Coastal Dynamics 2017
Paper No. 035

RIGOROUSLY VALUING THE ROLE OF CORAL REEFS IN COASTAL PROTECTION: AN EXAMPLE FROM MAUI, HAWAII, U.S.A.

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Abstract

The degradation of coastal habitats, particularly coral reefs, raises risks by exposing 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 not considered in decision-making. Here we present a new methodology that combines economic, ecological, and engineering tools to provide a rigorous financial valuation of the coastal protection benefits of coral reefs off Maui, Hawaii, USA. We follow risk-based valuation guidelines to quantitatively estimate the risk reduction benefits from coral reefs in terms of annual expected benefits in economic terms. Our ultimate goal is to identify how, where, and when coral reefs provide the most flood reduction benefits under current and future climates to inform reef conservation and management priorities.

Key words: coral reefs, coastal hazards, climate change, risk reduction, social impacts, economic impacts

1. 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 past 10 years (United Nations Office for Disaster Risk Reduction, 2011). The impacts of coastal flooding are predicted to worsen during this century, given population growth and climate change (Hallegatte et al., 2013; Hinkel et al., 2014). There is an urgent need to develop better risk reduction and adaptation strategies to reduce coastal flooding and associated hazards (Hinkel et al. 2014; National Research Council, 2014). For example, the U.S. spends, on average, $500 million per year mitigating such coastal hazards (https://www.fema.gov/coastal-flood-risks-achieving-resilience-together). Most of these funds are destined for the creation and maintenance of "grey infrastructure," such as seawalls, which have negative impacts on coastal ecosystems, and may not be cost effective for risk reduction when compared to natural (e.g., coral or oyster reef restoration) and hybrid (e.g., artificial new, hard substrate for natural re-colonization) alternatives.

There is growing national recognition of the role of natural and nature-based solutions to address coastal risks (Wells et al., 2006; Sutton-Grier et al., 2015). The US 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 their economic benefits.

Coral reefs can substantially reduce coastal flooding and erosion by dissipating up to 97% of incident wave energy (Ferrario et al., 2014). Reefs function like low-crested breakwaters, with hydrodynamic

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behavior well characterized by coastal engineering models (Hoeke et al., 2011; Taebi and Pattiaratchi, 2014; Quataert et al., 2015). Yet the value of coral reefs for coastal defense is not fully recognized, and thus they continue to be lost: 75% of the world's coral reefs are rated as threatened (Hoegh-Guldberg et al., 2007; Mumby et al., 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 et al., 2014; Yee et al., 2014; Pascal et al., 2016), these efforts have 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. These studies mainly provide a limited, index-based approach to quantifying the hazard 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).

Our goal here is to develop and apply a process-based 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 under numerous current and future climates. Here we apply the new tools to Maui as an initial test case, but plan to also apply them to all populated U.S. coral reef-lined coasts (States of Hawaii and Florida, the Territories of Guam, American Samoa, Puerto Rico, and the U.S. Virgin Islands, and the Commonwealth of the Northern Mariana Islands).

2. Methodology

Engineering, ecologic, social, and economic tools were combined to provide a quantitative valuation of the coastal protection benefits of coral reefs off Maui, Hawaii, USA. The goal of this effort was to identify how, where, and when coral reefs provide the most significant coastal flood reduction benefits socially and economically under current and future climate change scenarios. A risk-based 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) was followed. The methods follow a sequence of steps integrating physics-based hydrodynamic modeling, quantitative geospatial modeling, and economic and social analyses to quantify the hazard, the role of coral reefs in reducing the hazard, and the resulting consequences.

2.1 Projecting the coastal hazard

Sixty-one years (1948-2008) of validated long-term hourly hindcast deep-water wave data were extracted from the Global Ocean Wave database (Reguero et al., 2012) for the Main 8 Hawaiian Islands (Fig. 1A). Following the methodology of Camus et al. (2011), these 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 dataset (Fig. 1B).

