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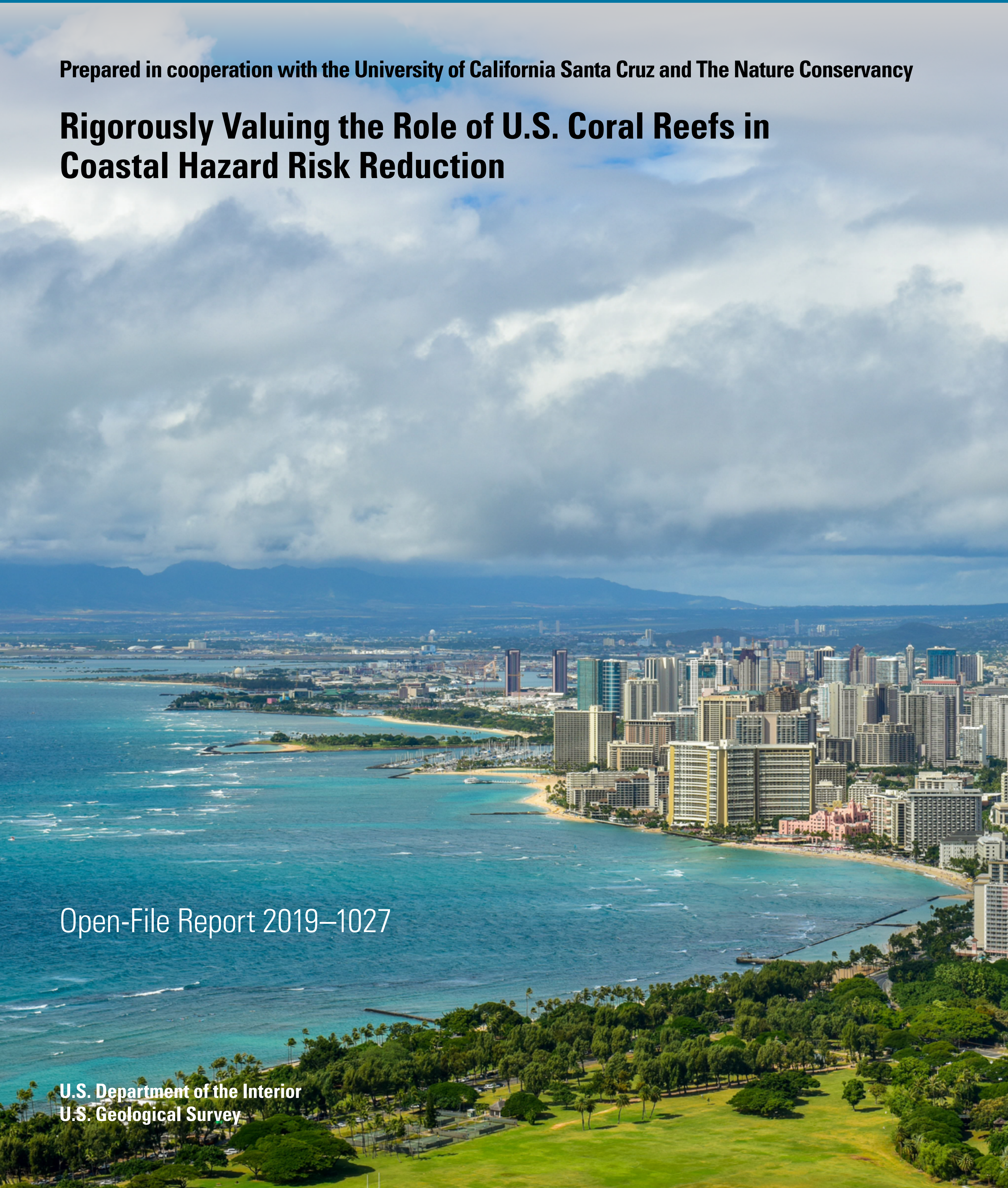
Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction



Open-File Report 2019–1027

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of waves breaking and dissipating their energy on the coral reefs off Waikīkī and Honolulu, Oʻahu, Hawaiʻi, demonstrating the coastal protection provided by these ecosystems. Photograph by Zetong Li on Unsplash.

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By Curt D. Storlazzi, Borja G. Reguero, Aaron D. Cole, Erik Lowe, James B. Shope, Ann E. Gibbs, Barry A. Nickel, Robert T. McCall, Ap R. van Dongeren, and Michael W. Beck

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DAVID BERNHARDT, Acting Secretary

U.S. Geological Survey
James F. Reilly II, Director

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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)

Abbreviations

DSAS	Digital Shoreline Analysis System
EAB	expected annual benefit
EAD	expected annual damage
FFWCC	Florida Fish and Wildlife Conservation Commission
FWRI	Fish and Wildlife Research Institute
GOW	Global Ocean Wave database
GDP	gross domestic product
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
OIA	Department of Interior’s Office of Insular Affairs
PacIOOS	Pacific Island Ocean Observing System
PIBHMC	Pacific Islands Benthic Habitat Mapping Center
SWAN	Simulating Waves Nearshore spectral wave model
TIGER	Topographically Integrated Geographic Encoding and Referencing
USGS	U.S. Geological Survey

Rigorously Valuing the Role of U.S. Coral Reefs in Coastal Hazard Risk Reduction

By Curt D. Storlazzi[1], Borja G. Reguero[2,3], Aaron D. Cole[3], Erik Lowe[3], James B. Shope[3], Ann E. Gibbs[1], Barry A. Nickel[3], Robert T. McCall[4], Ap R. van Dongeren[4], and Michael W. Beck[2,3]

Abstract

The degradation of coastal habitats, particularly coral reefs, raises risks by increasing the exposure of coastal communities to flooding hazards. The protective services of these natural defenses are not assessed in the same rigorous economic terms as artificial defenses, such as seawalls, and therefore often are not considered in decision making. Here we combine engineering, ecologic, geospatial, social, and economic tools to provide a rigorous valuation of the coastal protection benefits of all U.S. coral reefs in the States of Hawaiʻi and Florida, the territories of Guam, American Samoa, Puerto Rico, and Virgin Islands, and the Commonwealth of the Northern Mariana Islands. We follow risk-based valuation approaches to map flood zones at 10-square-meter resolution along all 3,100+ kilometers of U.S. reef-lined shorelines for different storm probabilities to account for the effect of coral reefs in reducing coastal flooding. We quantify the coastal flood risk reduction benefits provided by coral reefs across storm return intervals using the latest information from the U.S. Census Bureau, Federal Emergency Management Agency, and Bureau of Economic Analysis to identify their annual expected benefits, a measure of the annual protection provided by coral reefs. Based on these results, the annual protection provided by U.S. coral reefs is estimated in:

- Avoided flooding to more than 18,180 people;
- Avoided direct flood damages of more than $825 million to more than 5,694 buildings;
- Avoided flooding to more than 33 critical infrastructure facilities, including essential facilities, utility systems, and transportation systems; and
- Avoided indirect damages of more than $699 million in economic activity of individuals and more than $272 million in avoided business interruption annually.

Thus, the annual value of flood risk reduction provided by U.S. coral reefs is more than 18,000 lives and $1.805 billion in 2010 U.S. dollars. These data provide stakeholders and decision makers with spatially explicit, rigorous valuation of how, where, and when U.S. coral reefs provide critical coastal storm flood reduction benefits. The overall goal is to ultimately reduce the risk to, and increase the resiliency of, U.S. coastal communities.

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[4]Deltares.

Introduction

Coastal flooding and erosion from extreme weather events affect thousands of vulnerable coastal communities. Globally, insurers paid out more than $300 billion for coastal damages from storms in the 2000s (United Nations Office for Disaster Risk Reduction, 2011). The impacts of coastal flooding are predicted to worsen during this century owing to population growth and climate change (Hallegatte and others, 2013; Hinkel and others, 2014; Reguero and others, 2018; Storlazzi and others, 2018). There is an urgent need to develop better risk reduction and adaptation strategies to reduce coastal flooding and associated hazards (Hinkel and others, 2014; National Research Council, 2014). For example, the United States spends, on average, $500 million per year mitigating such coastal hazards (Federal Emergency Management Agency, 2016a). However, most of these funds are destined for the creation and maintenance of "gray infrastructure" (McCreless and Beck, 2016), such as seawalls, which have negative impacts on coastal ecosystems (Chapman and Underwood, 2011), and may not be cost effective for risk reduction when compared to natural (for example, coral or oyster reef restoration) and hybrid (for example, placing artificial new, hard substrate for natural recolonization) alternatives (Reguero and others, 2018).

There is growing national recognition of the role of natural and nature-based solutions to address coastal risks (Wells and others, 2006; Cheong and others, 2013; Temmerman and others, 2013; Costanza and others, 2014; Spalding and others, 2014; Sutton-Grier and others, 2015). The National Science and Technology Council highlights that "integrating ecosystem-service considerations into planning and decision making can help draw attention to the many critical contributions natural systems make toward improving the productivity, resilience, and livability of our Nation and communities" (National Science and Technology Council, 2015). The biggest limitation to advancing the use of natural defenses in coastal management, however, is the lack of quantitative assessments of their engineering performance and economic benefits.

Coral reefs, in particular, can substantially reduce coastal flooding and erosion by dissipating as much as 97 percent of incident wave energy (Ferrario and others, 2014). Reefs function like low-crested breakwaters, with hydrodynamic behavior well characterized by coastal engineering models (Hoeke and others, 2011; Taebi and Pattiaratchi, 2014; Quataert and others, 2015; Reguero and others, 2018). Yet the value of coral reefs for coastal defense is not fully recognized, and thus they continue to be lost—75 percent of the world's coral reefs are rated as threatened (Hoegh-Guldberg and others, 2007; Mumby and others, 2007). The loss of reefs and their protection services will continue unless their economic value is accurately quantified and mainstreamed into policy and management decisions. Although there have been attempts to determine the influence of coral reefs in coastal hazard risk reduction (van Zanten and others, 2014; Yee and others, 2014; Pascal and others, 2016), these efforts made broad generalizations of coral coverage and reef morphology and their resulting influence on waves and wave-driven water levels that define the coastal hazard. Most of these studies provide index-based approaches to quantifying coastal flooding hazards rather than physics-based hydrodynamic model results that account for all of the interactions between the intrinsic properties of the reef (coral coverage and morphology) and extrinsic forcing (wave heights and periods). We have built on the work of Beck and others (2018) to build coupled hydrodynamic and economic models of reef benefits.

Our goal here is to develop and apply a process-based, high-resolution, nonlinear model of coastal protection benefits from corals reefs, map these natural defense benefits at a resolution relevant to management scales, and provide a framework to rigorously value the people and property protected by coral reefs for a range of storm scenarios. These data were generated for all populated U.S. coral-reef-lined coasts, including the States of Hawai‘i and Florida; the territories of Guam, American Samoa, Puerto Rico, and Virgin Islands; and the Commonwealth of the Northern Mariana Islands (fig. 1).

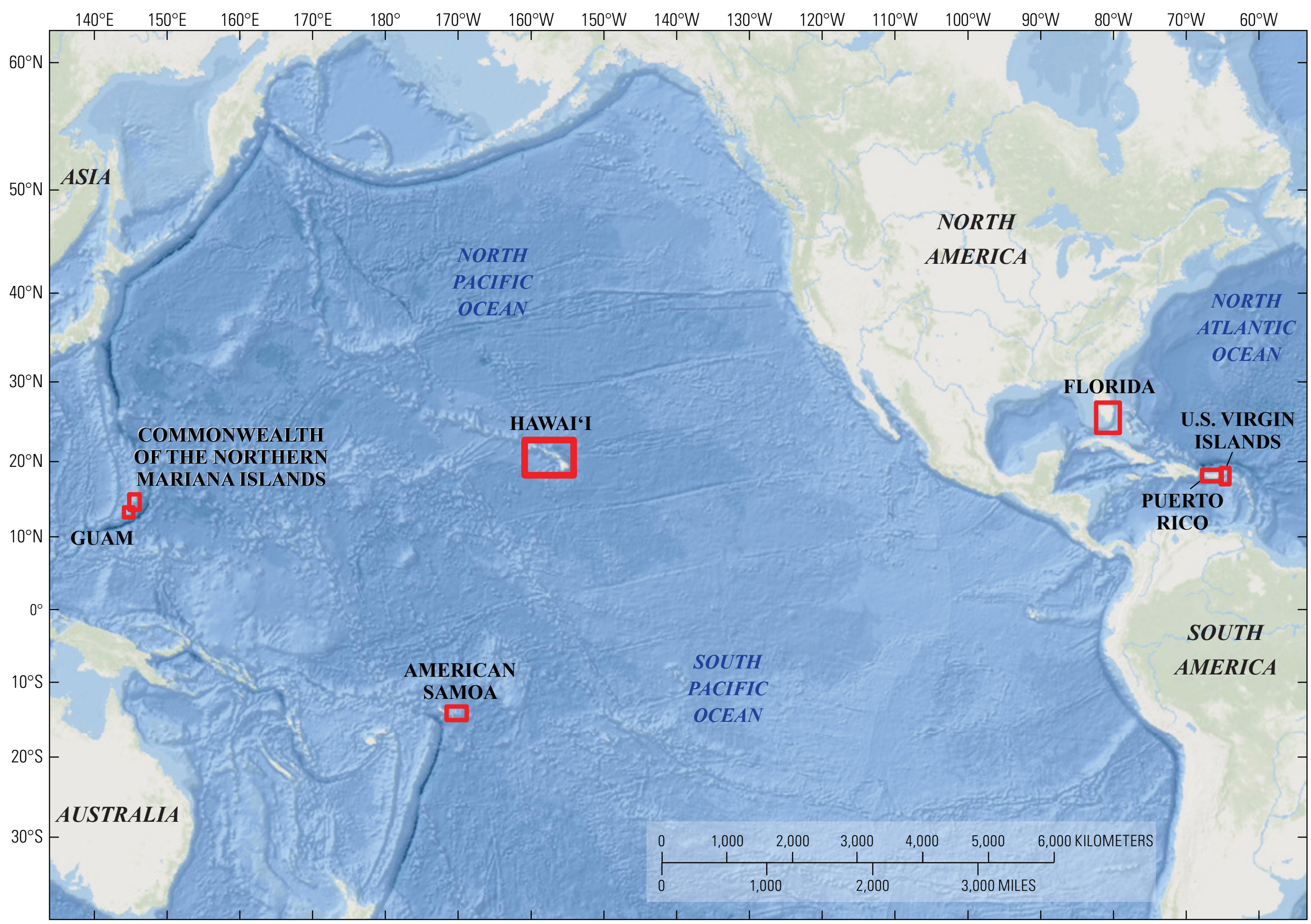

Figure 1. Map showing the location of the study areas (outlined in red boxes).

