are few and the geographic scope is large compared to regions where validation measurements are available. The vertical resolution of the HAZUS depth-damage curves is ±0.3 m. Uncertainties associated with the baseline DEM varied based on input data; see Reguero et al. (2021) and references listed in Appendix 5. Other limitations and assumptions pertaining to flood extents and the resulting computed social and economic consequences include:

- The extreme value analysis for selecting storm return periods was stationary and did not include nonstationary effects, such as interannual patterns like El Niño, in the selection of values. The fit of each time series had to be limited to a number of thresholds and could not be adapted iteratively. These thresholds were also different for each region, depending on the local characteristics of extremes in each time series (with a limit of at least 30 extreme values to fit the extreme value distribution).

- Because the coral coverage data are defined in 4 classes, the associated hydrodynamic roughness data were also classified in 4 classes. This resulted in a step-wise change in hydrodynamic roughness that could occur over a relatively small distance, defining two different coral coverage class polygons that could result from a small change (2 percent; for example, between 9 percent to 11 percent cover) in coral cover.

- Restoration scenarios were assumed to have consistent extents of coral composed of species that contribute to wave attenuation (for example, *Acropora palmata*). The coral restoration was considered to be successful in terms of survival and growth of outplants. Species-level habitat limitations were not included in this study.

- The model scheme used to define the extreme flood levels combined the wave and surge conditions for certain storm probabilities and did not consider dependencies between both variables or the joint distribution of wave heights, wave periods, and surge levels. However, it is likely that large surges and waves occur simultaneously for large return periods.

- Tide levels were not considered beyond those registered in the extreme values measured in the tidal gauges that were used to define the extreme sea level for each region.

- The modeling structure of one-dimensional cross-shore transects assumed shore-normal wave and flooding processes.

- The approach for assessing flood damages and the resulting benefits associated with each probability assumed that the probability of the extreme flooding conditions on the fore reef defines the probability of the flood zones and the resulting flood damages (thus, the 1-in-100-year total water level represents the 1-in-100-year damage).

- The most statistically accurate assessment of flood damages would require defining the statistical distribution of damages instead of flood levels—for example, calculating the extreme economic damages. However, this requires reconstructing the runup time series and calculating the spatial losses associated with each event, which was outside the scope of this work.

- Alternative ways to calculate these statistics of economic damages would imply taking larger simplifications and uncertainties in the modeling of flooding, which would likely affect the accuracy of the results.

- Flood depths and extents between cross-shore transects modeled were alongshore interpolations and were not exact representations of model output, as they did not consider topographic features between the transects.

- U.S. Census Bureau's (2016) TIGER/Line data and FEMA's (2016) flood hazard exposure data in the HAZUS database are based on the 2010 census and, thus, may not reflect current-day populations, demographics, building values, and distributions. More recent updates to these datasets, as well as updated building footprint data, were not available at the time of this study and were, therefore, not included in the analysis.

- The composition of the general building stock within a given census block was assumed to be evenly distributed throughout the block. Building footprint data at the building block level are provided in the maps for visualization purposes of the flooded areas.

- Values correspond to the 2010 USD value. They have not been updated to present as they are referenced in the original datasets.

- The 2010 average of 15.1 employees per business was uniformly applied to the number of commercial and industrial buildings to compute the economic activity protected for businesses not impacted by the loss of infrastructure from coastal flooding.

- The economic activity protected for people not displaced by the loss of housing from coastal flooding was independent of the economic activity protected for businesses not impacted by the loss of infrastructure from coastal flooding.

- Benefits did not include indirect benefits such as ecosystem services, tourism, etc.

- Restoration costs were an estimation and did not include maintenance costs.

- The most recent consistent map of live coral cover was developed by NOAA in 2001; TNC partnered with Arizona State University to generate updated live coral cover data by flying the Global Airborne Observatory over St. Croix in 2018; however, there are gaps in the data due to variable weather conditions, and St. Thomas and St. John were not flown. Though more recent live coral cover survey data are available, there are no consistently mapped live coral cover geospatial products for the territory. This data gap can be addressed to support future restoration planning.