The 500 synthesized deep-water wave conditions were then propagated to the coast using the physics-based Simulating Waves Nearshore (SWAN) spectral wave model (Booij et al., 1999; Ris et al., 1999), which simulates wave transformations nearshore by solving the spectral action balance equation (Fig. 1C). Wave propagation around reef-lined islands has been accurately simulated using SWAN (Hoeke et al., 2011; Taebi and Pattiaratchi, 2014; Storlazzi et al., 2015). Standard SWAN settings were used (e.g., Hoeke et al., 2011; Storlazzi et al., 2015), except that the directional spectrum was refined to 5-degree bins to better handle refraction and diffraction in and amongst the islands in the Hawaiian Chain. In order to accurately model from the scale of the Main 8 Hawaiian Islands (order~10s of km) down to management scales (order~100 m), a series of three dynamically-downscaled nested grids were used.

The 500 conditions were first propagated through a coarse SWAN grid of the entire Main 8 Hawaiian Islands composed of 57,128 5-km by 5-km grid cells (Fig. 2A) generated from the NOAA 3 arc-sec U.S. Coastal Relief Model (https://www.ngdc.noaa.gov/mgg/coastal/grddas10/grddas10.htm). This coarse grid then provided spatially-varying boundary conditions for a finer SWAN grid of the entire island of Maui composed of 12,556 1-km by 1-km grid cells that (Fig. 2B) then provided spatially-varying boundary conditions for two partially overlapping finer SWAN grids of the east and west portions of Maui composed of 58,300 and 44,850 200-m by 200-m grid cells (Fig. 2C), respectively. These finer grids were generated by grid-cell averaging of the NOAA 1 arc-sec Tsunami Inundation Digital Elevation Model datasets