Methodology

Engineering, ecologic, social, and economic tools were combined to provide a quantitative valuation of the coastal protection benefits of coral reefs off populated coastlines of the United States. The goal of this effort was to identify how, where, and when coral reefs provide the most significant coastal flood reduction benefits in social and economic terms. This analysis follows a risk quantification valuation framework to estimate the risk reduction benefits from coral reefs and provide annual expected benefits in social and economic terms (Beck and Lange, 2016; Beck and others, 2018). This national mapping represents a unique and innovative effort to provide risk reduction values in rigorous quantitative terms, based on high-resolution flood modeling and state-of-the-art damage modeling with calculations based on approaches used by the Federal Emergency Management Agency. The methods follow a sequence of steps (fig. 2) that integrate physics-based hydrodynamic modeling, quantitative geospatial modeling, and social and economic analyses to quantify the hazard, the role of coral reefs in reducing flooding, and the averted economic and social consequences.

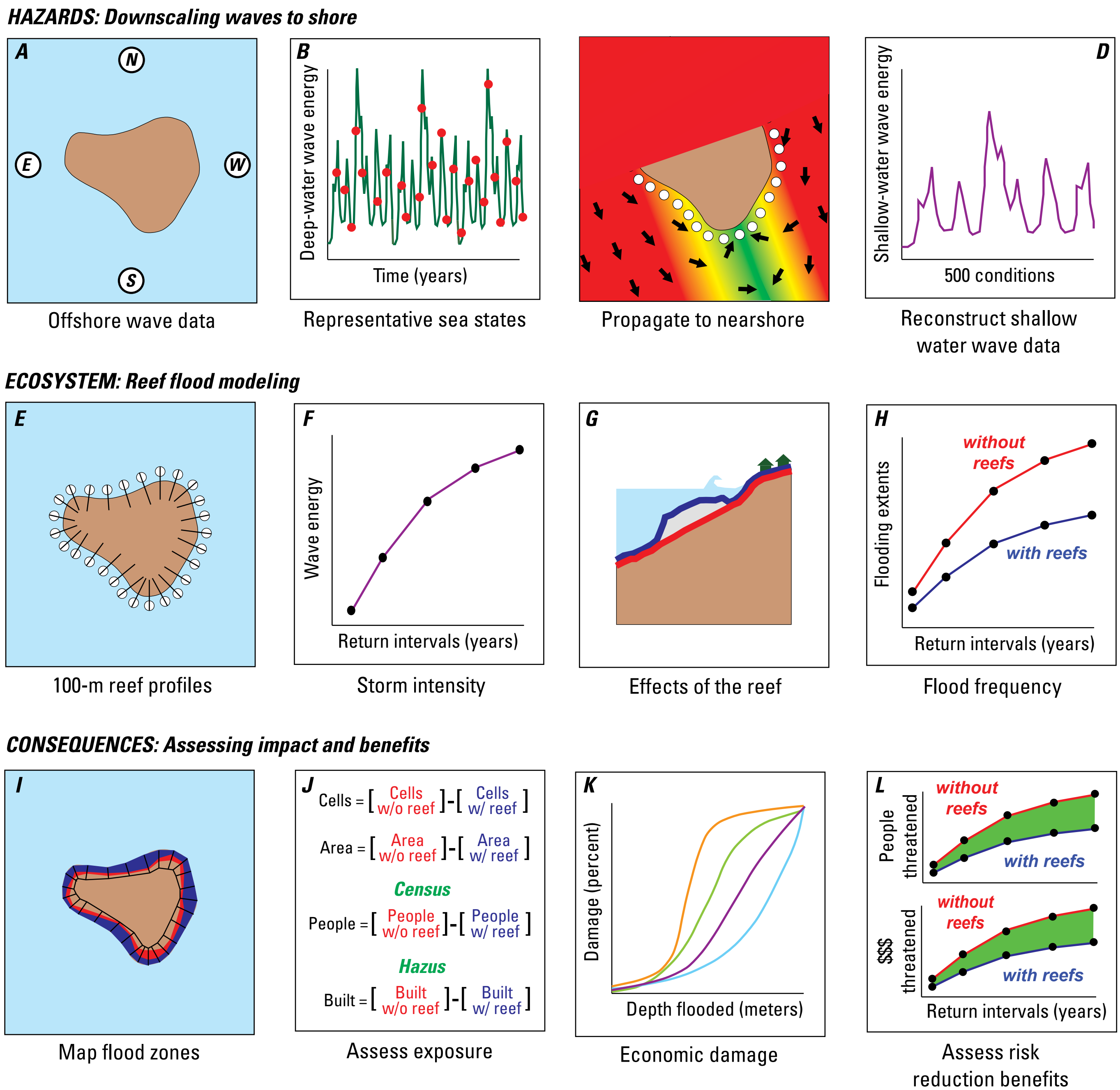

Figure 2. Schematic drawing that shows the methodology used to evaluate the role of coral reefs in hazard risk reduction. Each step is described in more detail in the methodology section.

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 and others, 2012) for the populated, reef-lined coastal areas (fig. 2*A*). Following the methodology of Camus and others (2011), we propagated more than half a million hourly data on wave climate parameters to the nearshore shore using a hybrid downscaling approach. The offshore wave climate data (wave heights, wave periods, and wave directions) were synthesized into 500 combinations of sea states that best represented the range of conditions from the GOW database (fig. 2*B*). These selected sea states were then propagated to the coast using the physics-based Simulating Waves Nearshore (SWAN) spectral wave model (Booij and others, 1999; Ris and others, 1999; Delft University of Technology, 2016), which simulates wave transformations nearshore by solving the spectral action balance equation (fig. 2*C*). Previous studies have demonstrated that SWAN is capable of accurately simulating wave propagation around reef-lined islands (Hoeke and others, 2011; Taebi and Pattiaratchi, 2014; Storlazzi and others, 2015). Standard SWAN settings were used (for example, Hoeke and others, 2011; Storlazzi and others, 2015), except that the directional spectrum was refined to 5-degree bins to better handle refraction and diffraction in and amongst islands (appendix 1).

In order to accurately model from the scale of the main island groups or large sections of coastline (order of tens of kilometers [km]) down to management scales (order of hundreds of meters [m]), a series of as many as three dynamically downscaled nested grids with square grid cells were used, depending on the region. The coarse SWAN grids provided spatially varying boundary conditions for finer scale SWAN grids (fig. 3*B*, *C*). The bathymetry for the SWAN grids was generated by grid-cell averaging of various bathymetric datasets (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 (fig. 2*D*), and then reconstructed into the 61-year hourly time series using multidimensional interpolation techniques (Camus and others, 2011).

Evaluating the Role of Coral Reefs in Coastal Protection

Benthic habitat maps of coral cover percentage and spatial extent (appendix 3) were used to delineate the location of nearshore coral reefs and relative coral abundance along the reef-lined shorelines (fig. 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 and others, 2009). Transects were cast in both landward and seaward directions using the smoothed baseline cast method with a 500-m smoothing distance, perpendicular to a baseline generated from coastlines digitized from U.S. Geological Survey 1:24,000 quadrangle maps and smoothed in ArcGIS using the polynomial approximation with exponential kernel algorithm and a 5,000-m smoothing tolerance (fig. 2*E*). Transects varied

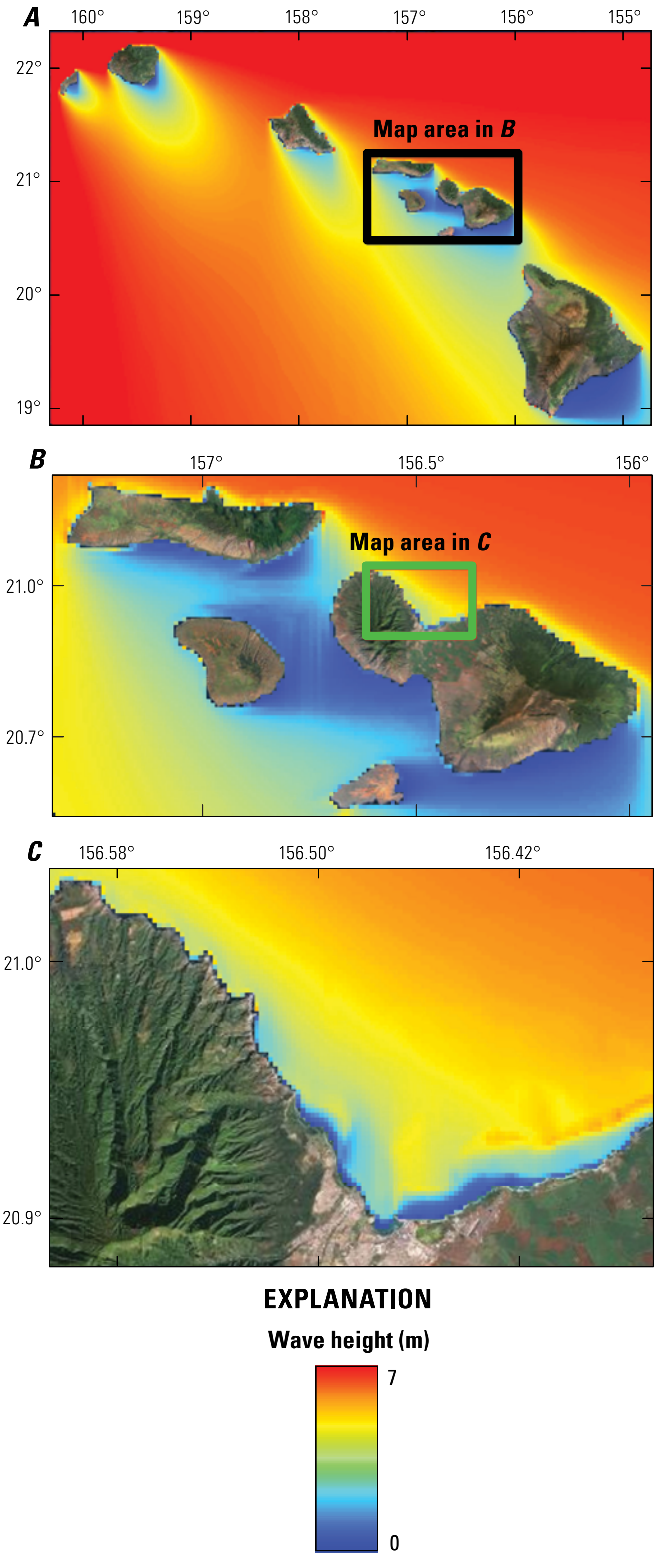

Figure 3. Maps showing output examples of the Simulating Waves Nearshore (SWAN) model and how one of the 500 wave conditions were dynamically downscaled to the 200-meter (m) grid scale offshore west Maui, Hawai'i. *A*. The 5-kilometer (km) resolution Hawaiian chain model. *B*. The 1-km resolution Maui Nui model embedded in the Hawaiian chain model. *C*. The 200-m resolution west Maui model embedded in the Maui Nui model. Colors indicate significant wave height, in meters.

