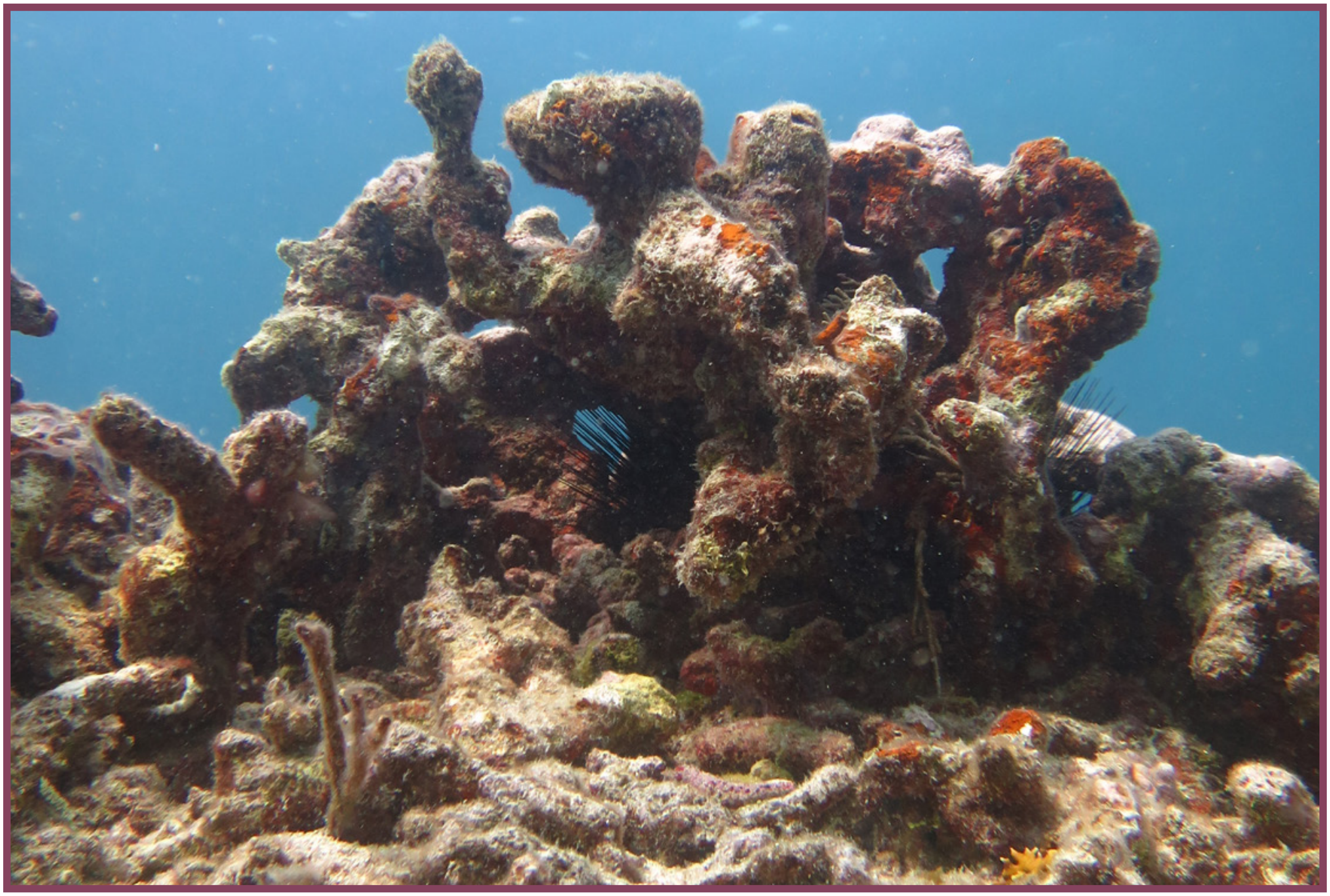
USGS science for a changing world | University of California Santa Cruz

Rigorously Valuing the Impact of Projected Coral Reef Degradation on Coastal Hazard Risk in Florida



Open-File Report 2021–1055

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

Cover. U.S. Geological Survey underwater photograph showing a degraded, algal-covered coral reef in Dry Tortugas National Park, Florida.

Rigorously Valuing the Impact of Projected Coral Reef Degradation on Coastal Hazard Risk in Florida

By Curt D. Storlazzi, Borja G. Reguero, Kimberly K. Yates, Kristen A. Cumming, Aaron D. Cole, James B. Shope, Camila Gaido L., David G. Zawada, Stephanie R. Arsenault, Zachery W. Fehr, Barry A. Nickel, and Michael W. Beck

Open-File Report 2021–1055

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

U.S. Geological Survey, Reston, Virginia: 2021

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Storlazzi, C.D., Reguero, B.G., Yates, K.K., Cumming, K.A., Cole, A.D., Shope, J.B., Gaido L., C., Zawada, D.G., Arsenault, S.R., Fehr, Z.W., Nickel, B.A., and Beck, M.W., 2021, Rigorously valuing the impact of projected coral reef degradation on coastal hazard risk in Florida: U.S. Geological Survey Open-File Report 2021–1055, 27 p., https://doi.org/10.3133/ofr20211055.

Associated data for this publication:
Cumming, K.A., Cole, A.D., Arsenault, S.R., Fehr, Z.W., Storlazzi, C.D., Reguero, B.G., Yates, K.K., Shope, J.B., Gaido L., C., Zawada, D.G., Nickel, B.A., and Beck, M.W., 2021, Projected flooding extents and depths based on 10-, 50-, 100-, and 500-year wave-energy return periods for the State of Florida with and without projected coral reef degradation: U.S. Geological Survey data release, https://doi.org/10.5066/P9D9LDEP.

ISSN 2331-1258 (online)

Contents

Figures

Tables

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)
yard (yd)	0.9144	meter (m)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^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)

Abbreviations

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
NOAA	National Oceanic and Atmospheric Administration
PAEK	Polynomial Approximation with Exponential Kernal
SBC	Smoothed Baseline Cast
SWAN	Deltares 2-dimensional short wave model
UCSC	University of California at Santa Cruz
USACE	United State Army Corps of Engineers
USGS	United States Geological Survey
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

Rigorously Valuing the Impact of Projected Coral Reef Degradation on Coastal Hazard Risk in Florida

By Curt D. Storlazzi,[1] Borja G. Reguero,[2] Kimberly K. Yates,[1] Kristen A. Cumming,[1] Aaron D. Cole,[2] James B. Shope,[2] Camila Gaido L.,[2] David G. Zawada,[1] Stephanie R. Arsenault,[1] Zachery W. Fehr,[1] Barry A. Nickel,[2] and Michael W. Beck[2]

Abstract

The degradation of coastal habitats, particularly coral reefs, raises risks by increasing the exposure of coastal communities to flooding hazards. In the United States, the physical protective services provided by coral reefs were recently assessed, in social and economic terms, with the annual protection provided by U.S. coral reefs off the coast of the State of Florida estimated to be more than 5,600 people and $675 million (2010 U.S. dollars). Degradation of coral reef ecosystems over the past several decades and during tropical storm events has caused regional-scale erosion of the shallow seafloor that serves as a protective barrier against coastal hazards along Southeast Florida, increasing risks to coastal populations. Here we combine engineering, ecologic, geospatial, social, and economic data and tools to provide a rigorous valuation of the increased hazard faced by Florida's reef-fronted coastal communities because of the projected degradation of its adjacent coral reefs. We followed risk-based valuation approaches to map flood zones at 10-square-meter resolution along all 430 kilometers of Florida's reef-lined shorelines for both the current and projected future coral reef conditions. We quantified the coastal flood risk increase caused by coral reef degradation using the latest information from the U.S. Census Bureau, Federal Emergency Management Agency, and Bureau of Economic Analysis for return-interval storm events. Using the damages associated with each storm probability, we also calculated the change in annual expected damages, a measure of the annual protection lost because of projected coral reef degradation. We found that degradation of the coral reefs off Florida increases future risks significantly. In particular, we estimated the protection lost by Florida's coral reefs from projected coral reef degradation will result in:

- Increased flooding to more than 8.77 square kilometers (3.39 square miles) of land annually;
- Increased flooding affecting more than 7,300 people annually;
- Increased direct damages of more than $385.4 million to more than 1,400 buildings annually; and
- Increased indirect damages to more $438.1 million in economic activity owing to housing and business damage annually.

Thus, the annual value of increased flood risk caused by the projected degradation of Florida's coral reefs is more than 7,300 people and $823.6 million (2010 U.S. dollars). These data provide stakeholders and decision makers with a spatially explicit, rigorous valuation of how, where, and when degradation of Florida's coral reefs will decrease critical coastal storm flood reduction benefits. These results help identify areas where reef management, recovery, and restoration could potentially help reduce the risk to, and increase the resiliency of, Florida's coastal communities.

Introduction

Coastal flooding and erosion from extreme weather events affect thousands of vulnerable coastal communities. The impacts of coastal flooding are predicted to worsen during this century because of population growth and climate change (Hallegatte and others, 2013; Hinkel and others, 2014; Reguero and others, 2015, 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).

Coral reefs, in particular, can substantially reduce coastal flooding and erosion by dissipating up to 97 percent of incident wave energy (Ferrario and others, 2014). Reefs function like low-crested structures such as breakwaters, with hydrodynamic behavior well characterized by coastal engineering models (Hoeke and others, 2011; Taebi and Pattiaratchi, 2014; Reguero and others, 2018). Recently, a process-based, high-resolution, non-linear model of coastal protection benefits provided by corals reefs that mapped these natural defense benefits at a resolution relevant to management scales, and provided a framework to rigorously value the people and property protected by coral reefs under numerous current and future climates, was developed for all populated U.S. coral reef-lined coasts (Storlazzi and others, 2019).

[1]U.S. Geological Survey.

[2]University of California at Santa Cruz.

Studies in Atlantic, Pacific, and Caribbean coral reef ecosystems indicate that coral reef degradation over the past several decades has caused regional-scale erosion of both reef structure and the surrounding shallow coastal seafloor (Yates and others, 2017). Measurement of seafloor elevation and volume-change in the upper Florida Keys from the mid-1930s to 2002 showed mean elevation and volume loss in 9 of 11 coral and non-coral dominated habitats corresponding to a total loss of up to 38 million cubic meters of seafloor during this time (Yates and others, 2017). Mean elevation loss across all habitats was 0.1 meters (m). However, maximum elevation losses were more than 1 m and ranged up to several meters in many locations, indicating reduced wave energy dissipation capability of both coral reefs and the surrounding shallow seafloor at these locations. Results showed that largest elevation losses occurred in coral-dominated habitat (15 percent of the study area) and largest volume losses occurred in non-coral dominated habitat (85 percent of the study area). Analysis of long-term erosion and deposition patterns in the Florida Keys indicates that physical transport of sediments is a primary driver of regional-scale seafloor elevation-loss as sediments (derived from degrading corals and other carbonate producing organisms) move seaward, downslope, and are exported offshore out of the shallow reef-system. Recent measurement of changes in seafloor structure and elevation at Looe Key Reef and Crocker Reef (in the lower and upper Florida Keys reef tract, respectively) before and after the passage of Hurricane Irma on September 10, 2017, showed significant loss of elevation primarily in coral-dominated habitat (Yates and others 2019a, 2019b) because of coral damage (Viehman and others, 2018, 2020a, 2020b) illustrating the key role major storms play in rapid degradation of coral reefs

As part of the Federal government's 2017 hurricane season's recovery and restoration efforts, the U.S. Geological Survey (USGS) and the University of California at Santa Cruz (UCSC) undertook an effort to assess and quantify, in social and economic terms, the impact of projected coral reef degradation off Florida and its adjacent coastal communities.