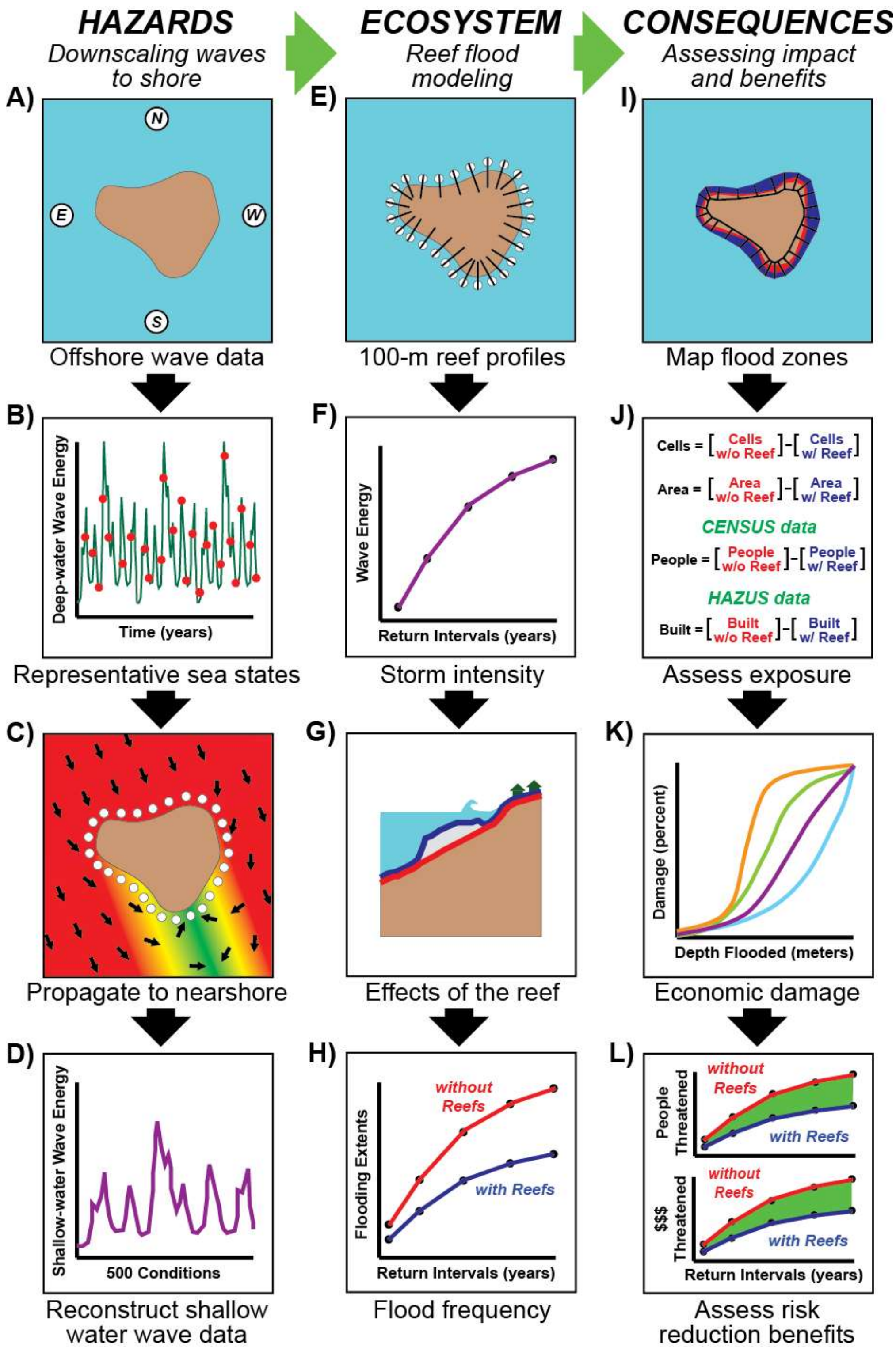

Figure 1 – Schematic of methodology used to evaluate role of coral reefs in coastal hazard risk reduction.

(https://www.ngdc.noaa.gov/dem/squareCellGrid/download/604). The propagated 500 shallow-water wave conditions from the finest SWAN grids were extracted at 100-m intervals along the coastline (Fig. 1D), and then were reconstructed using multidimensional interpolation techniques (Camus et al., 2011).