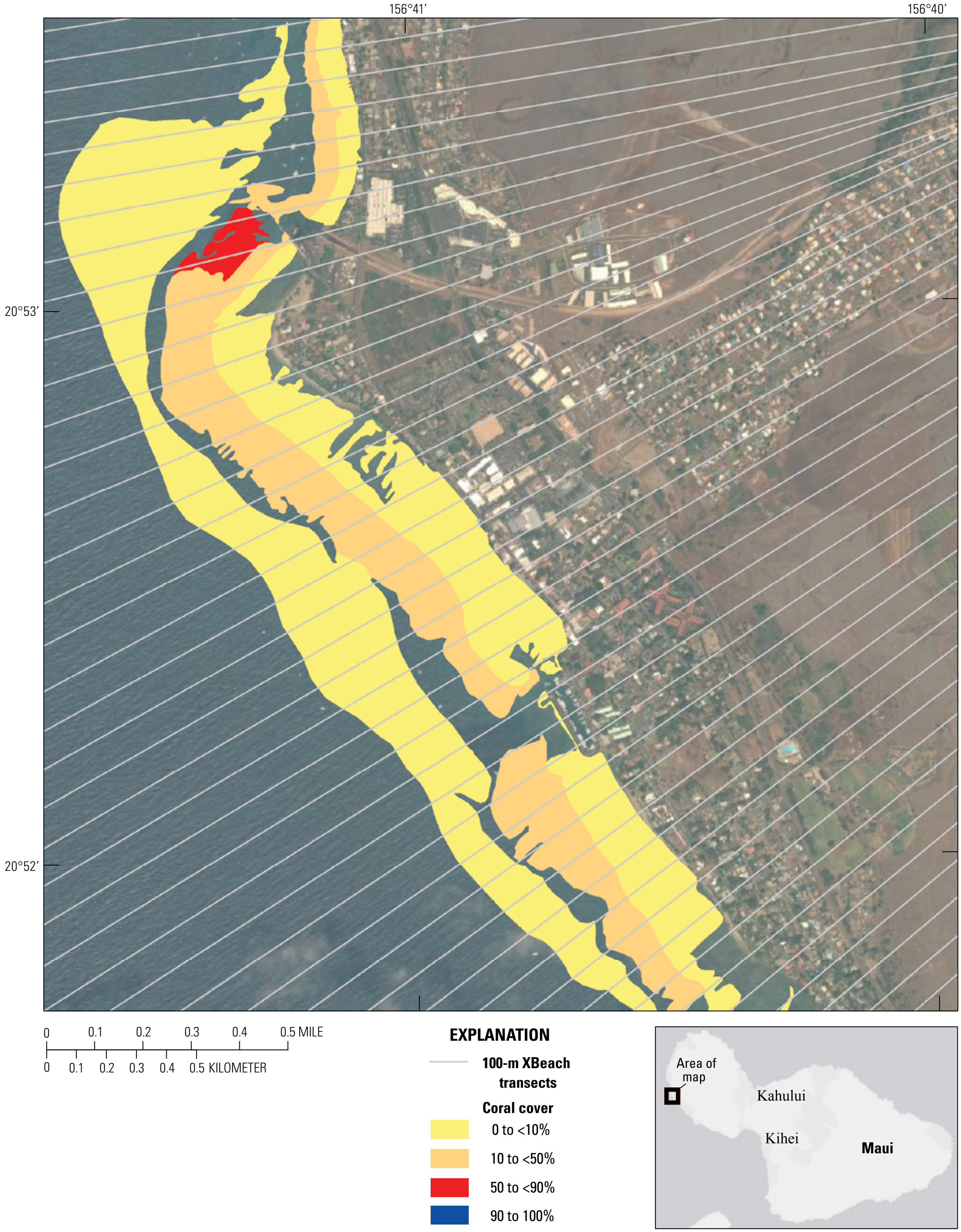

Figure 4. Map showing the coral extent and coverage offshore Lahaina, Maui, Hawai'i (Anderson, 2007). Colors indicate percentage (%) of coral coverage; gray lines show cross-shore transects at 100-meter (m) intervals.

in absolute length in order to cross the −30 and +20 m elevation contours. The bathymetric (appendix 5) and coral coverage (appendix 3) data were extracted along these shore-normal transects at a horizontal grid-cell resolution of 1 m.

The nearshore wave time series (hourly data from 1948 to 2008) were fit to a general extreme value distribution (Méndez and others, 2006; Menéndez and Woodworth, 2010) to obtain the significant wave heights associated with the 10-, 50-, 100-, and 500-year storm return periods (fig. 2*F*). Extreme water levels corresponding to the 10-, 50-, 100-, and 500-year storm return period for a given location were taken from the nearest National Oceanic and Atmospheric Administration tidal station, which include the effect of tropical cyclones (National Oceanic and Atmospheric Administration, 2017). The significant wave heights and peak periods associated with these return-value wave heights and sea levels were then propagated over the coral reefs along 100-m-spaced shore-normal transects (appendix 4) using the numerical model XBeach (Roelvink and others, 2009; Deltares, 2016), as demonstrated in figures 2*G* and 4. XBeach solves for water-level variations up to the scale of long (infragravity) waves using the depth-averaged, nonlinear shallow water equations. The forcing is provided by a coupled wave action balance, in which the spatial and temporal variations of wave energy owing 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 nonlinear 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 (Pomeroy and others, 2012; van Dongeren and others, 2013; Quataert and others, 2015; Storlazzi and others, 2018) and proved to accurately predict the key reef hydrodynamics.

XBeach was run for 3,600 seconds in one-dimensional hydrostatic mode along the cross-shore transects, at a varying horizontal resolution between 10 m seawards and 1 m landwards (resolution varies depending on depth). Additional formulations were applied 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 and others (2013). The friction induced by corals was parameterized 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 and others, 2013; Quataert and others, 2015). Coral coverage was assigned f_w and c_f (table 1) over the spatial extent of the reef along the profile as defined from the benthic habitat maps (appendix 3). The XBeach model runs generally stabilized after 100–150 seconds and thus generated good statistics on waves and wave-driven water levels for more than 50 minutes (model parameters given in appendix 6). Although the application of a one-dimensional model neglects some of the dynamics that occur on natural reefs, such as lateral flow, it provides a conservative estimate for infragravity wave generation and wave runup, as the forcing is shore normal. Thus, the flooding is likely underrepresented around promontories where wave-energy convergence would cause increased wave-driven flooding that is not captured with one-dimensional models, and likely underrepresented in small embayments where diffraction would disperse wave energy and thus reduce wave-driven flooding. The use of one-dimensional modeling is warranted in this case because the SWAN wave direction output at the most nearshore grid cells that provides forcing to the XBeach models were predominantly near normal. Upon completion of the simulations, the total water levels (setup plus runup) at each grid cell along the profiles were then extracted to define the wave-driven flooding along each of the profiles (fig. 5).

Table 1. Wave and current friction coefficients for different percentages of coral cover as determined from benthic habitat maps.

Coral coverage, in percent	Wave friction coefficient (f_w)	Current and infragravity wave friction coefficient (c_f)
None (sand)	0.10	0.01
0–10	0.15	0.07
10–50	0.30	0.10
50–90	0.45	0.13
90–100	0.60	0.15

The wave and sea level conditions were then propagated using the XBeach model over the same 100-m spaced shore-normal transects modified to account for the loss of the coral reef (fig. 2*G*). A loss of coral coverage and, thus, rugosity and frictional effects (for example, Quataert and others, 2015) was parameterized by setting the f_w and c_f to that of sand (table 1) per van Dongeren and others (2013). The loss of coral reef structure was parameterized by reducing the elevation (increasing the depth) of the shore-normal profile 1 m over the spatial extent of the reef along the profile based on observations of bathymetric change owing to reef loss by Sheppard and others (2005) and Yates and others (2017). Total water levels (setup plus runup) at each grid cell along the profiles were then extracted to define the wave-driven flooding along these profiles without the influence of the coral reefs (fig. 5).

Quantifying the Social and Economic Value of Coral Reef Protection

Wave-driven total water levels for each of the four return intervals (fig. 2*H*) along the shore-normal transects were then interpolated between adjacent shore-normal transects to develop a flood extent layer (fig. 6) for both model runs, with and without coral reefs (fig. 2*I*). The flood extent polygons were built by creating a minimum-bounding polygon between neighboring flood points (points in space, with information on flood water depth, along each 100-m spaced transect). The flood points were interpolated to create a flood depth raster (fig. 7) using natural neighbor interpolation and clipped by the extent of flooding polygon. For each flood-extent polygon, the cells flooded by wave-driven setup and runup for both scenarios were logged and areas computed (fig. 2*J*). The somewhat variable nature of the inland flooding extents (fig. 6) are caused by the interpolation between adjacent XBeach model profile cross-sections spaced every 100-m alongshore. The cross-shore profiles intersect different bathymetries, coral reefs, and flood up and over different topographies and therefore the extents of inland flooding sometimes vary substantially from one profile to the next. For example, a transect with high coral cover and a steeper shoreface with higher terrestrial elevations that limit flood extent may be adjacent to a section of coast characterized by lower coral cover, a more gently sloping shoreface, and lower terrestrial elevations that would result in greater inland flooding than the neighboring transect.

The resulting number of people threatened, damage, and economic impact were then computed using wave-driven flood extents and depths. The people and associated demographic attributes (race, income, and so on) impacted by wave-driven flooding were determined by cross-referencing the flooded cells with the U.S. Census Bureau's (2016) TIGER/Line database, as

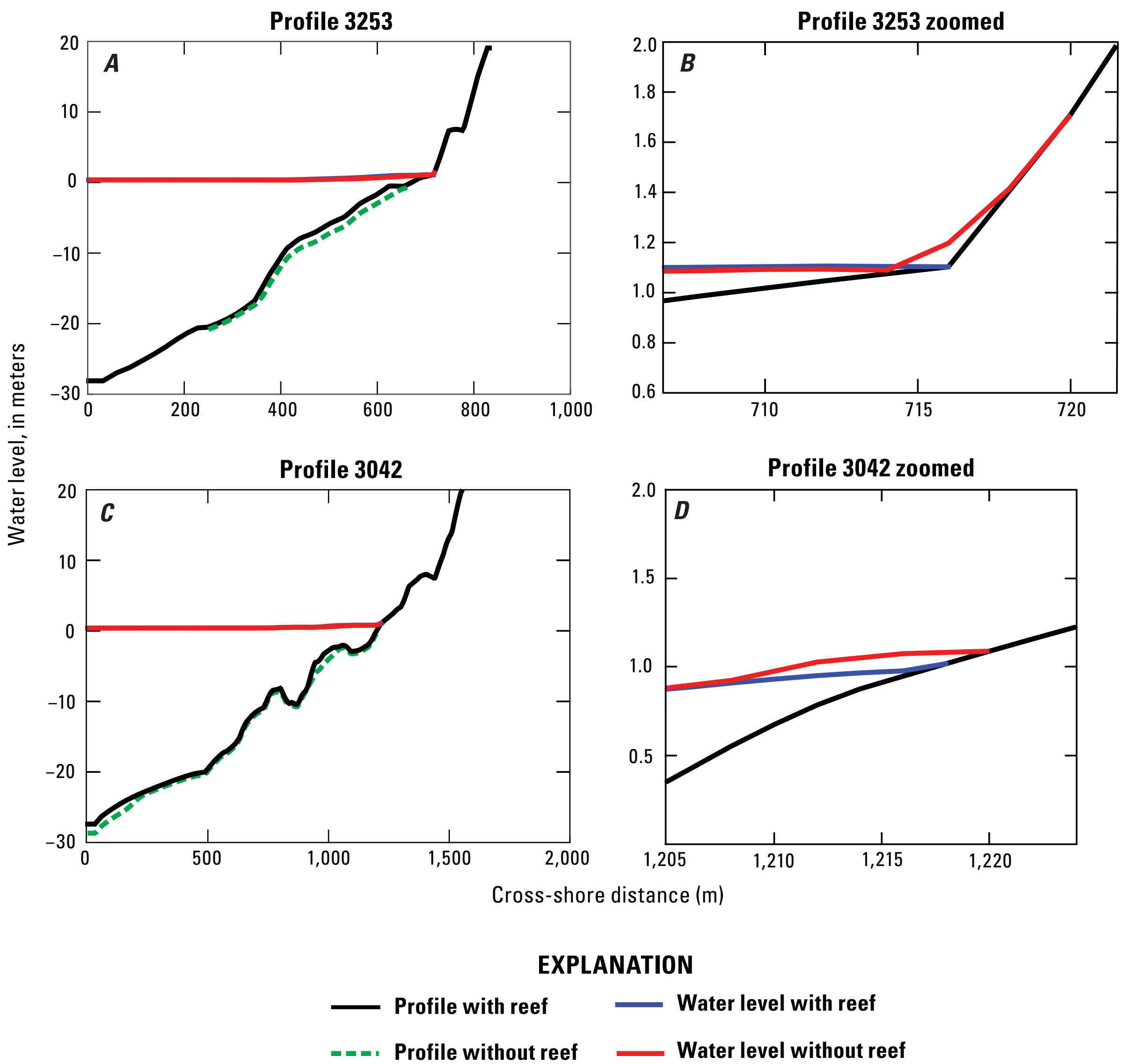

Figure 5. Plots of example topographic-bathymetric cross-sections and XBeach model wave-driven total water levels, in meters (m), with and without the presence of coral reefs offshore west Maui, Hawai'i. *A*. Cross-shore profile 3253 with a continuous fringing reef offshore. *B*. Zoomed-in view of profile 3253. *C*. Cross-shore profile 3042 with patch reefs offshore. *D*. Zoomed-in view of profile 3042. The black line denotes bathymetry and the blue line the total water level (setup plus runup) with coral reefs; the green line denotes bathymetry and the red line the total water level without coral reefs.