Methodology

Engineering, ecologic, social, and economic data and tools were combined to provide a quantitative valuation of the reduction in coastal protection benefits caused by projected coral reef degradation off the State of Florida (fig. 1). The goal of this effort was to identify how, where, and when projected coral reef degradation could decrease coastal flood reduction benefits socially and economically. 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 (Storlazzi and others, 2019). This study represents the first unique and innovative effort to rigorously quantify the increase in coastal hazard risk caused by coral reef degradation, based on high-resolution flooding modeling and state-of-the-art damage modeling and calculations based on approaches used by the Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers (USACE). The methods

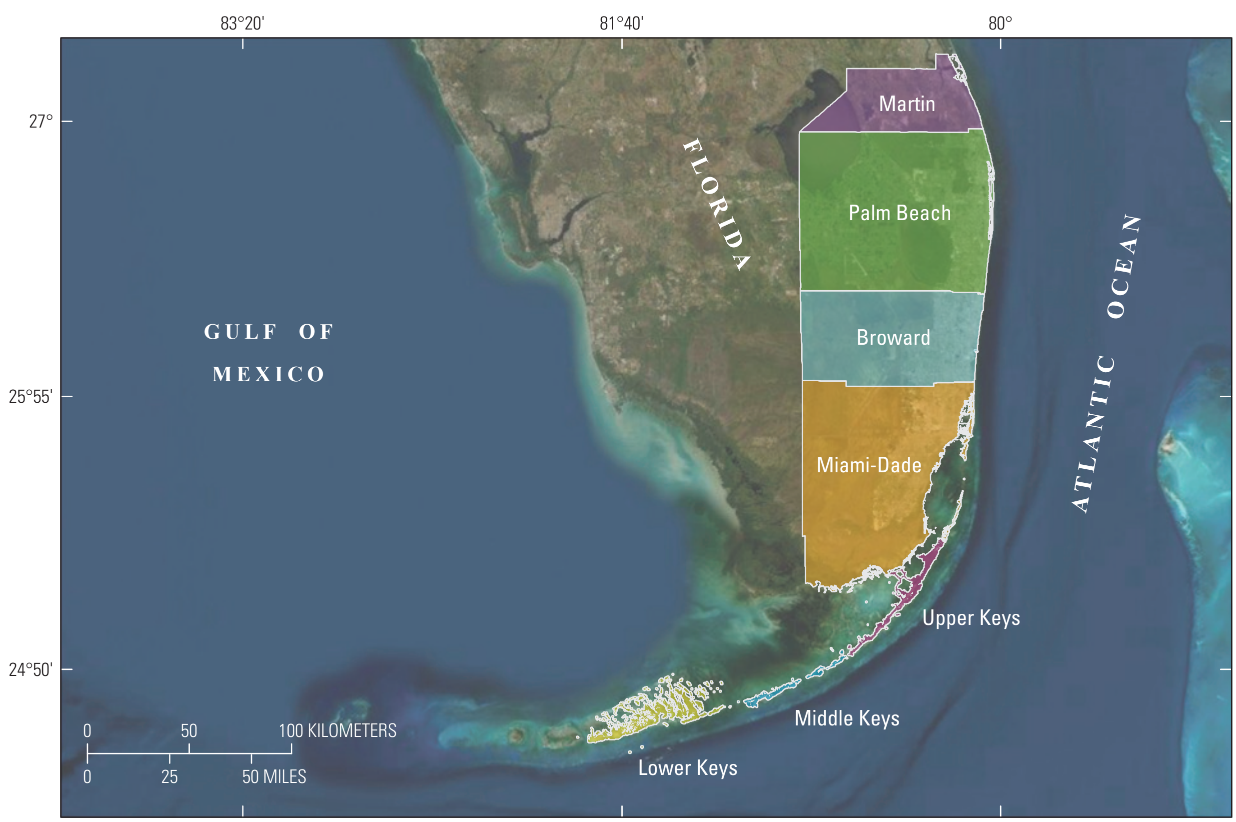


Figure 1. Map indicating the location of the study areas in Florida.

follow a sequence of steps (fig. 2) derived from Storlazzi and others (2019) that integrate physics-based hydrodynamic modeling, quantitative geospatial modeling, and social and economic analyses to quantify the hazard, the role of coral reef degradation in increasing coastal flooding, and the economic and social consequences.

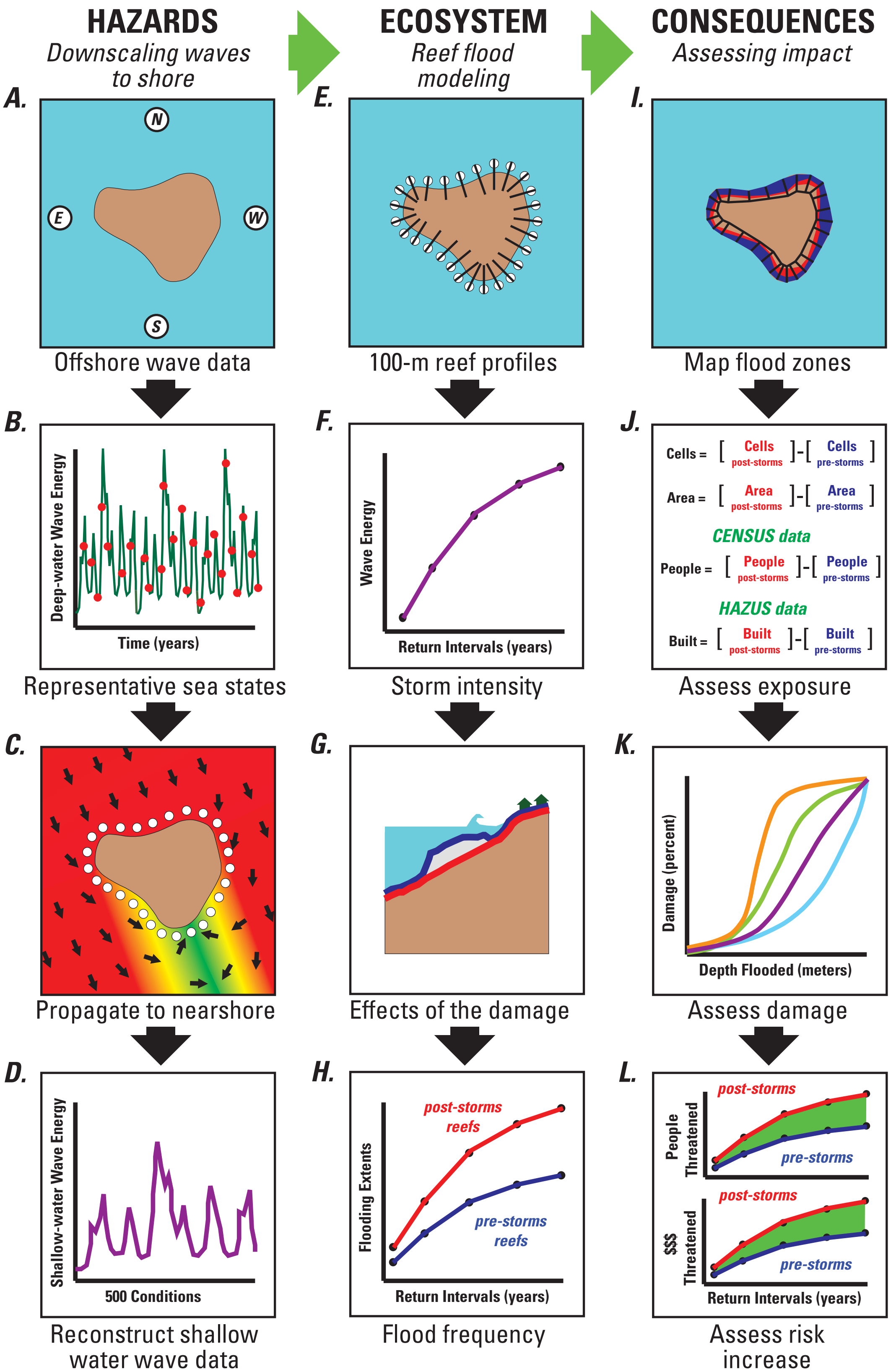


Figure 2. Schematic diagram that shows the methodology used to evaluate the increase in coastal flooding hazard risk owing to hurricane-induced damage to coral reefs. Modified after Storlazzi and others (2019). Each step is described in more detail in the methodology section. m, meter.

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 of Florida (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 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 (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*). Wave propagation around reef-lined islands has been accurately simulated using SWAN (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 (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 kilometers [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 (fig. 3). The bathymetry for the SWAN grids were 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 (fig. 2*D*), and then reconstructed into hourly time series using multidimensional interpolation techniques (Camus and others, 2011).

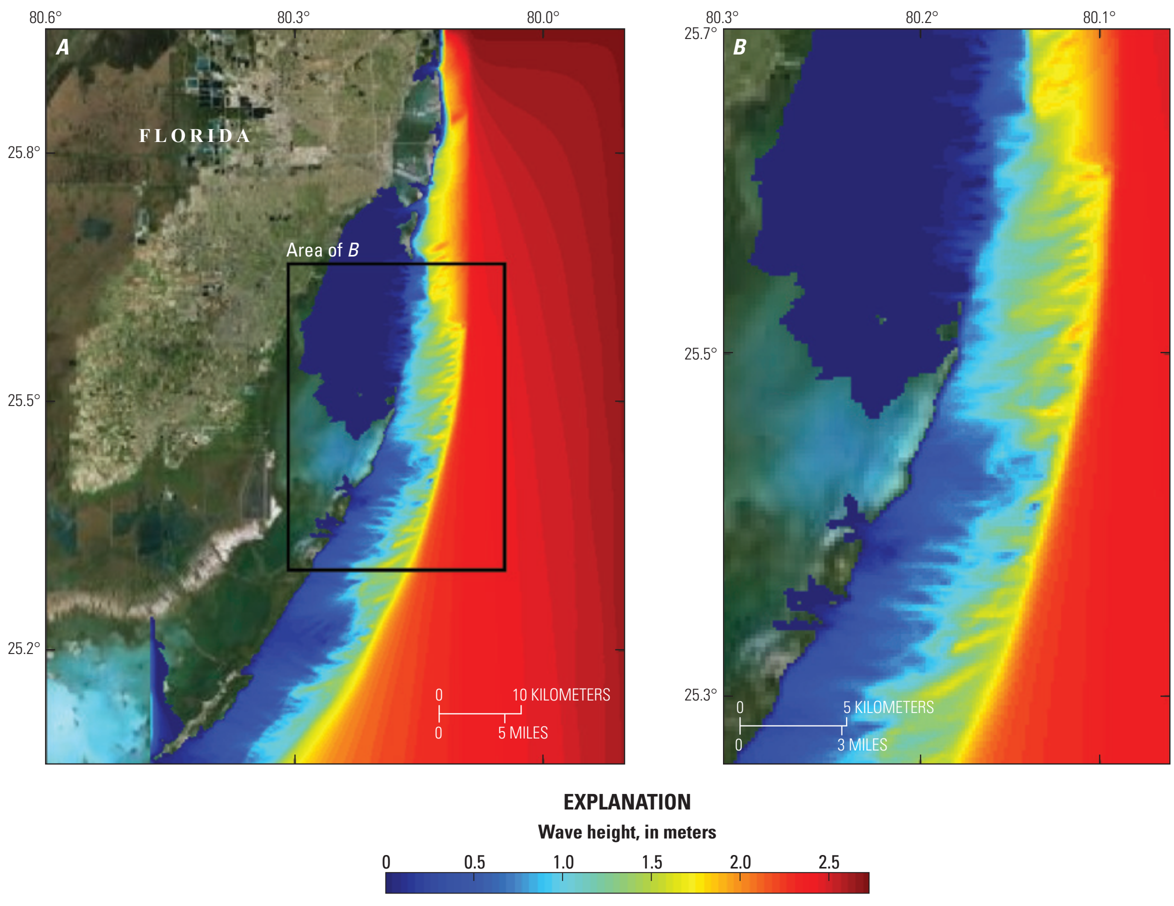


Figure 3. Maps showing output examples of the Simulating Waves Nearshore (SWAN) model and how one of the 500 wave conditions was dynamically downscaled to the 200-meter (m) grid scale offshore Biscayne Bay, Florida. *A*, The 200-m resolution Miami model. *B*, Zoomed-in view of the 200-m resolution Miami model demonstrating the gradients in wave height across and along the Florida reef tract. Colors indicate significant wave height, in meters. The black rectangle in subplot *A* indicates the extent of the area in subplot *B*.