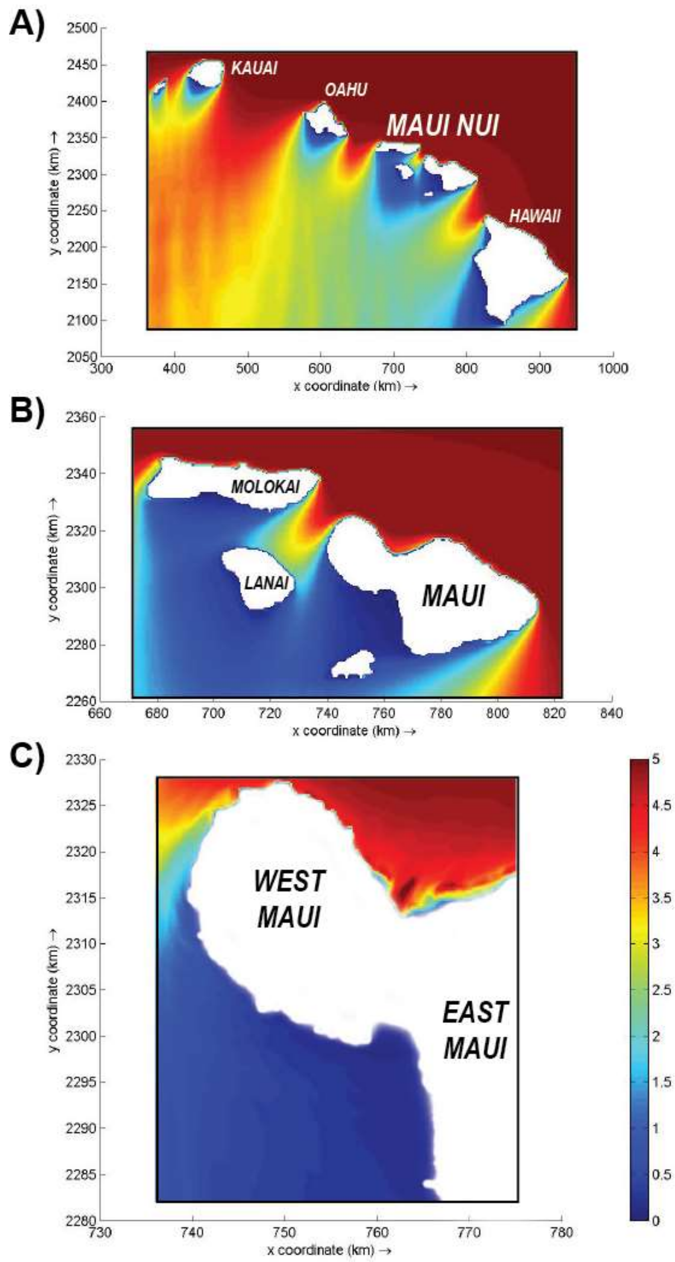

Figure 2 – SWAN model outputs showing an example of one of the 500 wave conditions cascaded down to the 200-m grid scale. A) 5-km resolution Hawaiian Chain model. B) 1-km resolution Maui Nui model embedded in the Hawaiian Chain model. C) 200-m resolution Maui model embedded in the Maui Nui model.

2.2 Evaluating the role of coral reefs

Benthic habitat maps defining coral reef spatial extent and percent coral cover (Battista et al., 2007) were used to delineate the location of nearshore coral reefs and their relative coral abundance around Maui.

Cross-shore transects were created every 100 m alongshore 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 a coastline digitized from USGS 1:24,000 Quadrangle Maps and smoothed in ArcGIS using the Polynomial Approximation with Exponential Kernal (PAEK) algorithm and a 5000 m smoothing tolerance (Fig. 1E). Transects varied in absolute length in order to cross the -30 m and +20 m elevation contours. The seamless bathymetric/topographic and coral coverage data were extracted along these shore-normal transects.

The 500 synthesized nearshore wave conditions were fit to a General Extreme Value Distribution (Méndez et al., 2006; Menéndez and Woodworth, 2010) to obtain the wave energies associated with the 5, 10-, 25-, 50-, 100-, and 250-year return periods (Fig. 1F). The wave heights and periods associated with the se return value wave energies were then propagated over the coral reefs along each 100-m spaced shore-normal transect using the numerical model XBEACH (Roelvink et al., 2009) (Fig. 1G). XBEACH solves for water level variations up to the scale of long (infragravity) waves using the depth-averaged, non-linear shallow water (NLSW) equations. The forcing is provided by a coupled wave action balance, in which the spatial and temporal variations of wave energy due to the incident-period wave groups are solved. The radiation stress gradients derived from these variations result in a wave force that is included in the NLSW 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 et al., 2012; van Dongeren et al., 2013; Quataert et al., 2015) and proved to accurately predict the key reef hydrodynamics.

XBEACH was run for 3600 s in one-dimensional hydrostatic mode along the cross-shore transects; the runs generally stabilize after 100-150 s and thus generate good statistics on wvaes and wave-driven water levels for more than 50 min. 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 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. The additional formulations that incorporate the effect of higher bottom roughness on incident wave decay through the incident wave friction coefficient (f_w) and the current and infragravity wave friction coefficient (c_f), as outlined by van Dongeren et al. (2013) were applied. The friction induced by corals was parameterized 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 different coral coverages (e.g., van Dongeren et al., 2013; Quataert et al., 2015). Coral coverage of were assigned f_w and c_f (Table 1) over the spatial extent of the reef along the profile as defined from the Battista et al. (2007) benthic habitat maps. Profiles of total water levels (set-up plus run-up) 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 benthic substrates.

Coral Coverage	Wave Friction Coefficient (f_w)	Current and Infragravity Wave Friction Coefficient (c_f)
0-10%	0.15	0.07
10-50%	0.30	0.10
50-90%	0.45	0.13
90-100%	0.60	0.15
None (sand)	0.10	0.01

The wave heights and periods associated with the return value wave energies were then propagated using the XBEACH over the same 100-m spaced shore-normal transects modified to account for the loss of the coral reef (Fig. 1G). A loss of coral cover and thus rugosity and frictional effects (e.g., Quataert et al., 2015) was parameterized by setting the f_w and c_f to that of sand (Table 1) per van Dongeren et al. (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 due to reef loss by Sheppard et al. (2005) and Yates et al. (2017). Profiles of total water levels (set-up plus run-up) at each grid cell over the profiles were then extracted to define the wave-driven flooding along these profiles without the influence of the coral reefs.