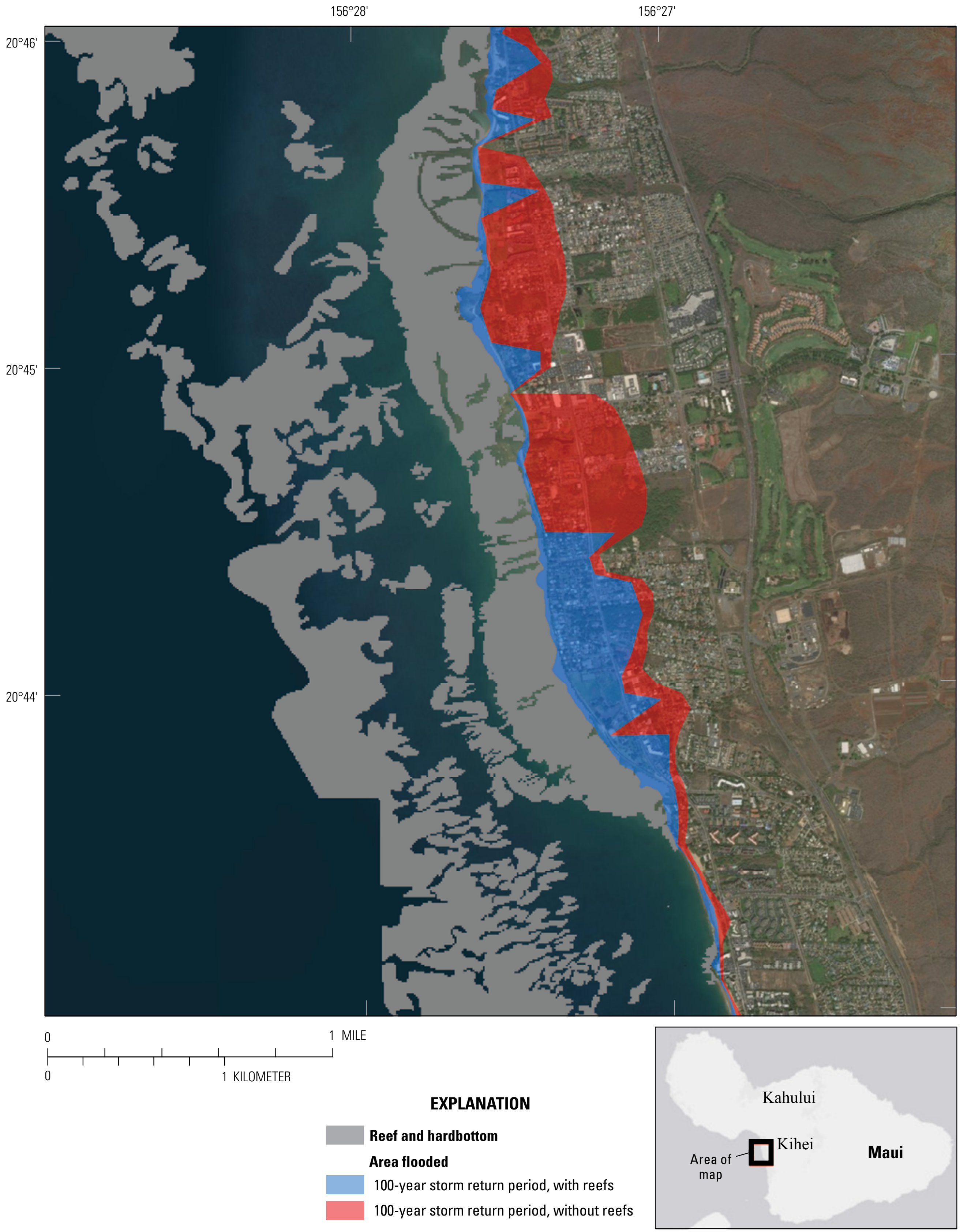

Figure 6. Map showing the 100-year floodplains with and without coral reefs on south Maui, Hawai'i. The blue regions denote the flooding extent from a 100-year storm with coral reefs present, and the red regions denote the additional flooding extent with 1 meter of coral reef loss (beyond the blue region). That is, the region protected by coral reefs from a 100-year storm is in the red band.

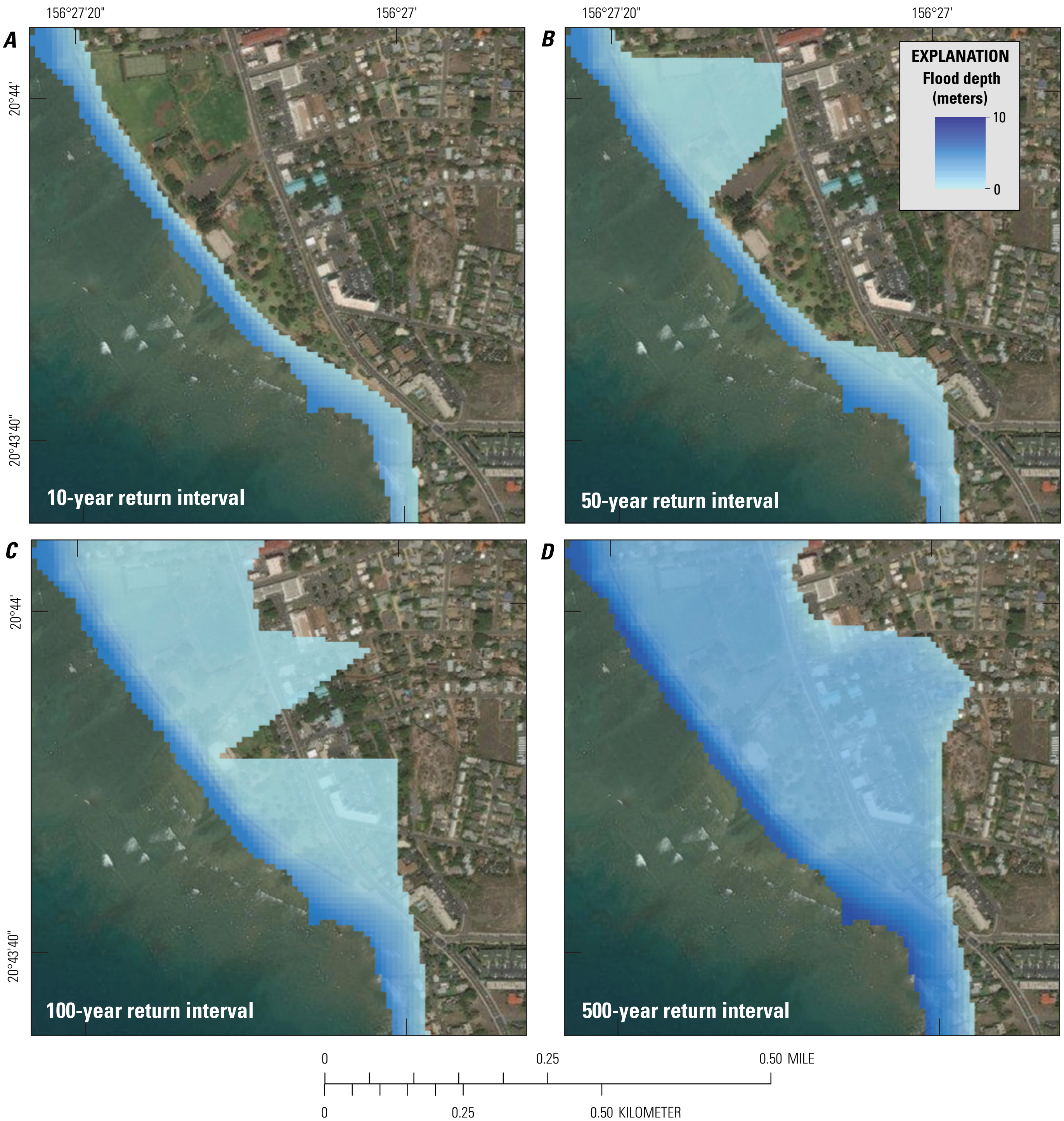

Figure 7. Maps showing example 10-meter resolution flood depth estimates for various storm recurrence intervals on south Maui, Hawai‘i. *A*. 10-year storm. *B*. 50-year storm. *C*. 100-year storm. *D*. 500-year storm. Colors indicate flood-water depth, in meters, interpolated from adjacent XBeach model profile transects spaced every 100 meters along the coast.

shown in figure 8. These TIGER/Line values are based on the 2010 census, and, thus, may not reflect current-day populations and demographics. The number of people flooded was calculated from the intersection between the flood-depth raster and people per unit area. The built infrastructure impacted by wave-driven flooding were determined by cross-referencing the flooded cells with the Federal Emergency Management Agency's (2016b) flood hazard exposure data in the Hazus database (Scawthorn and others, 2006a, b). These Hazus values are based on 2010 data, and, thus, may not reflect current-day building values and distributions. For the territories with no flood hazard exposure data (Guam, American Samoa, and the Northern Mariana Islands), tsunami hazard exposure data were used instead. However, the tsunami exposure data in these territories have a resolution of 1 square kilometer (km^2), whereas the flood hazard exposure data are at the census-block level (resolution of tens to hundreds of square meters). The extracted Hazus data original field names were changed, and the data projected into each respective Universal Transverse Mercator coordinate system (coordinate system from the transects belonging to that region).

For each type of Hazus asset (COM1, COM2, IND1, IND2, and so on), a damage-degree raster was created using the damage functions found in Hazus (fig. 2*K*) for the different categories of infrastructure, following the methodology of Wood and others (2013). These damage functions translate flood-water depth to the degree of damage (percentage of damage to each type of building). The damage-degree raster was built from the flood-depth raster and every cell represents the degree (or percentage) 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 dollars) was calculated for each asset as the building value per unit area multiplied by degree of damage, as shown in figure 9. Similarly, the number of flooded buildings result from the intersection between the flood-depth raster and buildings (and specific building types) per unit area, as shown in figure 9. Critical infrastructure in the flooded zones, obtained from the Hazus database, was also counted, if they were present in the flood zone. Finally, building damage, number of flooded buildings, and number of people flooded were summarized. The summary points were created as regularly 10-m spaced points within the union between all flood extents.

The value of coral reefs in terms of coastal hazard risk reduction was then determined as the difference in people and infrastructure impacted by wave-driven flooding in the simulations including coral reefs from those without coral reefs (fig. 2*L*). The calculated damages were aggregated by infrastructure type and summarized into tables (see results section) for each return period. The types of infrastructure were aggregated based upon the general building stock categories in Hazus (residential, commercial, industrial, agricultural, religious, government, and education buildings). Damage was estimated by percentage and was weighted by the area of flooding at a given depth for a given census block. The composition of the general building stock within a given census block was assumed to be evenly distributed throughout the block.

The summary tables provide damages for the different return periods and for each building stock type (appendix 8). 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 an event. For example, a return period of a flood of 100 years represents a probability of occurring in a given year of 1/100, or 0.01. The damages associated with the probability of occurrence characterize risk for the two reef scenarios, with and without reefs. 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 (with and without reefs; fig. 10) as

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

where D_i represents the loss in the damage curve (fig. 2*L*) for the probability of $1/T_i$, per Olsen and others (2015). The benefits were calculated as the difference in damages between the two scenarios: with and without reefs. The expected annual benefit (EAB), a measure of the annual protection of coral reefs, is calculated as

$$\mathrm{EAB} = \mathrm{EAD}_{\text{without reefs}} - \mathrm{EAD}_{\text{with reefs}}$$

The economic impact of wave-driven coastal flooding, however, is not only the 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). By multiplying the 2010 average contribution to GDP per person (table 2; Bureau of Economic Analysis, 2018) by the number of people living in the regions protected by coral reefs, one can compute the economic activity protected for people not displaced by the loss of housing from 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 GDP per person (table 2; Bureau of Economic Analysis, 2018) by the number of commercial and industrial buildings in the regions protected by coral reefs, one can compute the economic activity protected for businesses not impacted by the loss of infrastructure from coastal flooding. Because there are no data linking the people living in an area

Table 2. Gross domestic product (GDP) per person by island or region.

[Data from Bureau of Economic Analysis (2018)]

Location	GDP (in 2010 U.S. dollars)
American Samoa	10,353
Northern Mariana Islands	14,681
Guam	30,700
Florida	38,604
Hawaiʻi	49,418
Puerto Rico	26,436
Virgin Islands	40,043

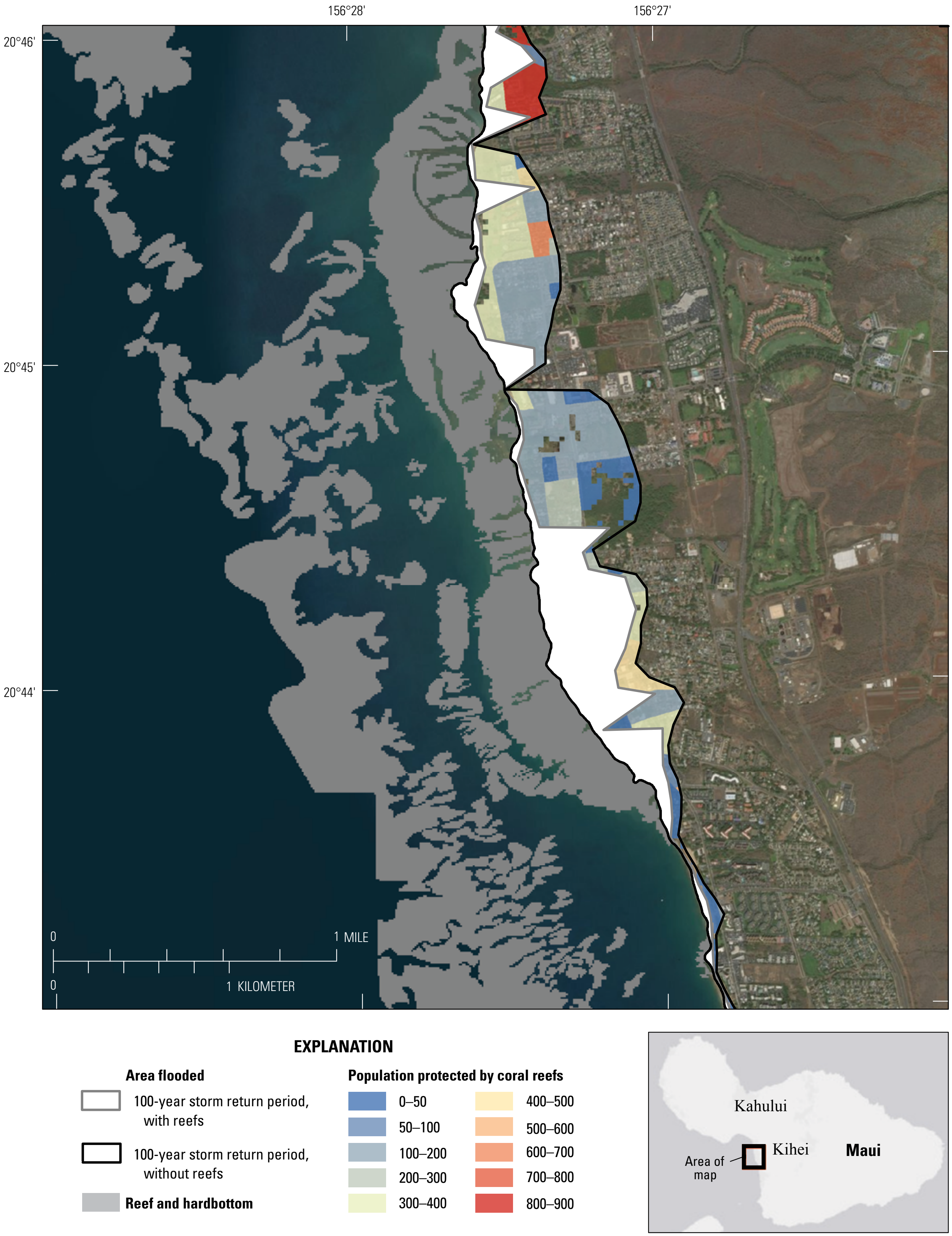

Figure 8. Map showing the distribution of people protected by coral reefs from flooding for the 100-year storm on south Maui, Hawai'i. Colors indicate the population density, based on U.S. Census Bureau's TIGER/Line data, in the area protected by coral reefs.