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 (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 USGS 1:24,000 quadrangle maps and smoothed in ArcGIS using the polynomial approximation with exponential kernal algorithm and a 5,000 m smoothing tolerance (fig. 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.

The nearshore wave time series (hourly data from 1948 to 2008) were fit to a General Extreme Value (GEV) 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*). The corresponding 10-, 50-, 100-, and 500-year storm return period extreme water levels for a given location were taken from the nearest National Oceanic and Atmospheric Administration (NOAA) tidal station (National Oceanic and Atmospheric Administration, 2017), which include the effects of tropical cyclones.

The return value significant wave heights and associated peak periods were then propagated over the coral reefs with corresponding return-value sea levels 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, 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

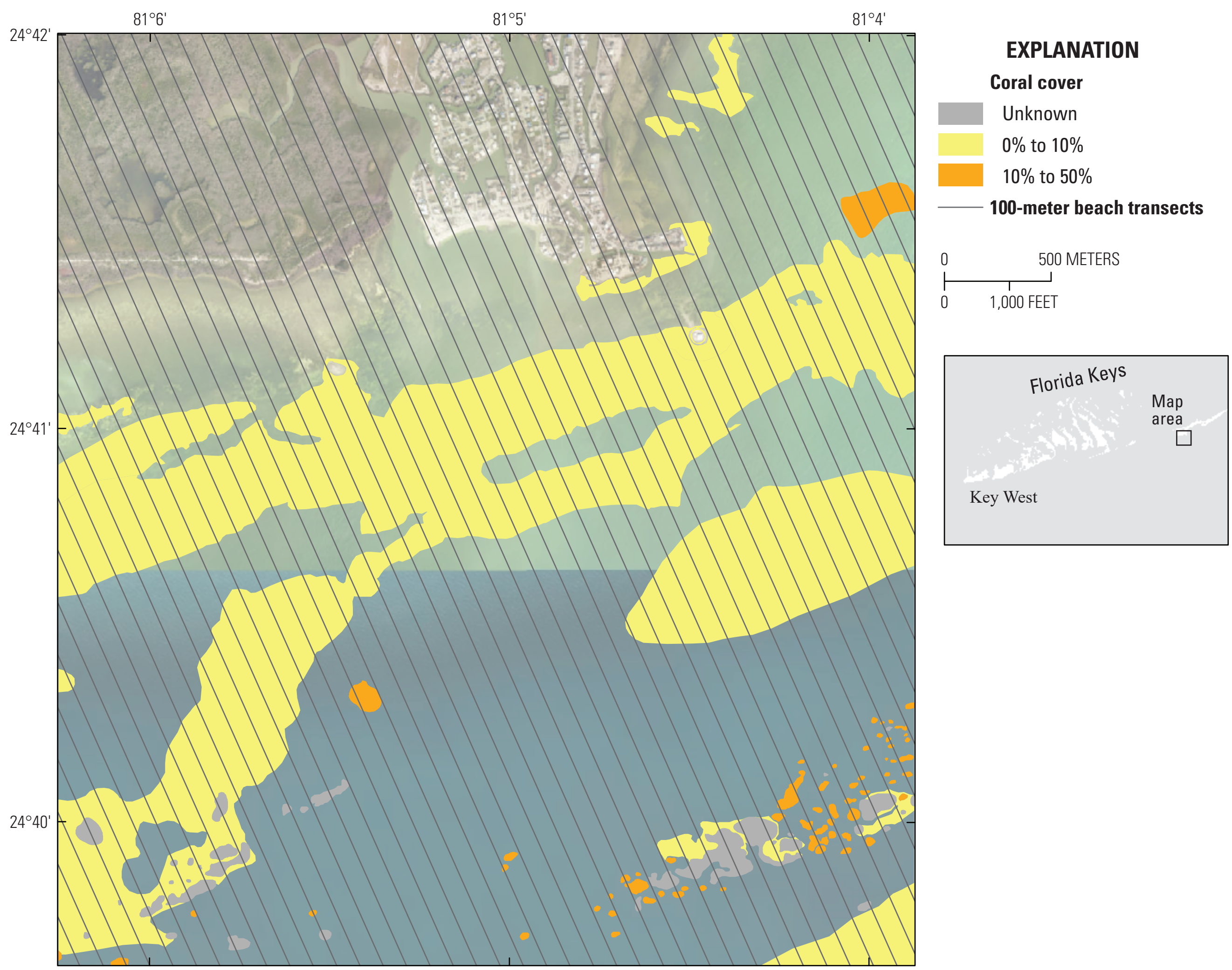


Figure 4. Example map showing the coral extent and coverage (Florida Fish and Wildlife Conservation Commission, 2016) and XBeach transects offshore Marathon, Vaca Key, Florida. Colors indicate percentage (%) of coral coverage; black lines show cross-beach transects at 100-meter (m) intervals.

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 (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 (s) in one-dimensional hydrostatic mode along the cross-shore transects, at a varying resolution between 10 m seawards and 1 m landwards (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 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. 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 and others (2013), were applied. 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 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 as defined from the benthic habitat maps (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 percentages of coral cover as determined from benthic habitat maps following Storlazzi and others (2019).

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

Evaluating the Role of Projected Coral Reef Degradation in Reducing Coastal Protection

The effect of future coral reef degradation on coastal protection was examined for two different seafloor elevation-change scenarios based on DEM projections of the study area out 100 years from 2001 using either 1) historical rates of mean elevation-change as a conservative change model, or 2) historical rates of mean erosion. Methods describing the generation of the mean elevation and mean erosion scenarios are described in detail by Yates and others (2018, 2019a, and 2019b), and are summarized here. Rates of seafloor elevation-change were projected from 26,341 individual elevation change data points in the upper Florida Keys reef tract originally calculated by Yates and others (2017) from the 1930s to 2002. An annual elevation-change rate was computed for each data point by dividing total elevation change by the number of years between the dates of the historical and modern bathymetric data used for these elevation-change calculations. Annual elevation change rates for each data point were then multiplied by 100 years to generate a 100-year projection DEM for the upper Florida Keys study area. The 100-year projection DEM for the upper Florida Keys study area was used to calculate mean 100-year elevation change and erosion rates for 17 habitats derived from the Florida Fish and Wildlife Conservation Commission, Unified Florida Reef Tract Map version 2.0. Mean elevation change was calculated using all elevation change data points (accretion and erosion) within a given habitat area. Mean erosion was calculated using only elevation change data points showing a decrease in seafloor elevation (or erosion) within a given habitat area. These mean 100-year elevation-change and erosion rates were then applied to the same habitats within a DEM extending from Port St. Lucie to Marquesas Key, Florida, to project future seafloor elevation out 100 years along the southeast coast of Florida. Four of the 17 habitat types were not found in the original upper Florida Keys study site; 100-year projections for these habitat types were computed using mean elevation and mean erosion values derived for the full upper Florida Keys study site. These mean elevation and mean erosion DEMs were then applied in subsequent analyses as coral reef future degradation scenarios. The DEM used for these projections (in other words, the basis to which the mean elevation and erosion values were applied) from

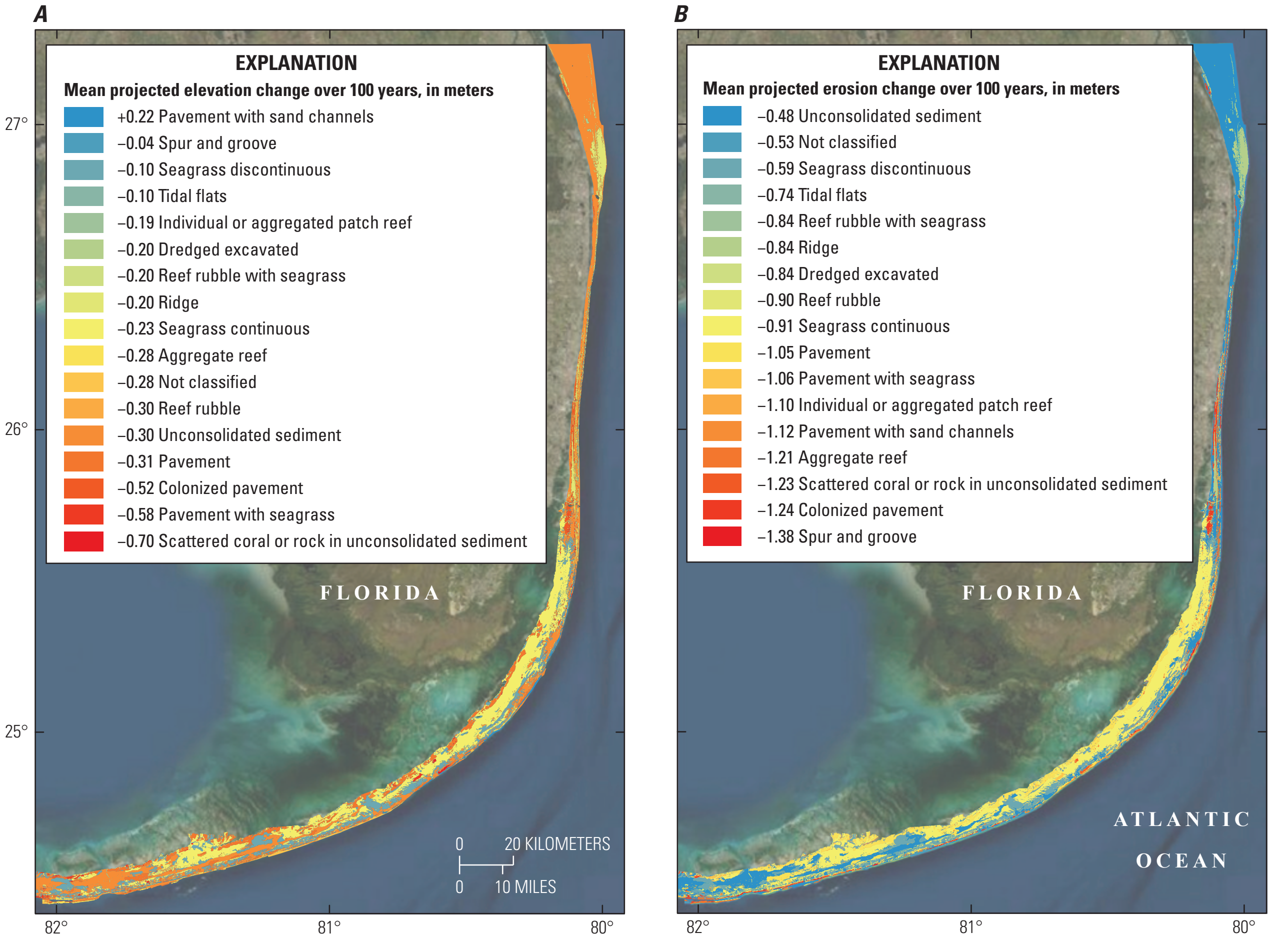


Figure 5. Maps showing example extent and projected magnitude of coral reef degradation based on Yates and others (2018, 2019a, 2019b). *A*, Mean elevation change scenario. *B*, Mean erosion change scenario. Colors indicate magnitude of coral reef change in elevation (in meters).