- The assumption of high (>50%) coral cover under restoration scenarios may not be realistic given current live coral cover conditions in USVI, given that the TNC and Arizona State University's 2017 live coral cover data found a maximum of 30% live coral cover in St. Croix and reefs have significantly degraded since then. The territory's current 10-year coral restoration plan has set a goal of achieving 10% live coral cover. The high coral cover assumption was necessary to increase the wave friction coefficients in the model; however, changes in bottom elevation (restoration height) used in the restoration scenarios are the primary flood-reduction driver (rather than friction coefficients).

- Current environmental regulations in the U.S. prohibit the placement of artificial reef structures on actual reefs. However, hybrid restoration was modeled and showed that regulatory exceptions, made for extreme cases of the need for coastal protection in the near future, would provide added protection.

RESULTS

Flooding Extents

This section summarizes the additional protected area (reduction in coastal flood exposure) attributed to the 'ecological' and 'hybrid' restoration scenarios across the three islands and for four storm return periods (10-, 50-, 100-, and 500-year). The decrease in exposure due to the implemented coral reef restoration strategies was quantified in terms of land surface area no longer in the flood hazard zone (Tables 2-4) and the number of people no longer in the flood hazard zone. The same method was applied to quantify the increase in exposure due to the reef degradation scenario ('No Reef'). The benefits or damages were computed by comparing the 'baseline' scenario with each of the reef scenarios in areas with the presence of coral reefs. Benefits are depicted as "**protected,**" while additional damages are denoted as "**affected**."

Table 2. Additional extent of **protected** area (km^2) from coastal flooding attributed to the **'ecological'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	0.78	1.01	0.82	0.69
St John	0.20	0.24	0.18	0.17
St Thomas	0.26	0.26	0.2	0.16

Table 3. Additional extent of **protected** area (km^2) from coastal flooding attributed to the **'hybrid'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	0.69	1.04	0.90	0.70
St John	0.21	0.25	0.20	0.17
St Thomas	0.28	0.21	0.23	0.17

Table 4. Additional extent of area (km^2) that would be **affected** by coastal flooding attributed to the '**No Reef'** degradation scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	2.94	3.15	3.31	2.71
St John	0.42	0.33	0.35	0.24
St Thomas	0.61	0.57	0.56	0.67

The EAB, in terms of the annual number of people who gained protection from coastal flooding owing to coral reef restoration due to the 'ecological' and 'hybrid' coral reef restoration scenarios, were 99 and 115 people, respectively, across the USVI. Degradation of reefs would reduce protection for 481 people across the USVI (Tables 14-16). The differences in individuals protected or exposed from the 'baseline' during four storm-return intervals are summarized below (Table 5–8).

Table 5. Additional number of people **protected** from coastal flooding attributed to the **'ecological'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	80	270	215	141
St John	11	8	8	9
St Thomas	73	48	63	55

Table 6. Additional number of people **protected** from coastal flooding attributed to the **'hybrid'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	102	364	244	162
St John	11	8	8	9
St Thomas	75	47	64	54

Table 7. Additional number of people **affected** by coastal flooding attributed to the '**No Reef'** degradation scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	Storm Return Interval			
	10-year	50-year	100-year	500-year
St Croix	677	611	603	462
St John	25	27	32	16
St Thomas	183	191	159	264

Economic Benefits

The EAB, in terms of the annual number of buildings that gained protection from coastal flooding owing to coral reef restoration because of the 'ecological' and 'hybrid' coral reef restoration scenarios, were 36 and 40 buildings, respectively, across the USVI. The EAB, in terms of the annual value of built capital that gained protection because of the 'ecological' and 'hybrid' coral reef restoration scenarios, was $6.1 million and $6.8 million, respectively, across the USVI. The differences in the numbers and values of all infrastructure in the USVI, as compared to the 'baseline' per return-interval storm by region, are depicted in Tables 8-13 below.

Table 8. Additional number of buildings (all infrastructure types) **protected** from coastal flooding attributed to the '**ecological'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	33	82	77	59
St John	7	6	5	7
St Thomas	20	14	20	15

Table 9. Additional number of buildings (all infrastructure types) **protected** from coastal flooding attributed to the **'hybrid'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	38	98	85	59
St John	6	6	6	6
St Thomas	22	14	20	15

Table 10. Additional number of buildings (all infrastructure types) **affected** by coastal flooding attributed to the '**No Reef'** degradation scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	227	231	224	187
St John	17	17	20	10
St Thomas	49	53	48	70