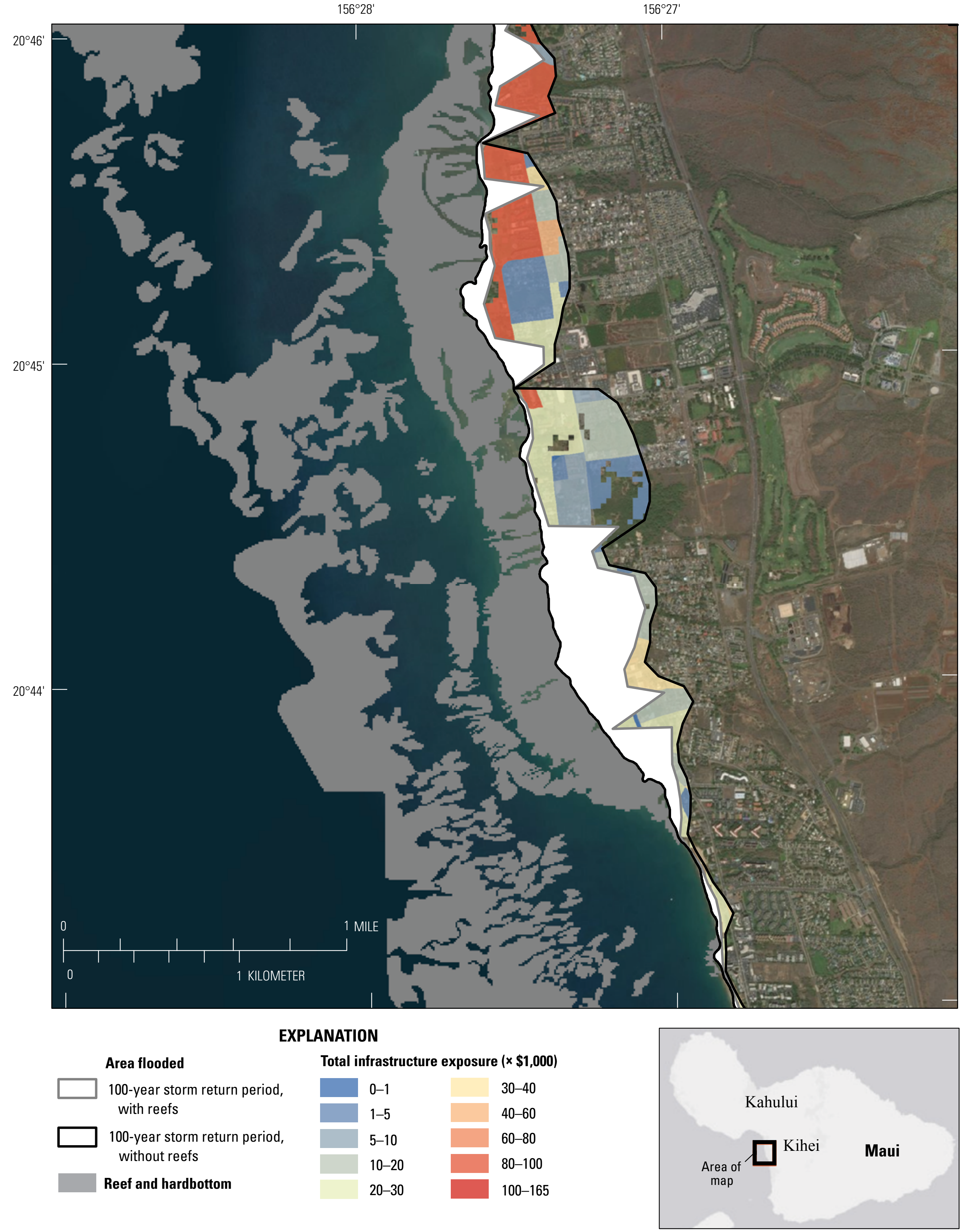

Figure 9. Map showing the value of infrastructure, in thousands of 2010 U.S. dollars, protected by coral reefs from flooding for the 100-year storm on south Maui, Hawai'i. Colors indicate the total value of infrastructure, based on Federal Emergency Management Agency's Hazus data, in the area protected by coral reefs.

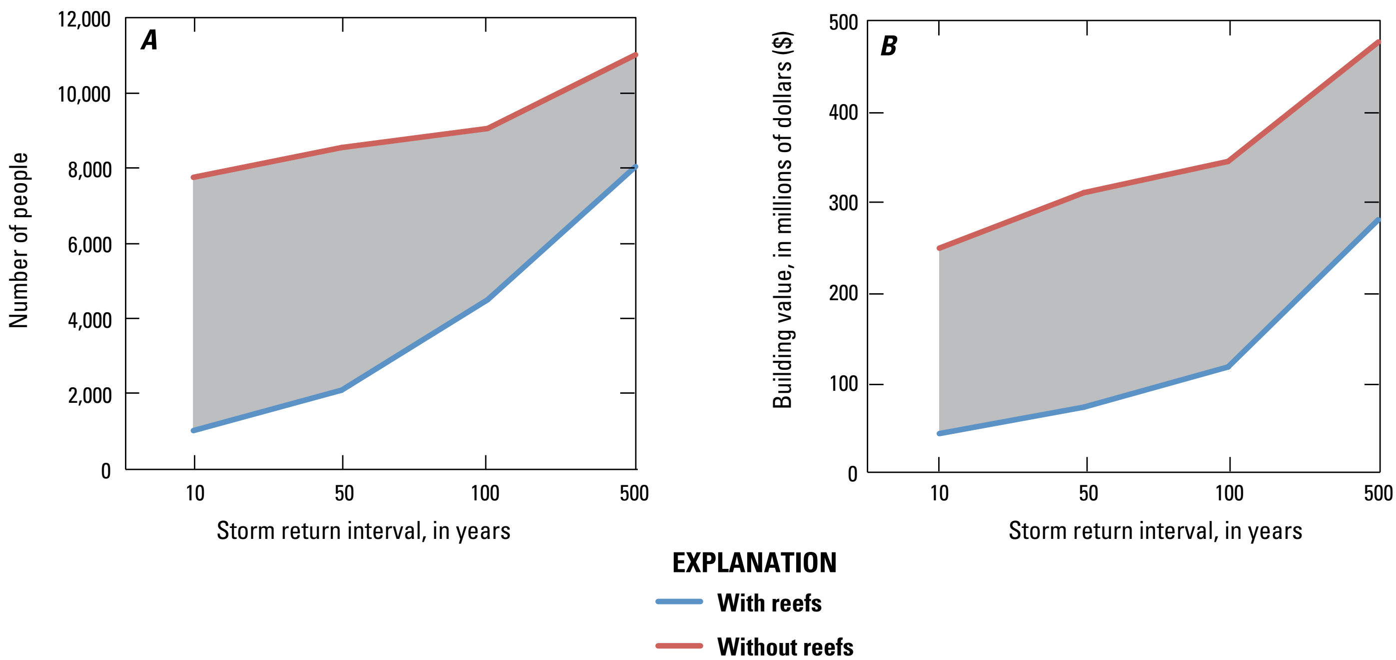

Figure 10. Example plots showing damage curves both for "with" and "without" reef scenarios for Maui, Hawai'i. *A*. Number of people displaced by loss of housing from coastal flooding. *B*. Values of damage to buildings by coastal flooding. The gray region denotes the protection provided by coral reefs.

to where those people work, we assume here that the economic activity protected for people not displaced by the loss of housing from coastal flooding is independent from the economic activity protected for businesses not impacted by the loss of infrastructure from coastal flooding.

Uncertainties, Limitations, and Assumptions

Numerical model errors were estimated to be ±50 centimeters. This value is greater than the root-mean-square and absolute errors computed between model results and measurements (van Dongeren and others, 2013; Quataert and others, 2015) but was used in an effort to mitigate for the fact that the number of storms tested are few and the geographic scope is large compared to where measurements for validation are available. The vertical resolution of the Hazus depth-damage curves is 0.3 m. Uncertainties associated with the baseline digital elevation model varied based on input data; see 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 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 number of extremes to select (with a limit of at least 30 extreme values to fit the extreme value distribution).
- The model scheme used to define the extreme flood levels were a combination of 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.
- We did not consider tide levels, 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 assumes shore-normal wave and flooding processes.
- The approach for assessing flood damages and the resulting benefits associated with each probability assumes 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 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 the reconstruction of the runup time series and the calculation of spatial losses associated with each event, which is 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 are alongshore interpolations and are 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 Federal Emergency Management Agency's (2016b) 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.
- The composition of the general building stock within a given census block was assumed to be evenly distributed throughout the block.
- 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 is independent from the economic activity protected for businesses not impacted by the loss of infrastructure from coastal flooding.

Results

Flooding Extents

This section summarizes the benefits provided by coral reefs for each region considered in the analysis for the four storm return periods. The benefits are expressed in terms of land surface, damage averted, and number and value of buildings or assets protected from coastal flooding. The benefits are calculated as the differences between the "with" and "without" reef scenarios. The expected annual benefit, in terms of area protected by U.S. coral reefs annually, is 82.9 km^2 (32.0 square miles, mi^2), or 4 percent of the coastal zone in the islands or regions studied in this report (tables 3 and 4).

Societal Impacts

The expected annual benefit, in terms of the number of people protected by U.S. coral reefs annually, is 18,180 people (table 5). The breakdown in benefits by demographics (children, senior citizens, low income, and minorities) is provided in appendix 7.

Economic Impacts

The expected annual benefit, in terms of the number of buildings protected by U.S. coral reefs annually, is 5,694 (table 6). The breakdown in benefits by type of structure (residential, commercial, industrial, government, educational, agricultural, and religious) is provided in appendix 8. The total value of those buildings protected by U.S. coral reefs annually is $825,926,417 (table 7). The expected annual benefit, in terms of the value of economic activity provided by housing that is protected by U.S. coral reefs annually, is $699,214,729 (appendix 9) and the value of economic activity provided by commercial and industrial buildings protected by U.S. coral reefs annually is $272,825,392 (appendix 9). In sum, the total expected annual benefit, in terms of the value of all coastal storm flooding protection (sum of tables 7 and 8) provided by U.S. coral reefs annually, is $1,805,511,877 (table 9).

Critical Infrastructure

The expected annual benefit, in terms of the number of essential facilities (hospitals, fire stations, police stations, schools, and emergency operation centers) protected in the United States by coral reefs annually, is 19 (table 10). The number of lifeline utility systems (water, wastewater, electrical, oil and gas, and communications) protected by coral reefs annually is 9 (table 11). The length of highway protected by coral reefs annually is 41.3 km (15.9 miles, mi) (table 12). Four transportation systems (ports and airports) are protected annually by coral reefs (tables 12 and 13).

Table 3. Spatial extent, in square kilometers, protected by coral reefs from flooding for different return-interval storms by island or region.

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	1.60	1.91	1.88	1.23
American Samoa	Ofu and Olosega	0.20	0.22	0.24	0.26
American Samoa	Ta‘ū	0.14	0.15	0.16	0.19
Northern Mariana Islands	Saipan	0.34	0.55	0.57	1.11
Northern Mariana Islands	Tinian	0.28	0.49	0.49	0.60
Guam	Guam	0.88	1.11	1.26	1.28
Florida	Peninsula	6.96	10.01	11.52	28.62
Florida	Florida Keys	3.19	5.36	8.13	2.58
Hawai‘i	Island of Hawai‘i	6.23	7.17	7.69	9.15
Hawai‘i	Maui	10.84	9.27	7.57	4.48
Hawai‘i	Lāna‘i	0.73	0.81	0.86	1.02
Hawai‘i	Moloka‘i	1.59	1.71	1.80	2.18
Hawai‘i	Kaho‘olawe	0.40	0.44	0.45	0.47
Hawai‘i	O‘ahu	11.08	9.71	9.52	9.00
Hawai‘i	Kaua‘i	2.60	3.85	4.32	5.89
Hawai‘i	Ni‘ihau	0.73	0.88	1.07	1.35
Puerto Rico	Isla de Puerto Rico	22.71	26.11	29.57	37.74
Puerto Rico	Isla de Culebra	0.29	0.40	0.62	0.77
Puerto Rico	Isla de Vieques	0.75	1.26	1.39	1.75
Virgin Islands	Saint Croix	2.17	2.75	3.01	3.34
Virgin Islands	Saint John	0.14	0.22	0.31	0.27
Virgin Islands	Saint Thomas	0.32	0.41	0.50	1.33

Table 4. Spatial extent, in percentage of total coastal area per island or region, protected by coral reefs from flooding for different return-interval storms by island or region.