Port St. Lucie to the Marquesas Keys, Florida, was modified from the original NOAA National Centers for Environment Information (NCEI) U.S. Coastal Relief Model coastal DEM (National Oceanic and Atmospheric Administration, 2001) by clipping it to the extent of the Unified Florida Reef Tract Map and a shoreline contour and removing subaerial features (fig. 5). Grid resolution for the DEM was 3-arc seconds (or approximately 90 m).

Although the water depths/seafloor elevations were modified based on the Yates and others (2018, 2019a, 2019b) projections, the hydrodynamic roughness for the different benthic habitat classes were kept the same as in Storlazzi and others (2019). The wave and sea level conditions were then propagated using the XBeach model over the same 100-m spaced shore-normal transects as in Storlazzi and other (2019) but modified to account for the damage to the coral reefs (fig. 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 profiles with the projected degradation to the coral reefs (fig. 6).

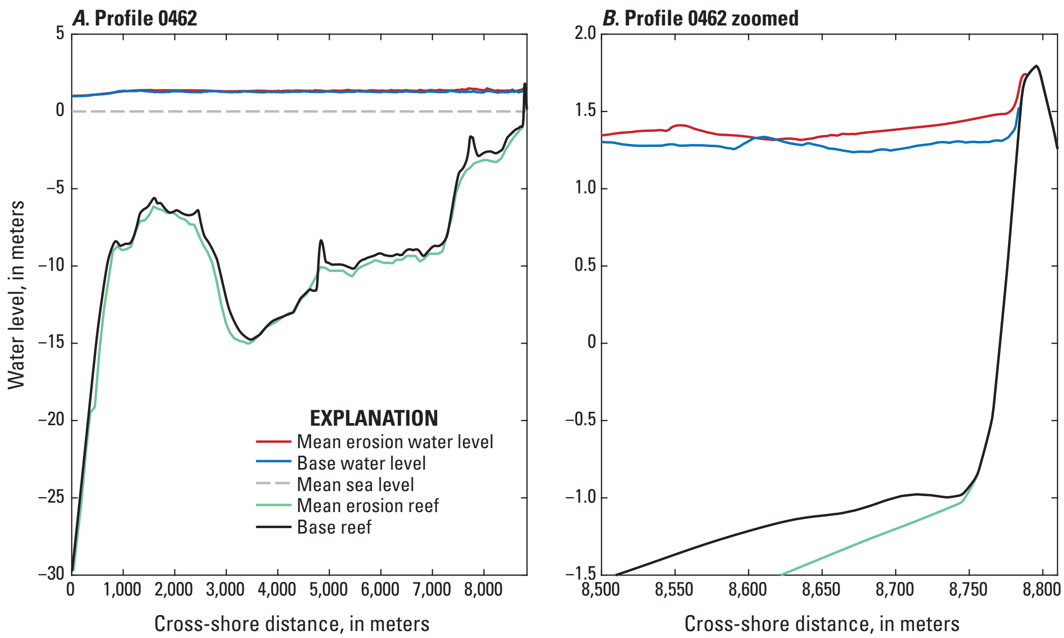


Figure 6. Plots of example Florida topographic-bathymetric cross-sections and XBeach model wave-driven total water levels (in meters) during the 100-year storm for the current reefs and for the mean erosion coral reef degradation scenario. *A*, Cross-shore profile 0462 offshore Key West. *B*, Zoomed-in view of profile 0462. The black line denotes bathymetry and the blue line the total water levels (setup plus runup) with current coral reefs, the green line denotes the bathymetry of the degraded coral reefs, and the red line the total water levels resulting from the mean erosion coral reef degradation scenario. Note the high vertical exaggeration.

Quantifying the Social and Economic Impact of Projected Coral Reef Degradation

Wave-driven total water level depths and extents were then interpolated between adjacent shore-normal transects for the four return intervals (fig. 2*H*) to develop flood mask layers for both the total water levels for both existing and post-elevation change coral reef conditions (fig. 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. The extent of the water depth raster defined the flood mask (fig. 7). Any pixels with a positive value were retained as flood-water depth (fig. 8). 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 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 return period: pre-storm scenario < post-storm scenario, and for each scenario: 10-year return period < 50-year return period < 100-year return period < 500-year return period.

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. For each flood mask, the cells flooded by wave-driven setup and runup for both scenarios were logged and areas computed (fig. 2*J*).

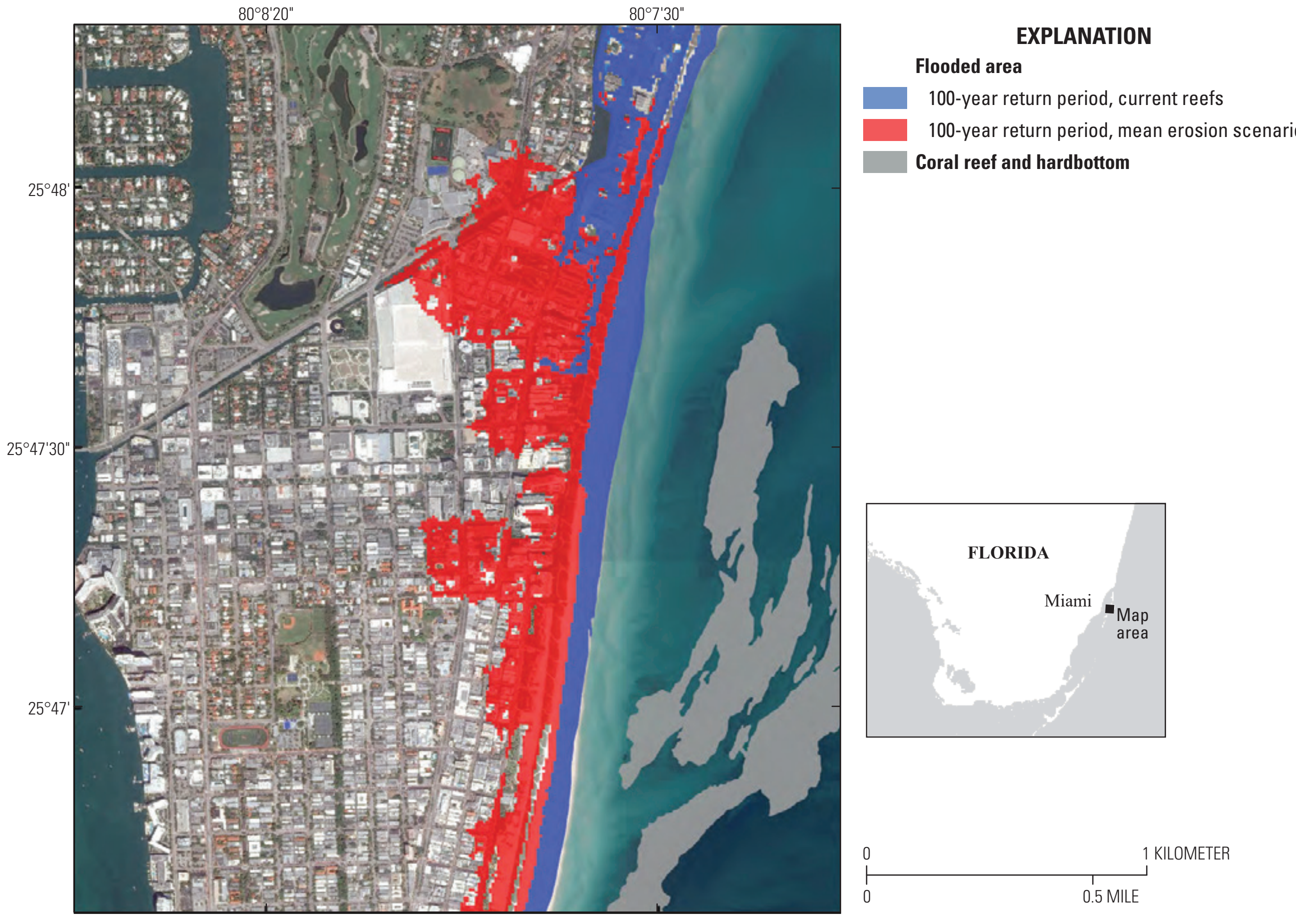


Figure 7. Map showing example 100-year floodplains for current coral reefs and projected coral reef degradation based on the mean erosion scenario in Miami, Florida. The blue regions denote the floodplains from a 100-year storm with coral reefs present, and the red regions denote the projected floodplain due to coral reef degradation. Note that projected coral reef degradation floodplain overlaps with and includes the floodplain with current coral reefs. The region exposed to coastal flooding because of projected coral reef degradation for the 100-year return-interval storm is the red band.

The resulting number of people threatened, building damage, and indirect economic impact were then computed using the wave-driven flood depths. The people impacted by wave-driven flooding were determined by cross-referencing the flooded cells with the U.S. Census Bureau's (2016) TIGER database, as shown in figure 9. The number of people at risk from flooding were 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 (2016b) flood hazard exposure data in the HAZUS database (Scawthorn and others, 2006a, 2006b). The data were projected into each respective Universal Transverse Mercator Coordinate System (coordinate system from the transects belonging to that region).

For each type of HAZUS asset (for example, different types of residential, commercial and industrial buildings), 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), as shown in figure 10. 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 and every cell