Table 11. Additional value of buildings (all infrastructure types) **protected** from coastal flooding attributed to the **'ecological**' coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	$6,149,847	$16,208,021	$16,359,986	$19,810,116
St John	$1,122,803	$1,421,222	$1,509,276	$2,252,060
St Thomas	$2,669,515	$2,869,901	$3,437,173	$4,334,883

Table 12. Additional value of buildings (all infrastructure types) **protected** from coastal flooding attributed to the **'hybrid'** coral reef restoration scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	$7,151,917	$18,493,874	$18,466,331	$19,885,891
St John	$1,084,175	$1,447,478	$1,566,011	$2,222,969
St Thomas	$2,961,649	$2,984,885	$3,794,671	$4,391,585

Table 13. Additional value of buildings (all infrastructure types) **affected** by coastal flooding attributed to the '**No Reef**' degradation scenario compared to the 'baseline' scenario for different return-interval storms by region.

Region	**Storm Return Interval**			
	10-year	**50-year**	**100-year**	**500-year**
St Croix	$42,635,682	$52,245,178	$60,192,801	$61,652,486
St John	$3,467,469	$4,034,561	$5,129,535	$4,534,225
St Thomas	$9,152,751	$11,292,324	$12,308,210	$18,373,903

Table 14. Annual value in number of people or 2010 U.S. dollars, **protected** from coastal flooding attributed to the **'ecological'** coral reef restoration scenario by region.

Region	**People**	**Buildings**	**Damages**	**Economic Activity**
St Croix	54	21	$3,969,266	$3,358,655
St John	6	4	$636,720	$433,977
St Thomas	39	11	$1,485,482	$1,721,481
Total	99	36	$6,091,469	$5,513,632

Table 15. Annual value, in number or 2010 U.S. dollars, **protected** from coastal flooding attributed to the **'hybrid'** coral reef restoration scenario.

Location	**People**	**Buildings**	**Damages**	**Economic Activity**
St. Croix	69	24	$4,582,404	$4,443,904
St. John	6	4	$619,368	$418,485
St. Thomas	40	12	$1,637,246	$1,757,728
Total	115	40	$6,839,018	$6,620,117

Table 16. Annual value, in number or 2010 U.S. dollars, **affected** by coastal flooding attributed to the '**No Reef'** degradation scenario.

Location	People	Buildings	Damages	Economic Activity
St. Croix	366	124	$24,030,862	$22,186,601
St. John	14	27	$1,944,918	$1,116,435
St. Thomas	101	9	$5,177,272	$5,080,957
Total	481	160	$31,153,052	$28,383,992

Per Storlazzi et al. (2019, 2021), the total economic impact of wave-driven coastal flooding is not only the direct physical damage to structures themselves but also to the disruption of peoples' and businesses' incomes and thus the contribution to the gross domestic product (GDP) of that housing and commercial/industrial infrastructure, respectively (Federal Emergency Management Agency, 2018). This indirect damage is calculated by multiplying the 2010 average contribution to the GDP per person, $40,043 in the U.S. Virgin Islands (U.S. Bureau of Economic Analysis, 2018), by the number of people living in the regions no longer exposed to flooding because of the coral reef restoration. One can compute the economic activity protected by reefs for people who would no longer be displaced owing to the loss of housing from decreased coastal flooding. Similarly, by multiplying the 2010 average of 15.1 employees per business (U.S. Census Bureau, 2018) by the 2010 average contribution to the GDP per person (Table 2; U.S. Bureau of Economic Analysis, 2018) to the number of commercial and industrial buildings in the regions no longer exposed to flooding because of the coral reef restoration, one can compute the economic activity no longer lost for businesses impacted owing to the loss of infrastructure from decreased coastal flooding. Because there are no data linking the people living in an area to where those people work, it was assumed that the economic activity lost for people displaced by the loss of housing from coastal flooding was independent of the economic activity lost for businesses impacted by the loss of infrastructure from coastal flooding.

The Expected Annual Benefits, in terms of the annual value of economic activity that gained protection because of the 'ecological' coral reef restoration scenario was $3.4 million in St. Croix, $0.4 million in St. John, and $1.7 million in St. Thomas. For the 'hybrid' restoration scenario, the economic activity indirect benefits were $4.4 million in St. Croix, $0.4 million in St. John, and $1.8 million in St. Thomas. Without the presence of reefs ('No Reef'), the increase in the indirect economic losses for the three islands would be $22.2 million, $1.1 million, and $5.1 million, respectively (Tables 12–14).