[Total coastal area refers to land less than 1 kilometer inland and below 10 meters in elevation]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	8	9	9	6
American Samoa	Ofu and Olosega	7	8	9	10
American Samoa	Ta‘ū	4	5	5	6
Northern Mariana Islands	Saipan	2	3	3	5
Northern Mariana Islands	Tinian	2	4	4	5
Guam	Guam	1	2	2	2
Florida	Peninsula	3	4	5	12
Florida	Florida Keys	1	2	3	1
Hawai‘i	Island of Hawai‘i	3	4	4	5
Hawai‘i	Maui	14	12	10	6
Hawai‘i	Lāna‘i	4	4	4	5
Hawai‘i	Moloka‘i	3	3	3	4
Hawai‘i	Kaho‘olawe	4	5	5	5
Hawai‘i	O‘ahu	5	4	4	4
Hawai‘i	Kaua‘i	3	5	6	8
Hawai‘i	Ni‘ihau	2	2	2	3
Puerto Rico	Isla de Puerto Rico	5	6	6	8
Puerto Rico	Isla de Culebra	3	4	6	7
Puerto Rico	Isla de Vieques	2	3	3	4
Virgin Islands	Saint Croix	4	5	6	6
Virgin Islands	Saint John	1	1	2	1
Virgin Islands	Saint Thomas	2	2	3	7

Table 5. Total number of people protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	1,046	1,009	990	649
American Samoa	Ofu and Olosega	6	8	9	12
American Samoa	Ta‘ū	15	17	17	25
Northern Mariana Islands	Saipan	704	878	560	1,580
Northern Mariana Islands	Tinian	9	51	58	23
Guam	Guam	197	156	198	312
Florida	Peninsula	7,820	15,981	20,130	53,584
Florida	Florida Keys	1,064	3,344	3,938	2,099
Hawai‘i	Island of Hawai‘i	600	724	743	796
Hawai‘i	Maui	6,248	6,013	4,235	2,749
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	2	3	3	13
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	5,586	5,637	3,957	3,553
Hawai‘i	Kaua‘i	193	189	313	355
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	6,840	12,424	17,609	35,279
Puerto Rico	Isla de Culebra	17	32	39	90
Puerto Rico	Isla de Vieques	1	1	1	1
Virgin Islands	Saint Croix	482	699	914	429
Virgin Islands	Saint John	6	8	25	8
Virgin Islands	Saint Thomas	108	113	93	80

Table 6. Total number of buildings (of all infrastructure types) protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	425	405	417	269
American Samoa	Ofu and Olosega	1	2	2	2
American Samoa	Ta‘ū	9	11	11	16
Northern Mariana Islands	Saipan	53	72	58	167
Northern Mariana Islands	Tinian	2	8	9	9
Guam	Guam	58	45	59	84
Florida	Peninsula	1,129	2,565	2,945	9,781
Florida	Florida Keys	537	1,703	1,985	1,099
Hawai‘i	Island of Hawai‘i	280	325	335	356
Hawai‘i	Maui	1,914	1,791	1,232	853
Hawai‘i	Lāna‘i	0	0	0	1
Hawai‘i	Moloka‘i	1	2	3	9
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	1,586	1,722	1,163	1,049
Hawai‘i	Kaua‘i	113	137	209	222
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	3,425	5,667	7,261	11,622
Puerto Rico	Isla de Culebra	17	29	37	69
Puerto Rico	Isla de Vieques	2	4	4	2
Virgin Islands	Saint Croix	175	250	274	190
Virgin Islands	Saint John	4	6	15	5
Virgin Islands	Saint Thomas	27	26	24	22

Table 7. Total value of all buildings (of all infrastructure types) protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	45,062,194	50,235,092	55,296,346	45,151,430
American Samoa	Ofu and Olosega	133,904	190,098	256,618	343,816
American Samoa	Ta‘ū	1,332,694	1,705,537	1,913,229	1,714,184
Northern Mariana Islands	Saipan	8,440,917	13,510,503	14,037,252	33,267,181
Northern Mariana Islands	Tinian	1,135,367	1,901,951	2,095,199	2,870,504
Guam	Guam	12,523,985	10,845,848	14,307,264	21,479,597
Florida	Peninsula	496,808,161	1,087,517,050	1,433,821,392	4,639,275,600
Florida	Florida Keys	51,302,037	114,538,932	152,395,028	115,357,921
Hawai‘i	Island of Hawai‘i	42,875,759	50,655,894	52,324,393	59,566,784
Hawai‘i	Maui	202,802,131	234,104,090	225,630,115	194,479,455
Hawai‘i	Lāna‘i	97,224	104,730	105,981	106,313
Hawai‘i	Moloka‘i	72,094	92,642	128,534	354,783
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	368,841,786	353,116,245	340,006,994	314,872,587
Hawai‘i	Kaua‘i	10,080,787	14,529,798	18,675,364	23,309,226
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	107,237,273	195,128,049	277,282,495	514,413,849
Puerto Rico	Isla de Culebra	232,754	498,925	693,718	1,439,420
Puerto Rico	Isla de Vieques	175,922	126,877	148,189	207,562
Virgin Islands	Saint Croix	30,521,477	50,437,724	63,035,367	57,335,990
Virgin Islands	Saint John	852,151	1,489,952	3,965,600	1,880,331
Virgin Islands	Saint Thomas	5,910,764	7,253,756	7,139,596	8,204,784

Table 8. Total value of economic activity protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	12,838,554	12,737,169	12,689,057	8,134,705
American Samoa	Ofu and Olosega	70,720	100,464	108,116	140,024
American Samoa	Ta‘ū	260,015	332,638	322,957	428,946
Northern Mariana Islands	Saipan	14,048,119	18,498,753	12,628,264	35,093,069
Northern Mariana Islands	Tinian	178,904	925,324	1,056,896	499,245
Guam	Guam	18,836,690	13,142,572	17,730,626	24,400,493
Florida	Peninsula	437,955,608	885,356,612	1,085,772,141	2,967,707,234
Florida	Florida Keys	61,747,854	194,808,506	245,200,855	160,115,742
Hawai‘i	Island of Hawai‘i	47,318,440	54,994,432	56,569,432	59,507,116
Hawai‘i	Maui	485,867,446	464,643,386	311,738,118	186,049,202
Hawai‘i	Lāna‘i	2,323	3,379	3,287	5,608
Hawai‘i	Moloka‘i	120,000	170,267	235,027	882,889
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	354,961,794	352,609,166	246,048,630	223,615,374
Hawai‘i	Kaua‘i	11,600,021	10,698,418	16,910,505	19,878,382
Hawai‘i	Ni‘ihau	1,620	4,454	3,914	3,914
Puerto Rico	Isla de Puerto Rico	186,767,291	342,346,484	488,469,977	976,771,828
Puerto Rico	Isla de Culebra	458,726	842,063	1,043,991	2,373,679
Puerto Rico	Isla de Vieques	17,019	19,333	28,346	31,696
Virgin Islands	Saint Croix	36,075,541	57,303,999	69,385,281	32,195,508
Virgin Islands	Saint John	511,379	801,300	2,743,726	792,042
Virgin Islands	Saint Thomas	6,585,099	5,650,708	4,585,817	4,316,449

Table 9. Annual value of protection provided by coral reefs from flooding by island or region.

[–, no value determined]

Location	Sublocation	Number of people	Buildings (2010 U.S. dollars)	Economic activity (2010 U.S. dollars)
American Samoa	Tutuila	570	25,019,327	7,074,370
American Samoa	Ofu and Olosega	3	77,852	41,228
American Samoa	Ta‘ū	8	753,845	148,637
Northern Mariana Islands	Saipan	396	5,003,426	8,047,866
Northern Mariana Islands	Tinian	7	672,257	145,767
Guam	Guam	107	6,839,500	10,155,754
Florida	Peninsula	4,947	323,835,761	276,082,074
Florida	Florida Keys	716	32,125,237	42,970,125
Hawai‘i	Island of Hawai‘i	336	23,997,824	26,686,848
Hawai‘i	Maui	3,381	112,716,317	264,474,795
Hawai‘i	Lāna‘i	0	53,732	1,359
Hawai‘i	Moloka‘i	1	42,071	73,122
Hawai‘i	Kaho‘olawe	–	–	–
Hawai‘i	O‘ahu	3,040	200,942,259	194,404,235
Hawai‘i	Kaua‘i	107	5,854,742	6,466,170
Hawai‘i	Ni‘ihau	0	0	1,066
Puerto Rico	Isla de Puerto Rico	4,210	65,880,224	117,301,923
Puerto Rico	Isla de Culebra	11	148,502	286,275
Puerto Rico	Isla de Vieques	0	94,075	9,710
Virgin Islands	Saint Croix	278	18,021,883	21,325,668
Virgin Islands	Saint John	3	527,814	323,358
Virgin Islands	Saint Thomas	59	3,319,769	3,565,110

Table 10. Total number of essential facilities protected by coral reefs from flooding for different return-interval storms by region.

Infrastructure type	Location	Storm return interval			
		10-year	50-year	100-year	500-year
Hospitals	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	0
	Hawai‘i	1	2	2	0
	Puerto Rico	0	1	1	4
	Virgin Islands	0	0	0	0
Police stations	American Samoa	0	0	0	1
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	1	0	2	3
	Hawai‘i	0	0	0	0
	Puerto Rico	3	5	6	7
	Virgin Islands	1	0	0	0
Fire stations	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	1	2	3	6
	Hawai‘i	2	3	2	0
	Puerto Rico	0	0	0	1
	Virgin Islands	0	0	2	1
Schools	American Samoa	1	0	0	0
	Northern Mariana Islands	0	1	1	0
	Guam	0	0	0	0
	Florida	2	1	2	1
	Hawai‘i	2	2	6	1
	Puerto Rico	4	5	6	18
	Virgin Islands	0	0	0	0
Emergency operation centers	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	1
	Hawai‘i	0	0	0	0
	Puerto Rico	0	0	0	1
	Virgin Islands	0	0	0	0

Table 11. Total number of lifeline utility systems protected by coral reefs from flooding for different return-interval storms by region.

Infrastructure type	Location	Storm return interval			
		10-year	50-year	100-year	500-year
Water	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	2
	Hawai‘i	0	0	0	0
	Puerto Rico	0	0	0	1
	Virgin Islands	0	0	0	0
Wastewater	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	0
	Hawai‘i	2	2	1	0
	Puerto Rico	0	1	1	2
	Virgin Islands	0	0	0	0
Electrical	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	1	0	0	0
	Hawai‘i	2	2	1	0
	Puerto Rico	0	0	0	0
	Virgin Islands	0	0	0	0
Oil and gas	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	0
	Hawai‘i	1	1	1	0
	Puerto Rico	0	0	0	0
	Virgin Islands	0	0	0	0
Communications	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	0	0	0
	Hawai‘i	3	3	0	0
	Puerto Rico	0	0	1	1
	Virgin Islands	0	0	0	0

Table 12. Total transportation systems protected by coral reefs from flooding for different return-interval storms by region.

[Values for highways in kilometers; port and airport values are number of facilities]

Infrastructure type	Location	Storm return interval			
		10-year	50-year	100-year	500-year
Highways	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	2.513	6.049	9.490	22.175
	Hawai‘i	30.376	31.943	31.175	28.179
	Puerto Rico	4.498	7.302	9.710	15.566
	Virgin Islands	0	0	0	0
Ports	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	1	4	1
	Hawai‘i	3	5	0	4
	Puerto Rico	0	0	0	0
	Virgin Islands	0	0	0	0
Airports	American Samoa	0	0	0	0
	Northern Mariana Islands	0	0	0	0
	Guam	0	0	0	0
	Florida	0	1	1	0
	Hawai‘i	0	0	0	0
	Puerto Rico	0	0	0	1
	Virgin Islands	0	0	0	0

Table 13. Critical infrastructure protected by coral reefs from flooding annually by region.

[km, kilometers]

Location	Number of essential facilities	Number of lifeline utilities	Number of transportation systems
American Samoa	0.95	0	0
Northern Mariana Islands	0.07	0	0
Guam	0	0	0
Florida	4.12	0.96	0.28
Hawai‘i	5.24	7.97	3.42
Puerto Rico	7.61	0.12	0.01
Virgin Islands	0.98	0	0

Evaluating Additional Potential Scenarios

The entire flood and impact model structure can also be implemented for different potential scenarios to evaluate climate, social, and economic changes. These scenarios can include: (a) various elevations of sea-level rise; (b) population and economic growth; and (c) a change in reef health that causes a change in coral cover and thus frictional effects. Scenario (a) could be used to determine how projected 21st-century sea-level rise (Vermeer and Rahmstorf, 2009; Grinsted and others, 2010; Kopp and others, 2014) may reduce the effectiveness of corals reefs in coastal hazard risk reduction, whereas scenario (b) can demonstrate how the importance of coral reefs in coastal hazard risk reduction will change with projected population growth in coastal areas based on datasets such as those provided by Neumann and others (2015), the United Nation's (2016) world population prospects, and the International Institute for Applied Systems Analysis' shared socioeconomic pathways database (Riahi and others, 2017). Lastly, scenario (c) can provide guidance as to where coral reef restoration (Fox and others, 2005; Haisfield and others, 2010; Rinkevich, 2015; Montoya-May and others, 2016) would be most effective in terms of coastal hazard risk reduction, as quantified by people, assets, and infrastructure protected or the potential impact of coral reef degradation on coastal hazards.

Conclusions

Here, we present a new methodology to combine engineering, ecologic, geospatial, social, and economic tools to provide a rigorous social and economic valuation of the coastal protection benefits of coral reefs off the U.S. States of Hawaiʻi and Florida, the U.S. territories of Guam, American Samoa, Puerto Rico, and the Virgin Islands, and the Commonwealth of the Northern Mariana Islands. The resulting data make it possible to identify where, when, and how U.S. coral reefs provide the most significant flood reduction benefits. The goal is to provide sound, scientific guidance for U.S. Federal, State, territorial, and local governments' efforts on 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 reefs to, ultimately, save dollars and protect lives. In addition, the data presented here can inform new financing opportunities for reef management. Assessing risk reduction benefits in economic terms will advance decision making for coral reefs and allow new investments in reef conservation and management from new funding sources, such as defense, transportation, and emergency management agencies.