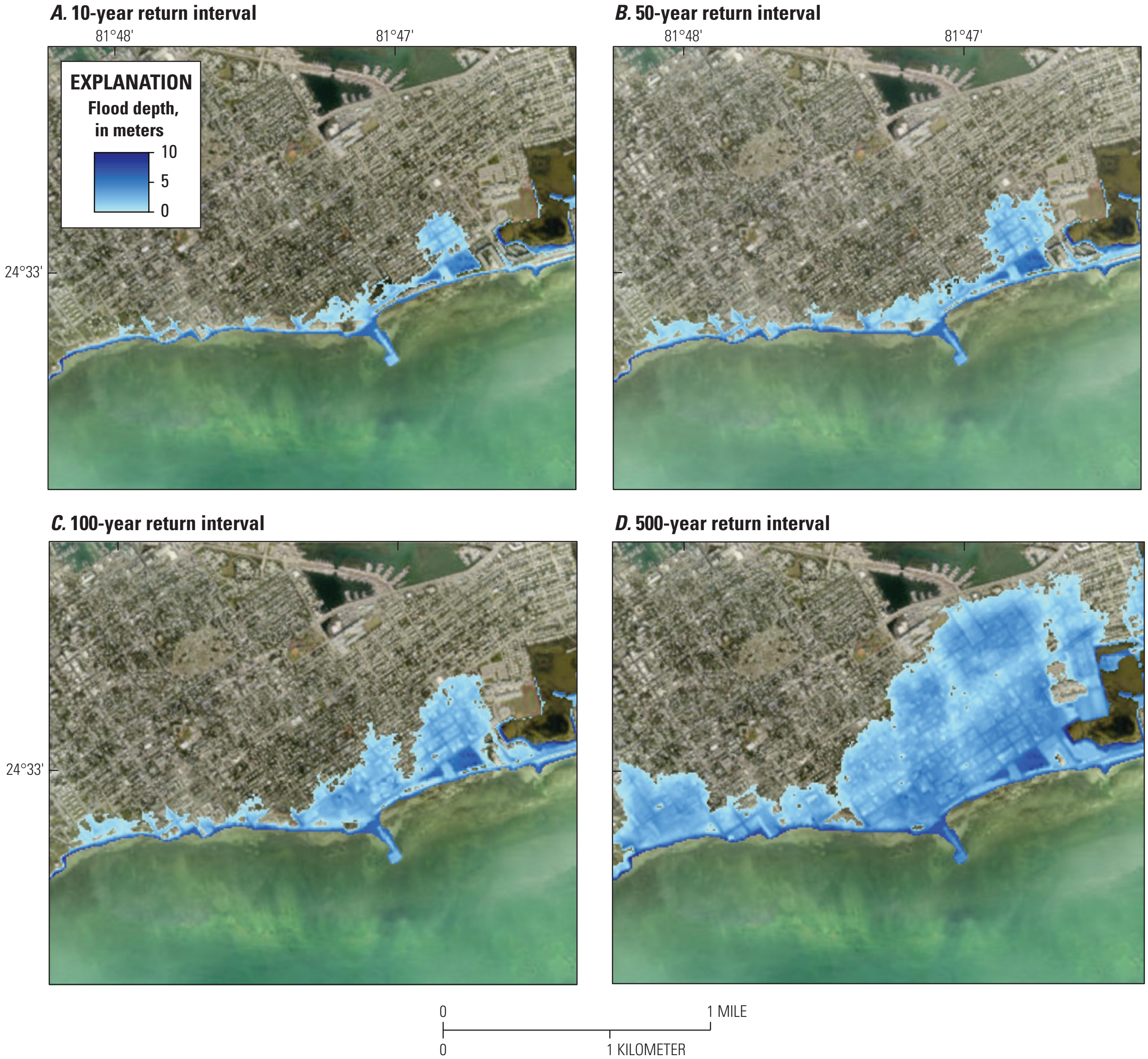


Figure 8. Maps showing example 10-meter (m) resolution flood depths for various storm recurrence intervals on Key West, Florida. *A*, 10-year storm. *B*, 50-year storm. *C*, 100-year storm. *D*, 500-year storm. Colors indicate flood-water depth, in meters (m), interpolated from adjacent XBeach model profile model transects spaced every 100-m along the coast.

represents the degree (or percent) of damage from flooding, and include 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: building value per unit area multiplied by degree of damage. Similarly, the number and extent flooded buildings were calculated by the intersections between the flood depth raster and buildings (and specific building types) per unit area, as shown in figure 10. Finally, building damage, number of flooded buildings, and people flooded were aggregated to 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 nearest transect.

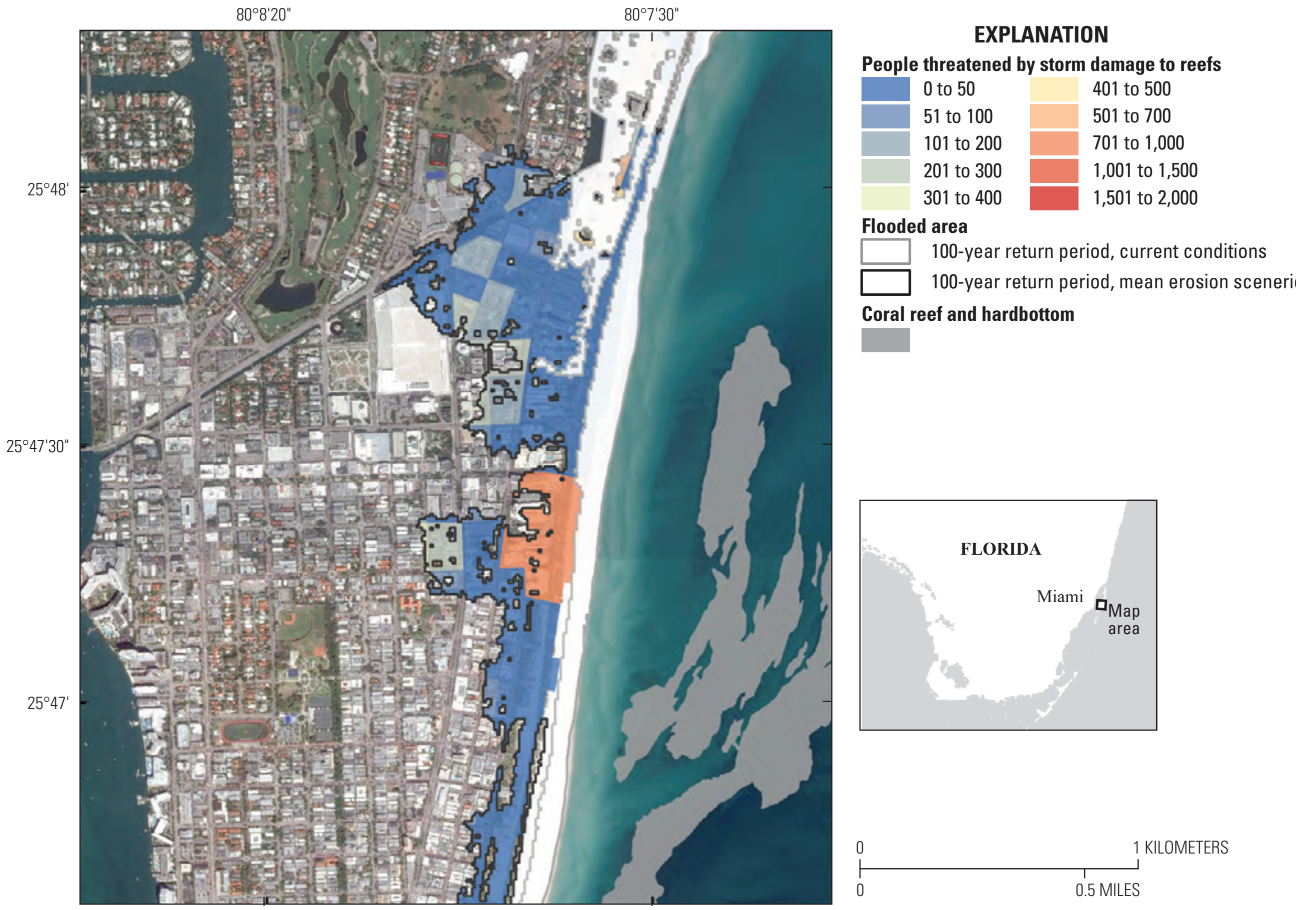


Figure 9. Map showing the distribution of people exposed to coastal flooding because of projected coral reef degradation based on the mean erosion scenario for the 100-year storm in Key West, Florida. Colors indicate population density, based on U.S. Census Bureau's TIGER data, in the area exposed to flooding for a 100-year storm on the basis of the projected mean erosion coral reef scenario.

The value of the damage to coral reefs in terms of increased coastal hazard risk was then determined as the difference in people and infrastructure impacted by wave-driven flooding in the simulations for the current coral reef conditions compared to the projected degraded conditions (fig. 2*L*) based on Yates and others (2018, 2019a, 2019b). The calculated damages by infrastructure type were aggregated and summarized into tables (see results section) for each return period. The types of infrastructure were aggregated into the types of the general building stock that includes residential, commercial, industrial, agricultural, religious, government, and education buildings. Damage was estimated in percent and was 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.

The summary tables 2–13 provide damages for the different storm return periods. 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 two reef scenarios: current coral reefs and projected future degraded reefs based on Yates and others (2018, 2019a, 2019b). 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

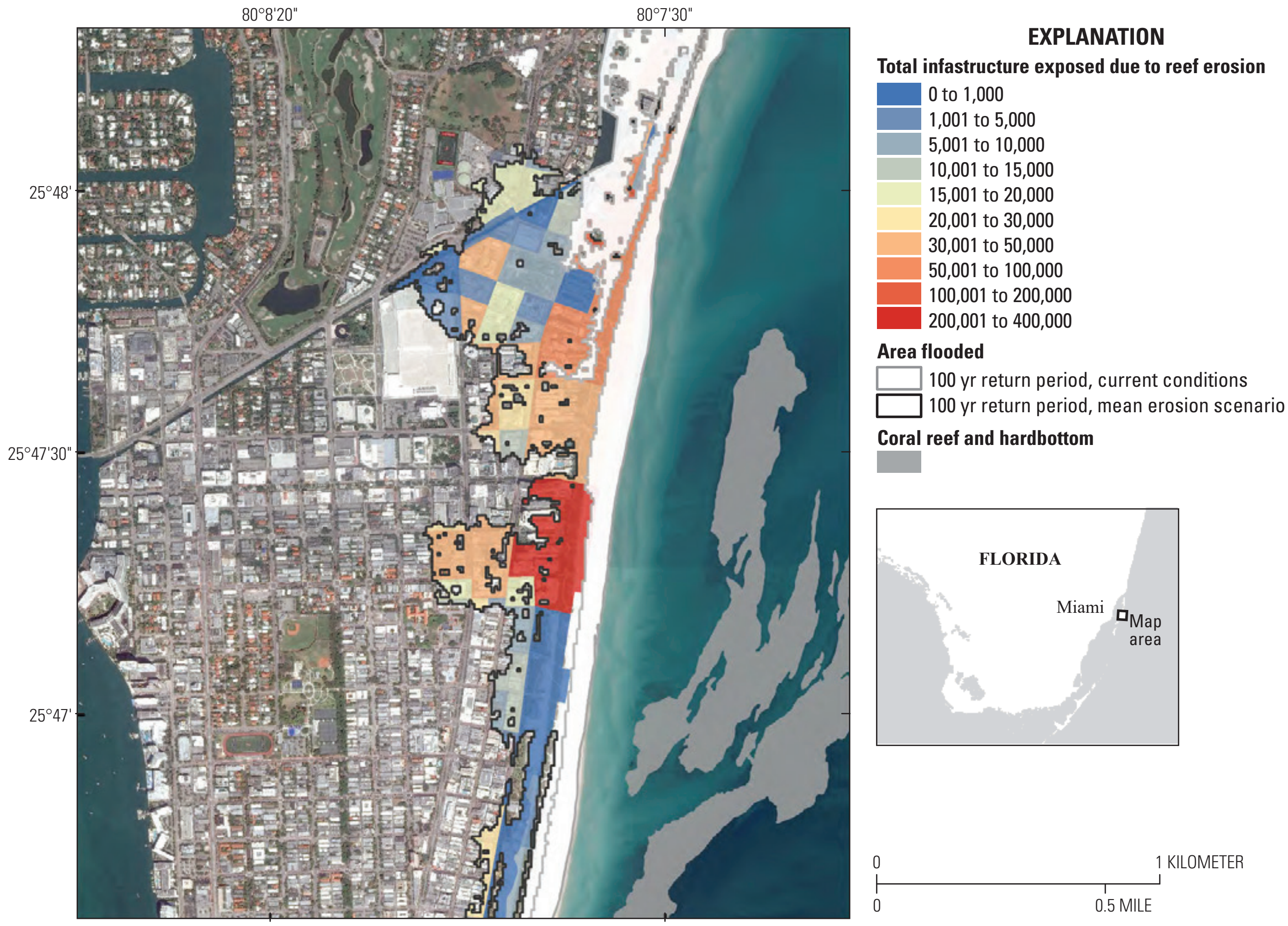


Figure 10. Map showing the value of infrastructure, in thousands of 2010 U.S. dollars, exposed to coastal flooding because of projected coral reef degradation based on the mean erosion scenario for the 100-year storm in Miami, Florida. Colors indicate the total value of infrastructure, based on the Federal Emergency Management Agency's HAZUS data, in the area now exposed to flooding for a 100-year storm on the basis of the projected mean erosion coral reef scenario.

what might be expected to occur in a given year. The EAD was calculated from each damage curve (current and projected degradation, figure 10) as:

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

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 (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 scenarios: current reefs and degraded reefs (fig. 11). The expected annual loss (EAL), a measure of the annual loss of protection provided coral reefs (or increased exposure) because of the projected degradation, is calculated as:

$$EAL = EAD_{post-storms} - EAD_{pre-storms} \quad (2)$$

The total economic impact of wave-driven coastal flooding, however, 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 ($38,604; U.S. Bureau of Economic Analysis, 2018) to the number of people living in the regions now exposed to flooding because of the projected coral reef degradation. One can compute the economic activity protected by reefs for people that would be displaced by the loss of housing from increased coastal flooding. Similarly, by multiplying the 2010 average of 15.1 employees per business (U.S. Census Bureau, 2018) to the 2010 average contribution to the GDP per person ($38,604; U.S. Bureau of Economic Analysis, 2018) to the number of commercial and industrial buildings in the regions now exposed to flooding owing to the projected coral reef degradation, one can compute the economic activity lost for businesses impacted because of the loss of infrastructure from increased coastal flooding. Because there are no data linking the people living in an area to where those people work, we assume here that the economic activity lost for people displaced by the loss of housing from coastal flooding is independent from the economic activity lost for businesses impacted by the loss of infrastructure from coastal flooding.