Benefit-to-Cost Analysis

Under prior FEMA rules, a project would be considered cost-effective when the BCR was 1.0 or greater and had a 7% discount rate. At the time of these analyses, FEMA was considering changing that discount rate to 2.8%, so that discount rate was also included in the analyses. FEMA has since finalized this policy and changed it to a discount rate of 3% (FEMA, 2023a). Based on this rule, possible priority areas in the USVI for 'ecological' restoration included the areas highlighted in red in Figure 13. For St. Croix, this included Long Reef, Llew's Reef, and reefs offshore from Green Cay, Teague Bay, Knight Bay, Grapetree Bay, Great Pond Bay, Halfpenny Bay, Frederiksted, Rainbow Beach, Carambola Beach Resort, Cane Bay, and Salt River Bay; for St. Thomas, reefs off of Sandy Bay, Cane Bay, Hull Bay, Mandal Bay, Water Bay, Muller Bay, Great Bay, Nazareth Bay, Bolongo Bay, Morningstar Bay, Cay Bay, Limestone Bay, Druif Bay, Perseverance Bay, and Fortuna Bay; for St. John, reefs off of Maho Bay, Pond Bay, Long Bay, Saltpond Bay, Great Lameshur Bay, Large Pond, and Frank Bay. As general results, the extension of the coastline subjected to different ranges of BCR values across the three islands can be found in Table 17 (2.8% discount rate) and Table 18 (7% discount rate).

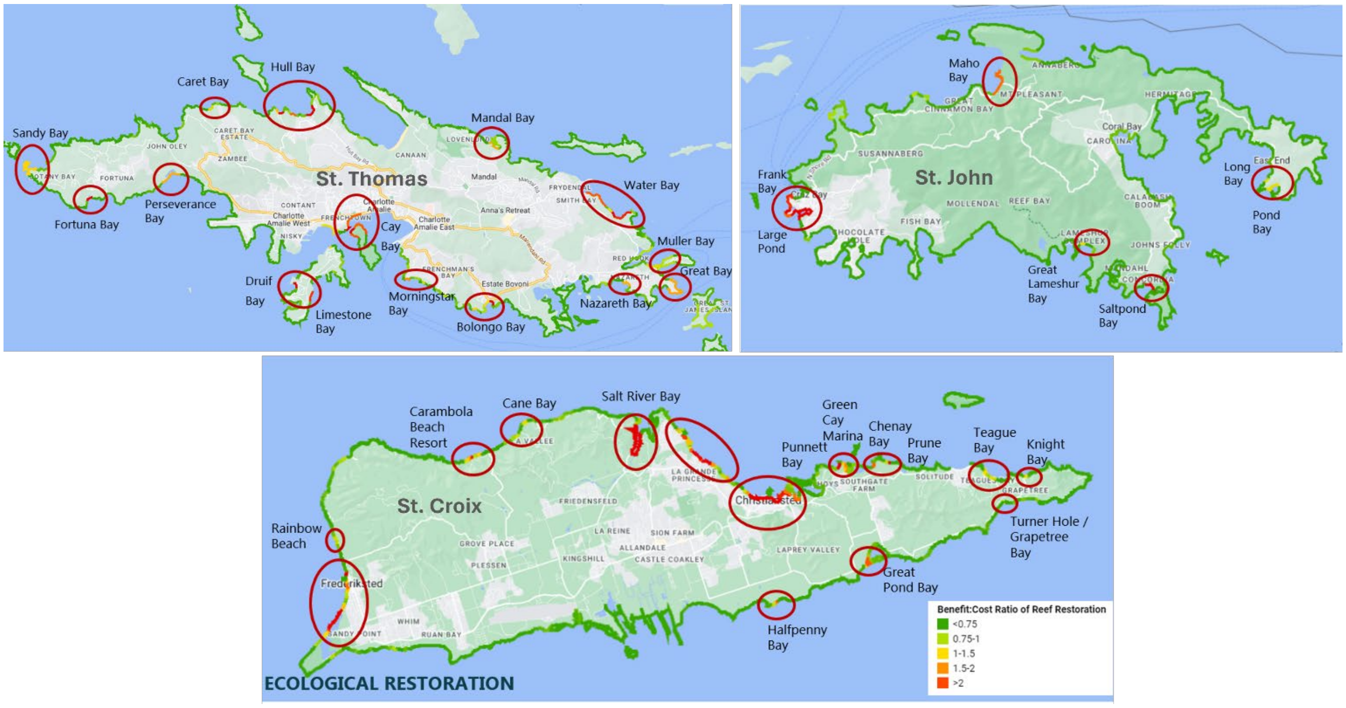

Figure 13. Map showing possible cost-effective areas (red ellipse) identified with BCR > 1 for the ‘ecological’ restoration.