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Additional Digital Information

The digital data used to produce this report can be found in:

Gibbs, A.E., Cole, A.D., Lowe, E., Reguero, B.G., and Storlazzi, C.D., 2019, Projected flooding extents and depths based on 10-, 50-, 100-, and 500-year wave energy return periods, with and without coral reefs, for the States of Hawai‘i and Florida, the territories of Guam, American Samoa, Puerto Rico, and the U.S. Virgin Islands, and the Commonwealth of the Northern Mariana Islands: U.S. Geological Survey data release, https://doi.org/10.5066/P9KMH2VX.

For more information on the U.S. Geological Survey’s Coral Reef Project, visit https://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 Nature Conservancy’s Global Oceans Program, visit https://global.nature.org/our-global-solutions/oceans.

For more information on The Nature Conservancy’s Coastal Resilience platform, visit https://coastalresilience.org.

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

For more information on Deltares’ Hydro- and Morphodynamics During Extreme Events group, visit https://www.deltares.nl/en/issues/event-driven-hydro-morphodynamics.

Contact Information

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Appendixes

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

Parameter	Value
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; NGDC, National Geophysical Data Center; PacIOOS, Pacific Islands Ocean Observing System]

Location	5-km grid cells	1-km grid cells	200-m grid cells	Grid dimensions (E-W × N-S)	Data source
American Samoa		AmSam		164 × 28	Lim and others, 2010
American Samoa			Tutuila	235 × 100	Carignan and others, 2013
American Samoa			Ofu-Olosega & Tau	155 × 79	Lim and others, 2010
Northern Mariana Islands			Saipan	151 × 136	PacIOOS, 2016a
Northern Mariana Islands			Tinian	127 × 155	PacIOOS, 2016b
Guam			Guam	221 × 285	Chamberlin, 2008
Florida			Dry Tortugas	295 × 190	NGDC, 2001
Florida			Key West	505 × 255	NGDC, 2001
Florida			Marathon	505 × 337	NGDC, 2001
Florida			Islamorada	383 × 334	NGDC, 2001
Florida			Miami	291 × 502	NGDC, 2001
Hawaiʻi	HiChain			295 × 192	NGDC, 2005
Hawaiʻi		Hawaii		142 × 159	NGDC, 2005
Hawaiʻi			Hawaii_North	400 × 190	NGDC, 2005
Hawaiʻi			Hawaii_East	235 × 300	NGDC, 2005
Hawaiʻi			Hawaii_Southeast	310 × 160	NGDC, 2005
Hawaiʻi			Hawaii_South	350 × 205	NGDC, 2005
Hawaiʻi			Hawaii_West	185 × 400	NGDC, 2005
Hawaiʻi		MauiNui		146 × 86	NGDC, 2005
Hawaiʻi			Lanai	145 × 120	NGDC, 2005
Hawaiʻi			Kahoolawe	115 × 170	NGDC, 2005
Hawaiʻi			Molokai	146 × 86	NGDC, 2005
Hawaiʻi			Maui_East	265 × 220	NGDC, 2005
Hawaiʻi			Maui_West	195 × 230	NGDC, 2005
Hawaiʻi			Oahu	420 × 290	NGDC, 2005
Hawaiʻi			Kauai	293 × 242	NGDC, 2005
Hawaiʻi			Niihau	128 × 178	NGDC, 2005
Puerto Rico		PR_all		245 × 94	Taylor and others, 2008b
Puerto Rico			PR_North-Central	330 × 155	Taylor and others, 2008b
Puerto Rico			PR_Northeast	330 × 155	Taylor and others, 2008b
Puerto Rico			PR_Northwest	315 × 155	Taylor and others, 2008b
Puerto Rico			PR_South-Central	320 × 160	Taylor and others, 2008b
Puerto Rico			PR_Southeast	320 × 165	Taylor and others, 2008b
Puerto Rico			PR_Southwest	230 × 160	Taylor and others, 2008b
Virgin Islands		USVI		74 × 108	Love and others, 2014a, b
Virgin Islands			StCroix	260 × 115	Love and others, 2014a, b
Virgin Islands			StJohnStThomas	270 × 206	Love and others, 2014a, b

Appendix 3. Benthic Habitat and Shoreline Datasets

[FFWCC, Florida Fish and Wildlife Conservation Commission; FWRI, Fish and Wildlife Research Institute; NOAA, National Oceanic and Atmospheric Administration; m^2, square meters]

Location	Sublocation	Benthic habitat data		Shoreline data source
		Minimum mapping unit	Data source	
American Samoa	Tutuila	1 acre	Anderson, 2004a	NOAA, 2002d
American Samoa	Ofu and Olosega	1 acre	Anderson, 2004a	NOAA, 2002a
American Samoa	Ta‘ū	1 acre	Anderson, 2004a	NOAA, 2002a
Northern Mariana Islands	Saipan	1 acre	Anderson, 2004c	NOAA, 2002b
Northern Mariana Islands	Tinian	1 acre	Anderson, 2004c	NOAA, 2002c
Guam	Guam	1 acre	Anderson, 2004b	NOAA, 2003
Florida	Dry Tortugas	<1 acre	FFWCC-FWRI, 2016	NOAA, 2015
Florida	Key West	<1 acre	FFWCC-FWRI, 2016	NOAA, 2015
Florida	Florida Keys	<1 acre	FFWCC-FWRI, 2016	NOAA, 2015
Florida	Miami	<1 acre	FFWCC-FWRI, 2016	NOAA, 2015
Florida	Palm Beach	<1 acre	FFWCC-FWRI, 2016	NOAA, 2015
Hawai‘i	Island of Hawai‘i	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Maui	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Lāna‘i	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Moloka‘i	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Kaho‘olawe	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Kaua‘i	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	Ni‘ihau	1 acre	Anderson, 2007	State of Hawaii, 1997
Hawai‘i	O‘ahu	1 acre	Anderson, 2007	State of Hawaii, 1997
Puerto Rico	Isla de Puerto Rico	1 acre	NOAA, 2001a	NOAA, 2015
Puerto Rico	Isla de Culebra	1 acre	NOAA, 2001a	NOAA, 2015
Puerto Rico	Isla de Vieques	1 acre	NOAA, 2001a	NOAA, 2015
Virgin Islands	Saint Croix	1 acre	NOAA, 2001b	NOAA, 2015
Virgin Islands	Saint John	1,000 m^2	Zitello and others, 2009	NOAA, 2015
Virgin Islands	Saint Thomas	1 acre	NOAA, 2001c	NOAA, 2015

Appendix 4. Cross-shore XBeach Transects

Location	Sublocation	Number of cross-shore transects
American Samoa	Tutuila	1,004
American Samoa	Ofu and Olosega	196
American Samoa	Taʻū	275
Northern Mariana Islands	Saipan	585
Northern Mariana Islands	Tinian	450
Guam	Guam	1,295
Florida	Dry Tortugas	300
Florida	Key West	545
Florida	Florida Keys	1,127
Florida	Miami	1,139
Florida	Palm Beach	1,168
Hawaiʻi	Island of Hawaiʻi	4,582
Hawaiʻi	Maui	2,087
Hawaiʻi	Lānaʻi	759
Hawaiʻi	Molokaʻi	2,886
Hawaiʻi	Kahoʻolawe	456
Hawaiʻi	Kauaʻi	1,455
Hawaiʻi	Niʻihau	677
Hawaiʻi	Oʻahu	1,997
Puerto Rico	Isla de Puerto Rico	4,588
Puerto Rico	Isla de Culebra	244
Puerto Rico	Isla de Vieques	687
Virgin Islands	Saint Croix	803
Virgin Islands	Saint John	396
Virgin Islands	Saint Thomas	466

Appendix 5. Bathymetric and Topographic Datasets

[NGDC, National Geophysical Data Center; NOAA, National Oceanic and Atmospheric Administration; PacIOOS, Pacific Islands Ocean Observing System; PIBHMC, Pacific Islands Benthic Habitat Mapping Center]

Location	Sublocation	Data source
American Samoa	Tutuila	Carignan and others, 2013
American Samoa	Ofu, Olosega, and Taʻū	Lim and others, 2010
Northern Mariana Islands	Saipan	PIBHMC, 2007a Amante and Eakins, 2009 PacIOOS, 2016a
Northern Mariana Islands	Tinian	PIBHMC, 2007b Amante and Eakins, 2009 PacIOOS, 2016b
Guam	Guam	Chamberlin, 2008
Florida	Dry Tortugas	NGDC, 2001
Florida	Key West	Grothe and others, 2011
Florida	Florida Keys	NGDC, 2001
Florida	Miami	Carignan and others, 2015
Florida	Palm Beach	NGDC, 2001
Hawaiʻi	Island of Hawaiʻi	NGDC, 2005
Hawaiʻi	Hilo	Love and others, 2011a
Hawaiʻi	Kawaihae	Carignan and others, 2011a
Hawaiʻi	Keauhou	Carignan and others, 2011b
Hawaiʻi	Maui Nui	NGDC, 2005
Hawaiʻi	Maui	NOAA, 2016 Taylor and others, 2008a
Hawaiʻi	Lānaʻi	NGDC, 2005
Hawaiʻi	Molokaʻi	NGDC, 2005
Hawaiʻi	Kahoʻolawe	NGDC, 2005
Hawaiʻi	Kauaʻi	Friday and others, 2012
Hawaiʻi	Niʻihau	Friday and others, 2012
Hawaiʻi	Oʻahu	Love and others, 2011b
Puerto Rico	Arecibo	Taylor and others, 2008c
Puerto Rico	Isla de Culebra	Taylor and others, 2008b
Puerto Rico	Fajardo	Taylor and others, 2008d
Puerto Rico	Guayama	Taylor and others, 2008e
Puerto Rico	Mayagüez	Taylor and others, 2008f
Puerto Rico	Ponce	Taylor and others, 2008g
Puerto Rico	San Juan	Taylor and others, 2008h
Puerto Rico	Isla de Vieques	Taylor and others, 2008b
Virgin Islands	Saint Croix	Love and others, 2014a
Virgin Islands	Saint Thomas	Love and others, 2014b
Virgin Islands	Saint John	Love and others, 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. Societal Impacts by Demographics

Table 7.1. Number of children protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	383	370	364	236
American Samoa	Ofu and Olosega	2	3	3	5
American Samoa	Ta‘ū	6	7	7	10
Northern Mariana Islands	Saipan	195	240	154	435
Northern Mariana Islands	Tinian	2	13	15	6
Guam	Guam	56	45	57	90
Florida	Peninsula	646	1,515	2,103	6,726
Florida	Florida Keys	173	582	610	257
Hawai‘i	Island of Hawai‘i	99	124	129	141
Hawai‘i	Maui	1,241	1,220	872	558
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	1	1	1	2
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	1,227	1,339	900	757
Hawai‘i	Kaua‘i	35	33	64	77
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	1,354	2,477	3,483	8,540
Puerto Rico	Isla de Culebra	2	4	5	13
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	122	176	235	106
Virgin Islands	Saint John	1	1	4	1
Virgin Islands	Saint Thomas	22	23	19	15

Table 7.2. Number of senior citizens protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	47	44	42	27
American Samoa	Ofu and Olosega	0	1	1	1
American Samoa	Ta‘ū	1	1	1	2
Northern Mariana Islands	Saipan	20	26	16	45
Northern Mariana Islands	Tinian	0	1	1	0
Guam	Guam	15	11	14	24
Florida	Peninsula	2,836	5,728	6,584	14,742
Florida	Florida Keys	156	525	581	339
Hawai‘i	Island of Hawai‘i	105	122	124	132
Hawai‘i	Maui	748	684	489	277
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	0	0	2
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	689	636	508	458
Hawai‘i	Kaua‘i	25	28	37	33
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	1,299	2,465	3,407	5,595
Puerto Rico	Isla de Culebra	6	10	11	18
Puerto Rico	Isla de Vieques	0	1	1	1
Virgin Islands	Saint Croix	63	91	114	58
Virgin Islands	Saint John	1	1	3	1
Virgin Islands	Saint Thomas	14	14	12	9

Table 7.3. Number of low-income (<$20,000 per year) individuals protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	55	53	52	34
American Samoa	Ofu and Olosega	1	1	1	2
American Samoa	Ta‘ū	1	2	2	2
Northern Mariana Islands	Saipan	92	113	72	210
Northern Mariana Islands	Tinian	1	4	5	2
Guam	Guam	10	8	10	15
Florida	Peninsula	862	1,896	2,203	5,753
Florida	Florida Keys	68	205	236	157
Hawai‘i	Island of Hawai‘i	45	52	52	49
Hawai‘i	Maui	346	354	272	158
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	0	0	1
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	158	145	81	73
Hawai‘i	Kaua‘i	19	21	38	50
Hawai‘i	Ni‘ihau	–	–	–	–
Puerto Rico	Isla de Puerto Rico	1,461	2,681	3,647	8,320
Puerto Rico	Isla de Culebra	5	9	11	23
Puerto Rico	Isla de Vieques	0	0	1	1
Virgin Islands	Saint Croix	55	82	108	46
Virgin Islands	Saint John	0	1	2	1
Virgin Islands	Saint Thomas	8	7	6	5

Table 7.4. Number of racial or ethnical minority individuals protected by coral reefs from flooding for different return-interval storms by island or region.