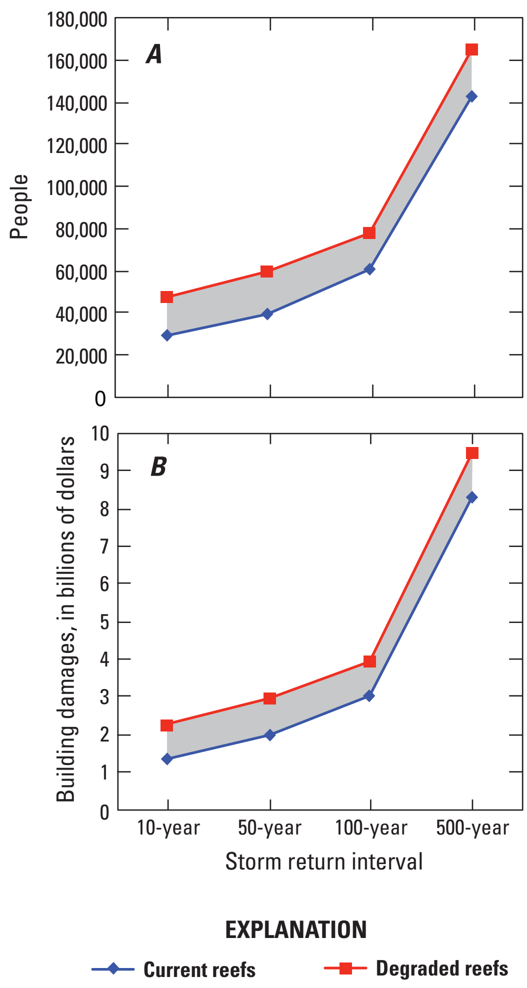


Figure 11. Example plots showing damage curves both for current coral reefs and the projected coral reef degradation based on the mean erosion scenario for Florida. *A*, Number of people displaced by loss of housing from coastal flooding for the mean erosion scenario. *B*, Values of damage to buildings by coastal flooding for the mean erosion scenario. The gray region denotes the increased exposure to coastal flooding on the basis of the projected mean erosion coral reef scenario.

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 and others, 2013; Quataert and others, 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 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).
- Changes in projected future sea level (Boon and others, 2018) or waves (Erikson and others, 2015) were not considered in these simulations.
- Because the coral coverage data are defined in 5 classes, the associated hydrodynamic roughness data are also classified in 5 classes. This results in a step-wise change in hydrodynamic roughness that can 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 and 11 percent cover) in coral cover.
- The model scheme used to define the extreme flood levels were a combination of the wave and surge conditions for certain storm probabilities, and it 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 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 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 FEMA'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 loss of coastal flood protection (increased exposure) because of projected coral reef degradation (Yates and others, 2018, 2019a, 2019b) for each region considered in the analysis for the 4 storm return periods. The losses are expressed in terms of land surface and number and value of buildings or assets now exposed to coastal flooding owing to projected coral reef degradation. The benefits are calculated as the differences between current and projected degraded coral reef conditions. EAL, or annual loss of area protected from coastal flooding because of the mean elevation and mean erosion scenarios, is 8.77 km^2 (3.39 mi^2) and 10.81 km^2 (4.17 mi^2), respectively (tables 2 and 3).

Social Impacts

The expected annual loss, annual number of people who lost protection from coastal flooding because of projected coral reef degradation for the mean elevation and mean erosion scenarios, is 7,314 and 9,872 people, per tables 4 and 5, respectively.

Table 2. Spatial extent, in square kilometers, of area no longer protected from coastal flooding because of projected coral reef degradation based on the mean elevation scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	2.69	1.89	1.58	0.91
Florida	Palm Beach	0.51	0.62	0.28	1.36
Florida	Broward	0.43	0.19	0.06	0.39
Florida	Miami-Dade	2.38	2.64	2.64	3.44
Florida	Upper Keys	0.59	0.33	0.80	1.32
Florida	Middle Keys	0.01	0.01	0.00	0.00
Florida	Lower Keys	9.18	12.36	14.66	23.73

Table 3. Spatial extent, in square kilometers, of area no longer protected from coastal flooding because of projected coral reef degradation based on the mean erosion scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	1.57	0.73	0.84	0.31
Florida	Palm Beach	0.74	0.47	0.08	1.09
Florida	Broward	0.81	0.66	0.53	0.12
Florida	Miami-Dade	2.80	3.44	3.25	3.65
Florida	Upper Keys	2.80	3.12	3.62	4.32
Florida	Middle Keys	1.04	1.04	1.01	1.03
Florida	Lower Keys	9.63	12.78	15.08	24.59

Table 4. Total number of people whom lost protection from coastal flooding because of projected coral reef degradation based on the mean elevation scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	259	184	138	219
Florida	Palm Beach	422	57	289	807
Florida	Broward	1,230	852	1,578	1,558
Florida	Miami-Dade	9,733	11,320	6,922	10,650
Florida	Upper Keys	14	33	14	12
Florida	Middle Keys	7	2	0	1
Florida	Lower Keys	1,626	2,295	2,845	8,546

Table 5. Total number of people whom lost protection from coastal flooding because of projected coral reef degradation based on the mean erosion scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	256	195	163	235
Florida	Palm Beach	742	12	424	406
Florida	Broward	2,182	1,988	1,689	724
Florida	Miami-Dade	11,479	13,540	9,798	11,788
Florida	Upper Keys	482	600	774	848
Florida	Middle Keys	731	746	741	755
Florida	Lower Keys	1,962	2,780	3,283	9,681

Economic Impacts

The expected annual loss, in terms of the annual number of buildings that lost protection from coastal flooding because of projected coral reef degradation, is for the mean elevation and mean erosion scenarios, is 1,404 and 2,176 buildings, respectively (tables 6 and 7). The EAL, in terms of the annual value of buildings that lost protection for the mean elevation and mean erosion scenarios, is $385,468,087 and $512,552,527, respectively (tables 8 and 9). The EAL, in terms of the annual value of economic activity that lost protection for the mean elevation and mean erosion scenarios, is $438,157,691 and $593,268,042, respectively (tables 10 and 11). The total EAL, in terms of the annual value of all lost coastal storm flooding protection (sum of tables 8 and 10 or 9 and 11) because of projected coral reef degradation for the mean elevation and mean erosion scenarios, is $823,625,778 and $1,105,820,569, respectively (tables 12 and 13).

Table 6. Total number of buildings (all infrastructure types) that lost protection from coastal flooding because of projected coral reef degradation based on the mean elevation scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	113	74	61	94
Florida	Palm Beach	214	91	93	624
Florida	Broward	247	174	8	223
Florida	Miami-Dade	937	1,162	1,197	1,807
Florida	Upper Keys	13	26	7	11
Florida	Middle Keys	4	1	2	1
Florida	Lower Keys	1,018	1,381	1,851	4,379

Table 7. Total number of buildings (all infrastructure types) that lost protection from coastal flooding because of projected coral reef degradation based on the mean erosion scenario for different return-interval storms by region.

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	115	83	71	100
Florida	Palm Beach	276	71	36	495
Florida	Broward	389	380	315	16
Florida	Miami-Dade	1,112	1,254	1,431	1,942
Florida	Upper Keys	395	486	616	687
Florida	Middle Keys	382	390	390	397
Florida	Lower Keys	1,233	1,697	2,095	4,916

Table 8. Total value of all infrastructure types that lost protection from coastal flooding because of projected coral reef degradation based on the mean elevation scenario for different return-interval storms by region.

[Values in 2010 U.S. dollars]

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	$37,771,929	$33,768,199	$30,778,086	$45,456,756
Florida	Palm Beach	$34,260,293	$9,912,935	$35,379,538	$73,012,294
Florida	Broward	$99,959,745	$62,673,236	$63,764,584	$183,660,959
Florida	Miami-Dade	$482,191,573	$570,222,580	$437,651,320	$797,918,607
Florida	Upper Keys	$1,106,034	$1,759,336	$3,449,172	$3,046,245
Florida	Middle Keys	$817,762	$1,800,127	$2,275,609	$2,589,620
Florida	Lower Keys	$46,192,775	$59,382,175	$76,467,763	$248,302,906

Table 9. Total value of all infrastructure types that lost protection from coastal flooding because of projected coral reef degradation based on the mean erosion scenario for different return-interval storms by region.

[Values in 2010 U.S. dollars]

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	$37,604,004	$35,853,167	$33,502,697	$47,112,563
Florida	Palm Beach	$59,994,152	$25,780,893	$33,249,483	$26,929,026
Florida	Broward	$169,312,861	$134,352,352	$95,123,069	$149,621,314
Florida	Miami-Dade	$552,850,891	$661,852,733	$577,591,266	$928,183,298
Florida	Upper Keys	$24,588,507	$31,592,973	$41,602,396	$54,570,195
Florida	Middle Keys	$25,552,638	$31,311,664	$33,962,755	$39,828,892
Florida	Lower Keys	$58,480,532	$75,258,120	$89,338,152	$278,144,619

Table 10. Total value of economic activity that lost protection from coastal flooding because of projected coral reef degradation based on the mean elevation scenario for different return-interval storms by region.

[Values in 2010 U.S. dollars]

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	$12,755,452	$12,755,452	$9,330,667	$7,250,793	$10,461,920
Florida	$35,796,791	$35,796,791	$2,797,046	$20,664,022	$61,899,243
Florida	$63,911,188	$63,911,188	$37,409,403	$63,039,344	$82,470,274
Florida	$538,050,778	$538,050,778	$627,950,304	$462,833,455	$819,440,852
Florida	$1,683,418	$1,683,418	$2,165,583	$1,743,039	$1,077,435
Florida	$989,086	$989,086	$725,488	$505,568	$400,997
Florida	$140,997,447	$140,997,447	$180,024,326	$210,365,864	$566,249,742

Table 11. Total value of economic activity that lost protection from coastal flooding because of projected coral reef degradation based on the mean erosion scenario for different return-interval storms by region.