Table 17. Percentage of the coastline (or length) exhibiting the respective BCR with a 2.8% discount rate.

		Benefit-to-Cost Ratio				
Region	**Restoration Scenario**	**<0.75**	**0.75-1.0**	**1.0-1.5**	**1.5-2.0**	**>2.0**
St. Croix	‘Ecological’	84.6%	1.8%	2.3%	1.1%	10.3%
St. Croix	‘Hybrid’	89.6%	0.7%	1.9%	1.8%	6.1%
St. John	‘Ecological’	94.0%	1.1%	0%	1.1%	3.8%
St. John	‘Hybrid’	95.3%	0.9%	0.3%	1.5%	2.0%
St. Thomas	‘Ecological’	86.1%	3.4%	1.9%	2.1%	6.5%
St. Thomas	‘Hybrid’	92.5%	1.4%	0.8%	2.6%	2.7%

Table 18. Percentage of the coastline (or length) exhibiting the respective BCR with a 7% discount rate.

		Benefit-to-Cost Ratio				
Region	**Restoration Scenario**	**<0.75**	**0.75-1.0**	**1.0-1.50**	**1.5-2.0**	**>2.0**
St. Croix	'Ecological'	87.6%	1.3%	1.6%	1.8%	7.7%
St. Croix	'Hybrid'	91.0%	1.3%	1.9%	1.0%	4.7%
St. John	'Ecological'	95.1%	0%	1.1%	0%	3.8%
St. John	'Hybrid'	96.2%	0.3%	1.5%	0.4%	1.6%
St. Thomas	'Ecological'	90.7%	0.6%	2.3%	2.3%	4.1%
St. Thomas	'Hybrid'	94.2%	0.6%	3.2%	0.1%	1.9%

Virgin Islands Restoration of Corals Squad Priority Restoration Results

The Virgin Islands Restoration of Corals Squad (VI-RoCS) has identified a number of priority sites for reef restoration based on biological and ecological criteria. In Table 19, the costs and benefits of restoring these sites for storm protection with the 'ecological' restoration were valued. Reefs in the region, at the time of reporting and currently, have degraded historically from climate stressors such as bleaching and disease, as well as local anthropogenic threats. Coral conservation work as part of VI-RoCS includes a combination of restoration activities, including outplanting and threat abatement activities, addressing issues such as water quality, sedimentation, and overfishing. To better understand the value of conservation actions (protection and restoration) in these specific areas, Table 19 outlines the value of an ecologically restored reef against a 'No Reef' scenario. However, some of the local sites would require higher granularity approaches than the regional modeling presented here.

Table 19. Modeled coastal protection values of the VI-RoCS priority sites.

Site	EAB ('ecological' restoration vs. 'baseline')	EAB ('baseline' vs. 'No Reef')	EAB ('Ecological' Restoration vs 'No Reef')	A. Benefits of 'Ecological' Restoration 1-in-100 ys	B. Benefits of Reef Protection, 1-in-100 ys ('baseline' vs. 'No Reef')	Benefits of restored + protected reefs during a 1-in-100 year storm (A + B)
Long Reef, St. Croix	$1,135,693/yr	$6,205,842/yr	$7,341,535/yr	$4,667,434	$12,651,097	$17,318,531
Llew's Reef, St. Croix	$11,209/yr	$101,445/yr	$112,654/yr	$65,846	$177,058	$242,904
Sweeper's Complex, St. Croix	*No modeled value*					
Butler Bay, St. Croix	$12,074/yr	$46,449/yr	$58,523/yr	$33,059	$102,897	$135,956
Coki, St. Thomas	*No modeled value*					
Flat Cay, St. Thomas	*No modeled value*					

Decision Support Tool

A decision support tool was developed to make the modeling results available to stakeholders and decision-makers in the territory. The Caribbean Coastal Resilience Decision Support Tool (CoastalProtection.TNC.org) allows users to view summary statistics, explore the benefits of both the 'ecological' and 'hybrid' restoration scenarios under various storm scenarios spatially, and inspect values in areas of interest. Reference layers can be layered onto the map, including the reef restoration line used in flood modeling, building footprints from Google, protected areas, and more. The tool also provides similar data on the coastal protection benefits of reefs and mangroves for the Dominican Republic, Jamaica, and Grenada from previous studies completed by UCSC and USGS in collaboration with The Nature Conservancy.