[–, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	32	35	35	28
American Samoa	Ofu and Olosega	–	–	–	–
American Samoa	Ta‘ū	0	0	0	0
Northern Mariana Islands	Saipan	403	509	321	914
Northern Mariana Islands	Tinian	4	24	27	10
Guam	Guam	44	35	44	70
Florida	Peninsula	2,166	4,675	6,879	21,530
Florida	Florida Keys	380	1,348	1,246	597
Hawai‘i	Island of Hawai‘i	112	133	135	140
Hawai‘i	Maui	1,860	1,807	1,269	837
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	0	0	1
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	1,377	1,499	1,000	1,002
Hawai‘i	Kaua‘i	43	26	37	34
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	6,638	12,038	17,003	34,333
Puerto Rico	Isla de Culebra	15	28	34	78
Puerto Rico	Isla de Vieques	0	0	0	1
Virgin Islands	Saint Croix	489	702	920	415
Virgin Islands	Saint John	3	5	17	4
Virgin Islands	Saint Thomas	98	98	81	66

Appendix 8. Economic Impacts by Building Structure Type

Table 8.1. Value of residential infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	33,831,291	35,131,604	38,529,048	32,590,895
American Samoa	Ofu and Olosega	67,572	99,621	138,684	195,713
American Samoa	Ta‘ū	979,633	1,253,973	1,405,927	1,367,881
Northern Mariana Islands	Saipan	3,649,547	5,934,616	6,190,926	15,359,567
Northern Mariana Islands	Tinian	891,117	1,466,437	1,641,087	2,499,046
Guam	Guam	6,614,534	6,486,163	8,223,696	12,904,144
Florida	Peninsula	393,787,800	870,988,321	1,114,074,635	3,640,927,246
Florida	Florida Keys	35,096,182	92,403,630	121,715,476	87,232,583
Hawai‘i	Island of Hawai‘i	31,979,469	38,307,443	39,460,911	44,747,586
Hawai‘i	Maui	136,066,606	153,366,244	147,298,242	135,261,344
Hawai‘i	Lāna‘i	97,224	104,730	105,981	106,313
Hawai‘i	Moloka‘i	72,094	85,088	103,682	269,043
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	250,403,517	245,814,252	244,366,409	245,122,832
Hawai‘i	Kaua‘i	9,617,881	13,906,300	18,061,072	22,350,362
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	106,402,960	192,671,038	272,776,125	503,020,038
Puerto Rico	Isla de Culebra	232,754	498,925	693,718	1,439,367
Puerto Rico	Isla de Vieques	175,922	126,877	148,189	207,562
Virgin Islands	Saint Croix	22,687,346	34,500,315	41,869,134	43,546,376
Virgin Islands	Saint John	677,743	1,182,595	2,813,744	1,542,423
Virgin Islands	Saint Thomas	4,808,621	6,432,601	6,506,281	7,263,312

Table 8.2. Value of commercial infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	2,497,856	2,891,048	3,320,393	2,998,042
American Samoa	Ofu and Olosega	8,878	16,023	25,543	32,671
American Samoa	Ta‘ū	151,389	231,368	260,800	189,936
Northern Mariana Islands	Saipan	3,328,281	5,567,321	5,684,539	13,104,137
Northern Mariana Islands	Tinian	110,229	178,011	186,918	212,014
Guam	Guam	4,707,465	3,276,176	4,476,962	6,618,367
Florida	Peninsula	70,779,270	158,484,599	211,204,322	749,154,281
Florida	Florida Keys	13,202,009	17,932,476	24,900,544	21,980,419
Hawai‘i	Island of Hawai‘i	9,468,004	10,641,551	11,058,822	11,935,230
Hawai‘i	Maui	56,580,494	68,875,325	67,116,489	51,672,735
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	0	0	10,369
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	104,592,002	94,887,537	84,407,560	60,415,336
Hawai‘i	Kaua‘i	331,970	473,012	486,311	793,352
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	431,821	1,450,881	2,473,692	6,519,534
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	5,696,426	11,794,367	15,815,058	9,408,406
Virgin Islands	Saint John	134,250	212,102	839,084	238,247
Virgin Islands	Saint Thomas	848,282	568,758	422,055	653,870

Table 8.3. Value of industrial infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	378,431	826,556	791,552	503,983
American Samoa	Ofu and Olosega	0	0	0	0
American Samoa	Ta‘ū	6,318	9,057	11,360	5,068
Northern Mariana Islands	Saipan	247,614	478,146	538,392	1,188,725
Northern Mariana Islands	Tinian	21,629	47,556	48,974	57,381
Guam	Guam	410,850	450,668	714,616	712,647
Florida	Peninsula	4,150,879	9,290,653	11,861,582	36,941,212
Florida	Florida Keys	640,065	1,286,780	1,881,503	2,009,020
Hawai‘i	Island of Hawai‘i	284,080	342,846	397,397	410,465
Hawai‘i	Maui	1,852,122	2,251,687	2,276,914	2,029,730
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	895	3,175	10,027
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	2,828,217	2,801,232	2,781,920	2,985,659
Hawai‘i	Kaua‘i	100,424	105,925	83,095	96,546
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	106,108	231,371	676,516	1,194,123
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	191,666	384,167	506,723	600,170
Virgin Islands	Saint John	3,741	6,211	13,156	18,906
Virgin Islands	Saint Thomas	52,075	58,144	57,608	94,079

Table 8.4. Value of government infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	2,051,849	4,282,505	4,544,835	3,720,292
American Samoa	Ofu and Olosega	0	0	0	0
American Samoa	Ta‘ū	30,489	24,397	34,071	67,256
Northern Mariana Islands	Saipan	179,859	197,541	277,848	670,420
Northern Mariana Islands	Tinian	41	300	295	172
Guam	Guam	187,436	111,554	174,973	227,319
Florida	Peninsula	650,807	1,224,301	1,119,474	8,298,899
Florida	Florida Keys	396,259	523,228	540,639	649,911
Hawai‘i	Island of Hawai‘i	258,004	316,281	329,951	435,692
Hawai‘i	Maui	950,263	1,075,179	1,064,243	445,783
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	0	0	292
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	532,180	426,681	299,716	127,649
Hawai‘i	Kaua‘i	1,902	2,441	2,262	2,402
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	13	102	142	489,508
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	585,965	952,243	1,359,997	743,617
Virgin Islands	Saint John	10,224	24,655	95,277	29,854
Virgin Islands	Saint Thomas	33,406	27,517	29,988	29,167

Table 8.5. Value of educational infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	2,822,995	3,255,719	3,157,165	2,324,187
American Samoa	Ofu and Olosega	41,462	47,143	49,964	69,307
American Samoa	Taʻū	85,818	150,048	157,648	51,374
Northern Mariana Islands	Saipan	801,881	1,014,898	1,050,111	2,273,112
Northern Mariana Islands	Tinian	96,753	180,063	187,141	89,008
Guam	Guam	173,162	122,408	181,847	283,441
Florida	Peninsula	2,097,751	2,232,487	1,727,128	23,268,631
Florida	Florida Keys	296,794	415,675	854,154	838,980
Hawaiʻi	Island of Hawaiʻi	94,516	147,366	155,592	657,161
Hawaiʻi	Maui	1,537,322	1,729,615	1,436,934	1,040,080
Hawaiʻi	Lānaʻi	0	0	0	0
Hawaiʻi	Molokaʻi	0	6,643	21,661	63,768
Hawaiʻi	Kahoʻolawe	–	–	–	–
Hawaiʻi	Oʻahu	5,213,860	4,746,944	4,346,526	3,852,285
Hawaiʻi	Kauaʻi	1,989	5,865	9,344	13,139
Hawaiʻi	Niʻihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	162,645	287,589	481,602	1,254,260
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	529,700	1,069,980	1,354,682	877,402
Virgin Islands	Saint John	11,407	21,442	97,059	11,299
Virgin Islands	Saint Thomas	79,195	66,600	57,996	105,354

Table 8.6. Value of agricultural infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	5,841	4,669	4,789	6,009
American Samoa	Ofu and Olosega	0	0	0	0
American Samoa	Taʻū	0	0	0	0
Northern Mariana Islands	Saipan	4,471	6,039	6,258	7,234
Northern Mariana Islands	Tinian	0	0	0	5
Guam	Guam	55,548	94,078	114,015	148,902
Florida	Peninsula	578,730	1,442,988	2,253,723	5,602,307
Florida	Florida Keys	442,971	388,619	485,908	408,680
Hawaiʻi	Island of Hawaiʻi	182,334	210,835	233,915	353,157
Hawaiʻi	Maui	172,903	270,735	312,827	358,768
Hawaiʻi	Lānaʻi	0	0	0	0
Hawaiʻi	Molokaʻi	0	0	0	0
Hawaiʻi	Kahoʻolawe	–	–	–	–
Hawaiʻi	Oʻahu	565,015	560,961	522,264	412,447
Hawaiʻi	Kauaʻi	7,353	9,058	8,247	11,153
Hawaiʻi	Niʻihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	16,899	225,027	539,543	954,575
Puerto Rico	Isla de Culebra	0	0	0	53
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	387,698	727,418	878,073	1,426,022
Virgin Islands	Saint John	456	2,002	2,752	4,207
Virgin Islands	Saint Thomas	3,143	5,603	2,561	3,972

Table 8.7. Value of religious infrastructure protected by coral reefs from flooding for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	3,473,932	3,842,989	4,948,566	3,008,020
American Samoa	Ofu and Olosega	15,992	27,312	42,427	46,125
American Samoa	Ta‘ū	79,047	36,694	43,423	145,552
Northern Mariana Islands	Saipan	229,265	311,942	289,177	663,988
Northern Mariana Islands	Tinian	15,598	29,585	30,784	12,877
Guam	Guam	374,990	304,800	421,156	584,777
Florida	Peninsula	24,762,911	43,853,718	91,580,513	175,083,019
Florida	Florida Keys	1,227,758	1,588,517	2,016,796	2,238,330
Hawai‘i	Island of Hawai‘i	609,353	689,573	687,805	1,027,498
Hawai‘i	Maui	5,642,424	6,535,304	6,124,466	3,671,018
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	16	16	1,285
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	4,707,008	3,878,652	3,282,646	1,956,345
Hawai‘i	Kaua‘i	19,269	27,197	25,035	42,272
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	116,826	262,042	334,877	981,811
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	442,674	1,009,232	1,251,697	733,994
Virgin Islands	Saint John	14,330	40,945	104,528	35,394
Virgin Islands	Saint Thomas	86,042	94,533	63,107	55,029

Appendix 9. Economic Impact Caused by Building Damage

Table 9.1. Value of economic activity protected by coral reefs from flooding of residential buildings for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	10,831,935	10,448,474	10,252,015	6,716,110
American Samoa	Ofu and Olosega	59,875	84,713	88,234	122,983
American Samoa	Ta‘ū	156,990	179,056	180,752	262,578
Northern Mariana Islands	Saipan	10,338,706	12,896,397	8,221,482	23,202,018
Northern Mariana Islands	Tinian	134,499	751,074	854,870	330,680
Guam	Guam	7,616,135	6,009,842	7,643,102	12,057,258
Florida	Peninsula	301,893,380	616,937,288	777,087,694	2,068,552,737
Florida	Florida Keys	41,093,945	129,102,830	152,019,985	81,048,150
Hawai‘i	Island of Hawai‘i	29,652,176	35,797,322	36,706,314	39,324,880
Hawai‘i	Maui	308,765,608	297,132,577	209,291,736	135,838,459
Hawai‘i	Lāna‘i	2,323	3,379	3,287	5,608
Hawai‘i	Moloka‘i	120,000	138,156	160,102	633,857
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	276,027,871	278,569,161	195,540,708	175,566,247
Hawai‘i	Kaua‘i	9,522,069	9,355,969	15,467,233	17,562,350
Hawai‘i	Ni‘ihau	1,620	4,454	3,914	3,914
Puerto Rico	Isla de Puerto Rico	180,828,651	328,437,459	465,515,833	932,628,767
Puerto Rico	Isla de Culebra	458,726	842,063	1,043,991	2,373,679
Puerto Rico	Isla de Vieques	17,019	19,333	28,346	31,696
Virgin Islands	Saint Croix	19,312,834	27,982,476	36,585,033	17,160,895
Virgin Islands	Saint John	225,862	338,741	993,239	312,446
Virgin Islands	Saint Thomas	4,316,419	4,516,121	3,743,125	3,185,976

Table 9.2. Value of economic activity protected by coral reefs from flooding of commercial and (or) industrial buildings for different return-interval storms by island or region.

[Values in 2010 U.S. dollars. –, no value determined]

Location	Sublocation	Storm return interval			
		10-year	50-year	100-year	500-year
American Samoa	Tutuila	2,006,618	2,288,695	2,437,042	1,418,594
American Samoa	Ofu and Olosega	10,845	15,751	19,882	17,042
American Samoa	Ta‘ū	103,025	153,582	142,204	166,368
Northern Mariana Islands	Saipan	3,709,412	5,602,356	4,406,782	11,891,051
Northern Mariana Islands	Tinian	44,405	174,250	202,026	168,565
Guam	Guam	11,220,555	7,132,730	10,087,524	12,343,235
Florida	Peninsula	136,062,228	268,419,324	308,684,446	899,154,497
Florida	Florida Keys	20,653,909	65,705,675	93,180,870	79,067,592
Hawai‘i	Island of Hawai‘i	17,666,264	19,197,111	19,863,118	20,182,236
Hawai‘i	Maui	177,101,838	167,510,809	102,446,382	50,210,743
Hawai‘i	Lāna‘i	0	0	0	0
Hawai‘i	Moloka‘i	0	32,111	74,925	249,032
Hawai‘i	Kaho‘olawe	–	–	–	–
Hawai‘i	O‘ahu	78,933,923	74,040,006	50,507,922	48,049,127
Hawai‘i	Kaua‘i	2,077,952	1,342,448	1,443,273	2,316,032
Hawai‘i	Ni‘ihau	0	0	0	0
Puerto Rico	Isla de Puerto Rico	5,938,640	13,909,025	22,954,144	44,143,060
Puerto Rico	Isla de Culebra	0	0	0	0
Puerto Rico	Isla de Vieques	0	0	0	0
Virgin Islands	Saint Croix	16,762,707	29,321,522	32,800,249	15,034,613
Virgin Islands	Saint John	285,517	462,560	1,750,487	479,596
Virgin Islands	Saint Thomas	2,268,680	1,134,587	842,692	1,130,473

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