[Values in 2010 U.S. dollars]

Location	Sublocation	Storm Return Interval			
		10-year	50-year	100-year	500-year
Florida	Martin	$12,650,666	$9,817,541	$8,407,704	$11,160,871
Florida	Palm Beach	$53,309,616	$1,614,326	$17,233,648	$37,283,469
Florida	Broward	$132,178,141	$117,742,927	$99,713,684	$40,158,048
Florida	Miami-Dade	$626,958,180	$730,399,470	$608,885,698	$878,230,890
Florida	Upper Keys	$31,503,511	$40,393,159	$54,690,837	$60,494,805
Florida	Middle Keys	$48,543,217	$49,687,235	$48,988,678	$49,974,083
Florida	Lower Keys	$166,756,004	$211,128,919	$239,208,760	$640,889,518

Table 12. Annual value that lost protection from coastal flooding because of projected coral reef degradation based on the mean elevation scenario by region.

Location	Sublocation	Number of People	Buildings (2010 U.S. dollars)	Economic Activity (2010 U.S. dollars)
Florida	Martin	137	$20,486,644	$6,777,156
Florida	Palm Beach	204	$17,259,992	$17,352,940
Florida	Broward	621	$50,492,046	$32,102,670
Florida	Miami-Dade	5,384	$269,064,423	$299,345,909
Florida	Upper Keys	5	$664,354	$707,427
Florida	Middle Keys	4	$512,548	$523,453
Florida	Lower Keys	960	$26,988,079	$81,348,135

Table 13. Annual value that lost protection from coastal flooding because of projected coral reef degradation based on the mean erosion scenario by region.

Location	Sublocation	Number of People	Buildings (2010 U.S. dollars)	Economic Activity (2010 U.S. dollars)
Florida	Martin	137	$20,529,329	$6,760,928
Florida	Palm Beach	365	$30,748,804	$26,055,036
Florida	Broward	1,171	$89,266,780	$70,802,512
Florida	Miami-Dade	6,369	$309,591,364	$349,070,379
Florida	Upper Keys	274	$14,062,755	$17,988,609
Florida	Middle Keys	401	$14,394,798	$26,662,897
Florida	Lower Keys	1,155	$33,958,698	$95,927,680

Conclusions

Here we apply a new methodology to combine engineering, ecologic, geospatial, social, and economic tools and data to provide a rigorous social and economic valuation of the coastal protection benefits lost because of projected coral reef degradation in the State of Florida. The resulting data make it possible to identify where, when, and how projected coral reef degradation increases the storm-induced flooding hazards to Florida's coastal communities. The goal is to provide sound, scientific guidance for U.S. Federal, State, 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 now exposed to hazards because of projected coral reef degradation to, ultimately, save dollars and protect lives.

Acknowledgments

This work was carried out by the U.S. Geological Survey (USGS) Coastal and Marine Hazards and Resources Program's Coral Reef Project as part of an effort in the United States and its trust territories to better understand the effect of geologic and oceanographic processes on coral reef systems. This work was supported by U.S. government funding from the 2017 Hurricanes and Wildfire Supplemental. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References Cited

Booij, N., Ris, R.C., and Holthuijsen, L.H., 1999, A third-generation wave model for coastal regions 1—Model description and validation: Journal of Geophysical Research Oceans, v. 104, p. 7649–7666.

Boon, J. D., Mitchell, M., Loftis, J.D., and Malmquist, D.M., 2018, Anthropocene sea level change—A history of recent trends observed in the U.S. East, Gulf, and West coast regions: Virginia Institute of Marine Science, College of William and Mary, Special Report in Applied Marine Science and Ocean Engineering, no. 467, https://doi.org/10.21220/V5T17T.

Bureau of Economic Analysis, 2018, Gross Domestic Product database, accessed December 6, 2018, at https://www.bea.gov/data/gdp/gross-domestic-product.

Camus, P., Mendez, F.J., Medina, R., and Cofino, A.S., 2011, Analysis of clustering and selection algorithms for the study of multivariate wave climate: Coastal Engineering, v. 58, no. 6, p. 453–462.

Cangialosi, J.P., Latto, A.S., and Berg, R.J., 2018, Tropical cyclone report—Hurricane Irma: National Hurricane Center, 111 p., accessed December 17, 2018, at https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf.

Carignan, K.S., McLean, S.J., Eakins, B.W., Beasley, L., Love, M.R., and Sutherland, M., 2015, Digital elevation model of Miami, Florida: National Oceanic and Atmospheric Administration, accessed March 9, 2021, at https://data.noaa.gov//metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/5270.xml&view=getDataView&header=none.

Chapman, M.G., and Underwood, A.J., 2011, Evaluation of ecological engineering of “armoured” shorelines to improve their value as habitat: Journal of Experimental Marine Biology and Ecology, v. 400, p. 302–313, https://doi.org/10.1016/j.jembe.2011.02.025.

Delft University of Technology, 2016, SWAN website, accessed December 19, 2016, at https://www.tudelft.nl/en/ceg/over-faculteit/departments/hydraulic-engineering/sections/environmental-fluid-mechanics/research/swan/.

Deltares, 2016, XBeach Open Source Community website, accessed December 19, 2016, at http://oss.deltares.nl/web/xbeach/.

Erikson, L.H., Storlazzi, C.D., Barnard, P.L., Hegermiller, C.E., and Shope, J.B., 2016, Wave and wind projections for United States coasts; Mainland, Pacific Islands, and United States-Affiliated Pacific Islands: U.S. Geological Survey data release, https://doi.org/10.5066/F7D798GR.

Federal Emergency Management Agency, 2016a, Coastal flood risks—Achieving resilience together website, accessed December 19, 2016, at https://www.fema.gov/coastal-flood-risks-achieving-resilience-together.

Federal Emergency Management Agency, 2016b, FEMA flood map service center—Hazus: Federal Emergency Management Agency, accessed December 19, 2016, at https://msc.fema.gov/portal/resources/hazus.

Federal Emergency Management Agency, 2018, Hazus multi-hazard loss estimation methodology, flood model, Hazus®-MH MR3 technical manual, 471 p., accessed February 22, 2018, at https://www.fema.gov/plan/prevent/hazus. [Document moved by time of publication; accessed March 5, 2019, at https://www.hsdl.org/?abstract&did=480580.]

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., and Airoldi, L., 2014, The effectiveness of coral reefs for coastal hazard risk reduction and adaptation: Nature Communications, v. 5, 9 p.

Florida Fish and Wildlife Conservation Commission, 2016, Unified Florida coral reef tract map version 2.0: Fish and Wildlife Research Institute, accessed September 17, 2017, at http://ocean.floridamarine.org/IntegratedReefMap/UnifiedReefTract.htm.

Fox, H.E., Mous, P.J., Pet, J.S., Muljadi, A.H., and Caldwell, R.L., 2005, Experimental assessment of coral reef rehabilitation following blast fishing: Conservation Biology, v. 19, p. 98–107.

Gardner, T.A., Cote, I.M., Gill, J.A., Grant, A., and Watkinson, A.R., 2005, Hurricanes and Caribbean coral reefs—Impacts, recovery patterns, and role in long-term decline: Ecology, v. 86, p. 174–184.

Grinsted, A., Moore, J.C., and Jevrejeva, S., 2010, Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD: Climate Dynamics, v. 34, p. 461–472.

Grothe, P.R., Taylor, L.A., Eakins, B.W., Carignan, K.S., Friday, D.Z., Lim, E., and Love, M.R., 2011, Key West, Florida 1/3 arc-second MHW coastal digital elevation model: National Oceanic and Atmospheric Administration, accessed on March 9, 2021, at https://data.noaa.gov//metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/431.xml&view=getDataView&header=none.

Haisfield, K.M., Fox, H.E., Yen, S., Mangubhai, S., and Mous, P.J., 2010, An ounce of prevention—Cost-effectiveness of coral reef rehabilitation relative to enforcement: Conservation Letters, v. 3, p. 243–250.

Hallegatte, S., Green, C., Nicholls, R.J., and Corfee-Morlot, J., 2013, Future flood losses in major coastal cities: Nature Climate Change, v. 3, p. 802–806.

Heron, S., Morgan, J., Eakin, C.M., and Skirving, W., 2008, Hurricanes and their effects on coral reefs, *in* Wilkinson, C., and Souter, D., Status of Caribbean coral reefs after bleaching and hurricanes in 2005: Global Coral Reef Monitoring Network, Reef and Rainforest Research Centre, p. 31–36.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., and Levermann, A., 2014, Coastal flood damage and adaptation costs under 21st century sea-level rise: Proceedings of the National Academy of Sciences, v. 111, no. 9, p. 3292–3297.

Hoeke, R.K., Storlazzi, C.D., and Ridd, P.V., 2011, Hydrodynamics of a bathymetrically complex fringing coral reef embayment—Wave climate, in situ observations, and wave prediction: Journal of Geophysical Research Oceans, v. 166, 19 p.

Kopp, R.E., Horton, R.M., Little, C.M., Mitrovica, J.X., Oppenheimer, M., Rasmussen, D.J., Strauss, B.H., and Tebaldi, C., 2014, Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites: Earth’s Future, v. 2, p. 383–406.

Lugo, A.E., Rogers, C.S., and Nixon, S.W., 2000, Hurricanes, coral reefs and rainforests—Resistance, ruin and recovery in the Caribbean: AMBIO—A Journal of the Human Environment, v. 29, p. 106–115.

McCreless, E., and Beck, M.W., 2016, Rethinking our global coastal investment portfolio: Journal of Ocean and Coastal Economics, v. 3, no. 6, 19 p.

Méndez, F.J., Menéndez, M., Luceño, A., and Losada, I.J., 2006, Estimation of the long-term variability of extreme significant wave height using a time-dependent Peak Over Threshold (POT) model: Journal of Geophysical Research Oceans, v. 111, 13 p.

Menéndez, M., and Woodworth, P.L., 2010, Changes in extreme high water levels based on a quasi-global tide-gauge data set: Journal of Geophysical Research Oceans, v. 115, 15 p.

Montoya-Maya, P.H., Smit, K.P., Burt, A.J., and Frias-Torres, S., 2016, Large-scale coral reef restoration could assist natural recovery in Seychelles, Indian Ocean: Nature Conservation, v. 16, p. 1–17.

National Geophysical Data Center, 2001, U.S. coastal relief model—Florida and east Gulf of Mexico: National Oceanic and Atmospheric Administration National Geophysical Data Center, accessed December 19, 2016, at https://doi.org/10.7289/V5W66HPP.

National Oceanic and Atmospheric Administration, 2001, Benthic habitats of Puerto Rico: National Oceanic and Atmospheric Administration Coastal Services Center, accessed September 17, 2017, at https://products.coastalscience.noaa.gov/collections/benthic/e95usvi_pr/default.aspx.

National Oceanic and Atmospheric Administration, 2015, Electronic navigational charts: National Oceanic and Atmospheric Administration Office of Coast Survey, accessed March 10, 2021, at https://www.nauticalcharts.noaa.gov/charts/noaa-enc.html.

National Oceanic and Atmospheric Administration, 2017, Extreme water levels—Annual exceedance probability curves, accessed December 19, 2016, at https://tidesandcurrents.noaa.gov/est/.

National Research Council, 2014, Reducing Coastal Risks on the East and Gulf Coasts: The National Academies Press, Washington, D.C., 208 p., https://doi.org/10.17226/18811.

National Science and Technology Council, 2015, Ecosystem-service assessment—Research needs for coastal green infrastructure: Office of Science and Technology Policy, 40 p.