CONCLUSION

The applied methodology combined oceanographic, coastal engineering, ecologic, geospatial, social, and economic data and tools to provide a rigorous social and economic valuation of the coastal protection benefits in the United States Virgin Islands gained from coral reef restoration scenarios ('ecological' and 'hybrid') and the loss due to a reef degradation scenario ('No Reef'). These analyses can help identify where reef restoration might offer the greatest risk reduction benefits and where the loss of the current reef can cause the greatest damage. These results are not meant to provide design-level projections of hazard risk reduction benefits. That is, it is expected that project proponents might use these results to understand where to design specific kinds of projects. Overall, these values are expected to provide the minimum (or at least low-end) estimates of the flood reduction benefits of projects with similar reef restoration height and width characteristics. In any specific area, proponents could design projects to achieve even greater flood reduction benefits, such as by restoring reefs in shallower water and increasing the friction with taller and (or) broader species.

The hazard risk reduction benefits of coral reef restoration are spatially variable. In many areas, calculations showed little or no benefits from reef restoration (for example, restoration sites were far offshore or relatively deep). However, there were a number of key areas where reef restoration could have substantial benefits for flood risk reduction and could be critical (and cost-effective) components of a hazard mitigation strategy. These data make it possible to identify where and how coral reef restoration reduces storm-induced flooding hazards to coastal communities in the USVI. The goal is to provide sound, scientific guidance for U.S. Federal, State, Commonwealth, and local governments' efforts on hazard risk reduction and coral reef conservation, restoration, and management by providing rigorous, spatially explicit, high-resolution, social and economic valuations of the people and property protected by coral reef restoration to, ultimately, save dollars and protect lives.

The results of the modeling should not be viewed as prescriptive and should always be paired with local knowledge to support decision-making. It is also important to note that this study is focused on coastal protection value, but reefs provide significant value beyond coastal protection through many other ecosystem service benefits such as tourism, fisheries, livelihoods, biodiversity, and cultural value.

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Additional Digital Information

The digital data used to produce this report can be found here:
https://caribbeanscienceatlas.tnc.org/datasets/fe515cb748b6406cb2816dea1a19d404/about

For more information on the U.S. Geological Survey's Coral Reef Project, visit
http://coralreefs.wr.usgs.gov/

For more information on the U.S. Geological Survey Coastal and Marine Program's Coastal Change Hazards portal, visit
https://marine.usgs.gov/coastalchangehazardsportal/

For more information on the University of California, Santa Cruz's Coastal Resilience Laboratory, visit
https://www.coastalresiliencelab.org/

For more information on the University of California, Santa Cruz's Center for Integrated Spatial Research, visit
http://spatial.cisr.ucsc.edu/

For more information on NOAA National Centers for Coastal Ocean Science, visit
https://coastalscience.noaa.gov/

Direct Contact Information

Regarding the flood modeling methods in this report, contact Curt D. Storlazzi, USGS Coral Reef Project Chief (cstorlazzi@usgs.gov).

Regarding the web tool, GIS data layers, or overall project, contact Valerie Pietsch McNulty, Conservation Scientist for the Caribbean Program at The Nature Conservancy (valerie.mcnulty@tnc.org).

Regarding TNC's coral restoration work in the U.S. Virgin Islands, contact Jessica Ward, Virgin Islands Coral Program Director at The Nature Conservancy (jessica.ward@tnc.org).

Appendices

Appendix 1. SWAN Model Settings

Parameter	Value
General	
OnlyInputVerify	false
SimMode	stationary
DirConvention	nautical
WindSpeed	0.0000000e+000
WindDir	0.0000000e+000
Processes	
GenModePhys	3
Breaking	true
BreakAlpha	1.0000000e+000
BreakGamma	7.3000002e-001
Triads	false
TriadsAlpha	1.0000000e-001
TriadsBeta	2.2000000e+000
WaveSetup	false
BedFriction	jonswap
BedFricCoef	6.7000002e-002
Diffraction	true
DiffracCoef	2.0000000e-001
DiffracSteps	5
DiffracProp	true
WindGrowth	false
WhiteCapping	Komen
Quadruplets	false
Refraction	true
FreqShift	true
WaveForces	dissipation 3d
Numerics	
DirSpaceCDD	5.0000000e-001
FreqSpaceCSS	5.0000000e-001
RChHsTm01	2.0000000e-002
RChMeanHs	2.0000000e-002
RChMeanTm01	2.0000000e-002
PercWet	9.8000000e+001
MaxIter	100
Output	
TestOutputLevel	0
TraceCalls	false
UseHotFile	false
WriteCOM	false

Domain	
DirSpace	circle
NDir	72
StartDir	0.0000000e+000
EndDir	0.0000000e+000
FreqMin	5.0000001e-002
FreqMax	1.0000000e+000
NFreq	24
Output	true
Boundary	
Definition	orientation
SpectrumSpec	parametric
SpShapeType	jonswap
PeriodType	peak
DirSpreadType	power
PeakEnhanceFac	= 3.3000000e+000
GaussSpread	9.9999998e-003

Appendix 2. SWAN Model Grid Information
[km, kilometer; m, meter]

Location	1-km Grid Cells	200-m Grid Cells	Grid Dimensions (E-W x N-S)	Data Source
Virgin Islands	USVI	-	74 x 108	Love et al., 2014a, b
Virgin Islands	-	St. Croix	260 x 115	Love et al., 2014a, b
Virgin Islands	-	St. John, St. Thomas	270 x 206	Love et al., 2014a, b

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Appendix 3. Benthic Habitat and Shoreline Datasets

[NOAA, National Oceanic and Atmospheric Administration]

Location	Sublocation	Benthic Habitat data		Shoreline Data Source
		Minimum Mapping Unit	Data Source	
Virgin Islands	St. Croix	1 acre	NOAA, 2001a	NOAA, 2015
Virgin Islands	St. Thomas	1 acre	NOAA, 2001b	NOAA, 2015
Virgin Islands	St. John	1,000 m^2	Zitello and others, 2009	NOAA, 2015

Appendix 4. Cross-Shore XBeach Transects

Location	Sublocation	Number of Cross-Shore Transects
Virgin Islands	St. Croix	803
Virgin Islands	St. Thomas	466
Virgin Islands	St. John	396

Appendix 5. Bathymetric Datasets

Location	Sublocation	Data Source
Virgin Islands	St. Croix	Love et al., 2014a
Virgin Islands	St. Thomas	Love et al., 2014b
Virgin Islands	St. John	Love et al., 2014b

Appendix 6. XBeach Model Settings

Category	Parameter	Value
Flow Boundary Condition Parameters	front	abs_1d
	left	wall
	right	wall
	back	wall
Flow	bedfriction	chezy
	bedfricfile	fric.txt
Grid Parameters	thetamin	-60
	thetamax	60
	dtheta	10
Model Time	tstop	3600
Tide Boundary Conditions	tideloc	1
Wave Boundary Condition Parameters	instat	jons
	dir0	270
Output Variables	outputformat	netcdf
	rugdepth	0.020000
	tintm	3500
	tintp	10
	tintg	3100
	tstart	100
Output Options	nglobalvar	4
	H	
	zs	
	zb	
	E	
	nmeanvar	3
	H	
	zs	
	zb	
	npoints	1
	nrugauge	1

Appendix 7. Restoration Costs

Source	$/Meter
Outplanting Fragments	
TNC Coral Innovation Hub – USVI (Personal Communication)	1081
TNC Resilient Islands (2019)	
Jamaica (Number of projects = 4)	640
Dominican Republic (N = 1)	2025
Florida (N = 7)	2469
Caribbean (N = 3)	1286
Average	**1500**
Hybrid Reef	
Storlazzi et al. 2021	1290
Reef Innovations/Reef Ball Distributor	4785
Ocean Rescue Alliance (Pers. Communication)	1000-3000
SEAHIVE (Barbarigos, 2022)	4167
TNC Resilient Islands (2019)	
Grenada (N = 1)	3136
Caribbean (N = 4)	2964
Av. Range	**2890-3223**
Average	**3057**