Neumann, B., Vafeidis, A.T., Zimmermann, J., and Nicholls, R.J., 2015, Future coastal population growth and exposure to sea-level rise and coastal flooding—A global assessment: PLOS ONE, v. 10, no. 3, 34 p., https://doi.org/10.1371/journal.pone.0118571.

Olsen, A.S., Zhou, Q., Linde, J.J., and Arnbjerg-Nielsen, K., 2015, Comparing methods of calculating expected annual damage in urban pluvial flood risk assessments: Water, v. 7, p. 255–270.

Pasch, R.J., Penny, A.B., and Berg, R., 2018, Tropical cyclone report—Hurricane Maria: National Hurricane Center, 48 p., accessed December 17, 2018, at https://www.nhc.noaa.gov/data/tcr/AL152017_Maria.pdf.

Pomeroy, A., Lowe, R.J., Symonds, G., van Dongeren, A.R., and Moore, C., 2012, The dynamics of infragravity wave transformation over a fringing reef: Journal of Geophysical Research, v. 117, 17 p.

Quataert, E., Storlazzi, C.D., van Rooijen, A., Cheriton, O.M., and van Dongeren, A.R., 2015, The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines: Geophysical Research Letters, v. 42, no. 15, p. 6407–6415.

Reguero, B.G., Beck, M.W., Agostini, V.N., Kramer, P., and Hancock, B., 2018, Coral reefs for coastal protection—A new methodological approach and engineering case study in Grenada: Journal of Environmental Management, v. 210, p. 146–161.

Reguero, B.G., Menéndez, M., Méndez, F.J., Mínguez, R., and Losada, I.J., 2012, A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards: Coastal Engineering, v. 65, p. 38–55.

Rinkevich, B., 2015, Climate change and active reef restoration—Ways of constructing the “reefs of tomorrow”: Journal of Marine Science and Engineering, v. 3, p. 111–127.

Ris, R.C., Holthuijsen, L.H., and Booij, N., 1999, A third-generation wave model for coastal regions—Part 2. Verification: Journal of Geophysical Research Oceans, v. 104, no. C4, p. 7667–7681.

Roelvink, D., Reniers, A., van Dongeren, A.R., van Thiel de Vries, J., McCall, R. and Lescinski, J., 2009, Modelling storm impacts on beaches, dunes and barrier islands: Coastal Engineering, v. 56, p. 1133–1152.

Rogers, C.S., 1993, Hurricanes and coral reefs—The intermediate disturbance hypothesis revisited: Coral Reef, v. 12, p. 127–137.

Scawthorn, C., Blais, N., Seligson, H., Tate, E., Mifflin, E., Thomas, W., Murphy, J., and Jones, C., 2006a, HAZUS-MH flood loss estimation methodology I—Overview and flood hazard characterization: Natural Hazards Review, v. 7, p. 60–71.

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., and Lawrence, M., 2006b, HAZUS-MH flood loss estimation methodology II—Damage and loss assessment: Natural Hazards Review, v. 7, p. 72–81.

Scoffin, T.P., 1993, The geological effects of hurricanes on coral reefs and the interpretation of storm deposits: Coral Reefs, v. 12, p. 203–221.

Sheppard, C., Dixon, D.J., Gourlay, M., Sheppard, A., and Payet, R., 2005, Coral mortality increases wave energy reaching shores protected by reef flats—Examples from the Seychelles: Estuarine, Coastal and Shelf Science, v. 64, p. 223–234.

Storlazzi, C.D., Elias, E.P.L., and Berkowitz, P., 2015, Many atolls may be uninhabitable within decades due to climate change: Scientific Reports, v. 5, no. 14546, 9 p.

Storlazzi, C.D., Gingerich, S.B., van Dongeren, A.R., Cheriton, O.M., Swarzenski, P.W., Quataert, E., Voss, C.I., Field D.W., Annamalai, H., Piniak G.A., and McCall, R., 2018, Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding: Science Advances, v. 4, https://doi.org/10.1126/sciadv.aap9741.

Storlazzi, C.D., Reguero, B.G., Cole, A.D., Lowe, E., Shope, J.B., Gibbs, A.E., Nickel, B.A., McCall, R.T., van Dongeren, A.R., and Beck, M.W., 2019, Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction: U.S. Geological Survey Open-File Report 2019–1027, 42 p., https://doi.org/10.3133/ofr20191027.

Taebi, S., and Pattiaratchi, C., 2014, Hydrodynamic response of a fringing coral reef to a rise in mean sea level: Ocean Dynamics, v. 64, no. 7, p. 975–987.

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., and Ergul, A., 2009, The Digital Shoreline Analysis System (DSAS) version 4.0—An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008–1278, https://doi.org/10.3133/ofr20081278.

United Nations, 2016, World Population Prospects 2016 database, accessed December 19, 2016, at https://esa.un.org/unpd/wpp/.

U.S. Census Bureau, 2016, TIGER products database, accessed December 19, 2016, at https://www.census.gov/geo/maps-data/data/tiger.html.

U.S. Census Bureau, 2018, 2010 Statistics of U.S. businesses (SUSB) annual datasets by establishment industry: U.S. Census Bureau online database, accessed February 22, 2018, at https://www.census.gov/data/tables/2010/econ/susb/2010-susb-annual.html.

van Dongeren, A.R., Lowe, R.J., Pomeroy, A., Trang, D.M., Roelvink, D., Symonds, G., and Ranasinghe, R., 2013, Numerical modeling of low-frequency wave dynamics over a fringing coral reef: Coastal Engineering, v. 73, p. 178–190.

van Zanten, B.T., van Beukering, P.J.H., and Wagtendonk, A.J., 2014, Coastal protection by coral reefs—A framework for spatial assessment and economic valuation: Ocean and Coastal Management, v. 96, p. 94–103.

Viehman, T.S., Buckel, C., Griffin, S., Groves, S., Nemeth, M., Moore, J., and Moore, T., 2020a, NCCOS Assessment—Assessment of Puerto Rico's coral reefs following Hurricanes Irma and Maria from 2018-02-25 to 2018-06-15 (NCEI Accession 0221189): National Oceanic and Atmospheric Administration National Centers for Environmental Information Dataset, accessed March 3, 2020, at https://doi.org/10.25921/a1c4-bg06.

Viehman, T.S., Gittings, S., Groves, S., Moore, J., Moore, T., and Stein, J., 2018, NCCOS Assessment—Coral Disturbance Response Monitoring (DRM) along the Florida reef tract following Hurricane Irma from 2017-10-09 to 2017-10-18 (NCEI Accession 0179071): National Oceanic and Atmospheric Administration National Centers for Environmental Information Dataset, accessed March 3, 2020, at https://doi.org/10.25921/sscd-6h41.

Viehman, T.S., Nemeth, M., Groves, S., Buckel, C., Griffin, S., Moore, T., and Moore, J., 2020b, Coral assessment and restoration in the U.S. Caribbean after 2017 hurricanes: National Oceanic and Atmospheric Administration National Ocean Service, National Centers for Coastal Ocean

Vermeer, M., and Rahmstorf, S., 2009, Global sea level linked to global temperature: Proceedings of the National Academy of Sciences, v. 106, no. 51, p. 21,527–21,532.

Wood, N.J., Ratliff, J., and Peters, J., 2013, Community exposure to tsunami hazards in California: U.S. Geological Survey Scientific Investigations Report 2012–5222, 49 p.

Yates, K.K., Zawada, D.G., Smiley, N.A. and Tiling-Range, G., 2017, Divergence of seafloor elevation and sea level rise in coral reef ecosystems: Biogeosciences, v. 14, p. 1739–1772.

Yates, K.K., Zawada, D.G., and Arsenault, S.R., 2018, Projected seafloor elevation change in the Upper Florida Keys 25, 50, 75, and 100 years from 2002: U.S. Geological Survey data release, https://doi.org/10.5066/P9CI9LNH.

Yates, K.K., Zawada, D.G., and Arsenault, S.R., 2019a, Projected seafloor elevation along the Florida reef tract from Port St. Lucie to Marquesas Key, Florida—100 years from 2001 based on historical rates of mean elevation change: U.S. Geological Survey data release, https://doi.org/10.5066/P9E9X66R.

Yates, K.K., Zawada, D.G., and Arsenault, S.R., 2019b, Projected seafloor elevation along the Florida Reef Tract from Port St. Lucie to Marquesas Key, Florida—100 years from 2001 based on historical rates of mean erosion: U.S. Geological Survey data release, https://doi.org/10.5066/P9V7917B.

Zitello, A.G., Bauer, L.J., Battista, T.A., Mueller, P.W., and Kendall, M.S., 2009, Benthic habitats of St. John, U.S. Virgin Islands: National Oceanic and Atmospheric Administration Technical Memorandum NOS NCCOS 96, accessed September 17, 2017, at https://products.coastalscience.noaa.gov/collections/benthic/e94stjohn/default.aspx.

Additional Digital Information

The digital data used to produce this report can be found here: https://doi.org/10.5066/P9D9LDEP

For an online portable document format (PDF) version of this report, visit https://doi.org/10.3133/ofr20211055

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 at Santa Cruz's Coastal Resilience Laboratory, visit https://coastalresilience.ucsc.edu/

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

Direct Contact Information

Regarding this report, contact Curt D. Storlazzi (USGS Coral Reef Project Chief): cstorlazzi@usgs.gov

Appendixes 1 – 6

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; NGDC, National Geophysical Data Center; PR, Puerto Rico, —, no data]

Location	1-km grid cells	200-m grid cells	Grid dimensions (E-W x N-S)	Data source
Florida	—	Dry Tortugas	295 x 190	NGDC, 2001
Florida	—	Key West	505 x 255	NGDC, 2001
Florida	—	Marathon	505 x 337	NGDC, 2001
Florida	—	Islamorada	383 x 334	NGDC, 2001
Florida	—	Miami	291 x 502	NGDC, 2001

Appendix 3. Benthic Habitat and Shoreline Datasets

[FFWCC, Florida Fish and Wildlife Conservation Commission; NOAA, National Oceanic and Atmospheric Administration]

Location	Sublocation	Benthic habitat data		Shoreline data source
		Minimum mapping unit	Data source	
Florida	Dry Tortugas	<1 acre	FFWCC, 2016	NOAA, 2015
Florida	Key West	<1 acre	FFWCC, 2016	NOAA, 2015
Florida	Keys	<1 acre	FFWCC, 2016	NOAA, 2015
Florida	Miami	<1 acre	FFWCC, 2016	NOAA, 2015
Florida	Palm Beach	<1 acre	FFWCC, 2016	NOAA, 2015

Appendix 4. Cross-shore XBeach Transects

Location	Sublocation	Number of cross-shore transects
Florida	Dry Tortugas	300
Florida	Key West	545
Florida	Keys	1,127
Florida	Miami	1,139
Florida	Palm Beach	1,168

Appendix 5. Bathymetric Datasets

[NGDC, National Geophysical Data Center]

Location	Sublocation	Data source
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

Appendix 6. XBeach Model Settings

[—, no data]

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	3,500
	tintp	10
	tintg	3,100
	tstart	100
Output options	nglobalvar	4
	H	—
	zs	—
	zb	—
	E	—
	nmeanvar	3
	H	—
	zs	—
	zb	—
	npoints	1
	nrugauge	1

Moffett Field Publishing Service Center, California
Manuscript approved for publication May 6, 2021
Edited by John Mark Brigham
Layout and design by Kimber Petersen
Cartography and illustration support by JoJo Mangano

Storlazzi and others—**Rigorously Valuing the Impact of Projected Coral Reef Degradation on Coastal Hazard Risk in Florida**—Open-File Report 2021–1055

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20211055