2.3 Quantifying the social and economic values of coral reefs

Each wave-driven total water levels for the 6 return intervals (Fig. 1H) along the shore-normal transects were then interpolated between adjacent shore-normal transects to develop a flood mask layer for both the total water levels with and without coral reefs (Fig. 1I). For each flood mask, the cells flooded by wave-driven set-up and run-up for both scenarios were logged and areas computed (Fig. 1J). The people and associated social characteristics (race, income, etc) impacted by wave-driven flooding were determined by cross-referencing the flooded cells with the U.S. Census Bureau's TIGER database (https://www.census.gov/geo/maps-data/data/tiger.html). The built infrastructure impacted by wave-driven flooding were determined by cross-referencing the flooded cells with the U.S. Federal Emergency Management Agency's HAZUS database (https://msc.fema.gov/portal/resources/hazus); the resulting damage and economic impact were then computed using wave-driven flood depths along the profiles and the flood depth-damage curves (Fig. 1K) for the different categories of infrastructure following the methodology of Wood et al. (2013). 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 compared to those without coral reefs (Fig. 1L).

3. Generalization of Results

Large areas of Maui, like most high tropical, reef-lined islands have most of their population and critical infrastructure located within a few meters of sea level adjacent to coral reefs (Fig. 3A-C). These low-lying areas, however, are susceptible to flooding, especially during less frequent, high-energy events (Fig. 3D) when wave-driven set-up and run-up are dominated by infragravity and very-low frequency motions (Quataert et al., 2015; Cheriton et al., 2016; Gawehn et al., 2016).

The influence of corals (in terms of hydrodynamic roughness) and coral reefs (in terms of bathymetry) on wave-driven total water levels (set-up and run-up) is shown in Figure 4. The reduced hydrodynamic roughness and bathymetric expression without coral reefs resulted in not only higher wave-driven total water levels, but greater inland extent of flooding than with the presence of coral reefs.

4. Evaluating Potential Future Scenarios

The entire model can then be re-run for different potential scenarios to evaluate climate, social, and economic changes. These scenarios will include: (a) 1 m of sea-level rise, a level likely achieved during the 21st century; (b) population and economic growth; and (c) an increase in reef health causing in an increase in coral cover and thus frictional effects. Scenario 'a' will be used to determine how sea-level rise (Vermeer and Rahmstorf, 2009; Grinsted et al., 2010; Kopp et al., 2014) may reduce the effectiveness of corals reefs in coastal hazard risk reduction, whereas scenario 'b' will show how the importance of coral reefs in coastal hazard risk reduction will change with projected population growth in coastal areas, e.g., United Nation's world population prospects (https://esa.un.org/unpd/wpp/) and International Institute for Applied Systems Analysis' shared socioeconomic pathways (https://secure.iiasa.ac.at/web-apps/ene/SspDb) databases. Lastly, scenario 'c' will provide guidance as to where coral reef restoration (Fox et al., 2005; Haisfield et al., 2010; Rinkevich, 2015; Montoya-May et al., 2016) would be most effective in terms of coastal hazard risk reduction in terms of people, assets, and infrastructure protected.

5. Conclusions

Here we presented a new methodology to combine economic, ecological, and engineering tools to provide a rigorous financial valuation of the coastal protection benefits of coral reefs off Maui, Hawaii, USA. These tools will then be applied to all populated U.S. coral reef-lined coasts, including the States of Hawaii and Florida, the Territories of Guam, American Samoa, Puerto Rico, and the U.S. Virgin Islands, and the Commonwealth of the Northern Mariana Islands. The resulting data will make it possible to identify where, when, and how U.S. coral reefs provide the most significant flood reduction benefits socially and economically under current and future climate change scenarios to inform reef conservation and management priorities. Ultimately, our goal is to inform U.S. Federal, State, Territorial, and local governments' efforts on coral reef conservation, restoration, and management by providing rigorous, spatially-explicit, high-resolution, economic valuations of the people and property protected by coral reefs under numerous current and future climate change scenarios.

In addition, we hope to 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. The results of the project will be made available in a

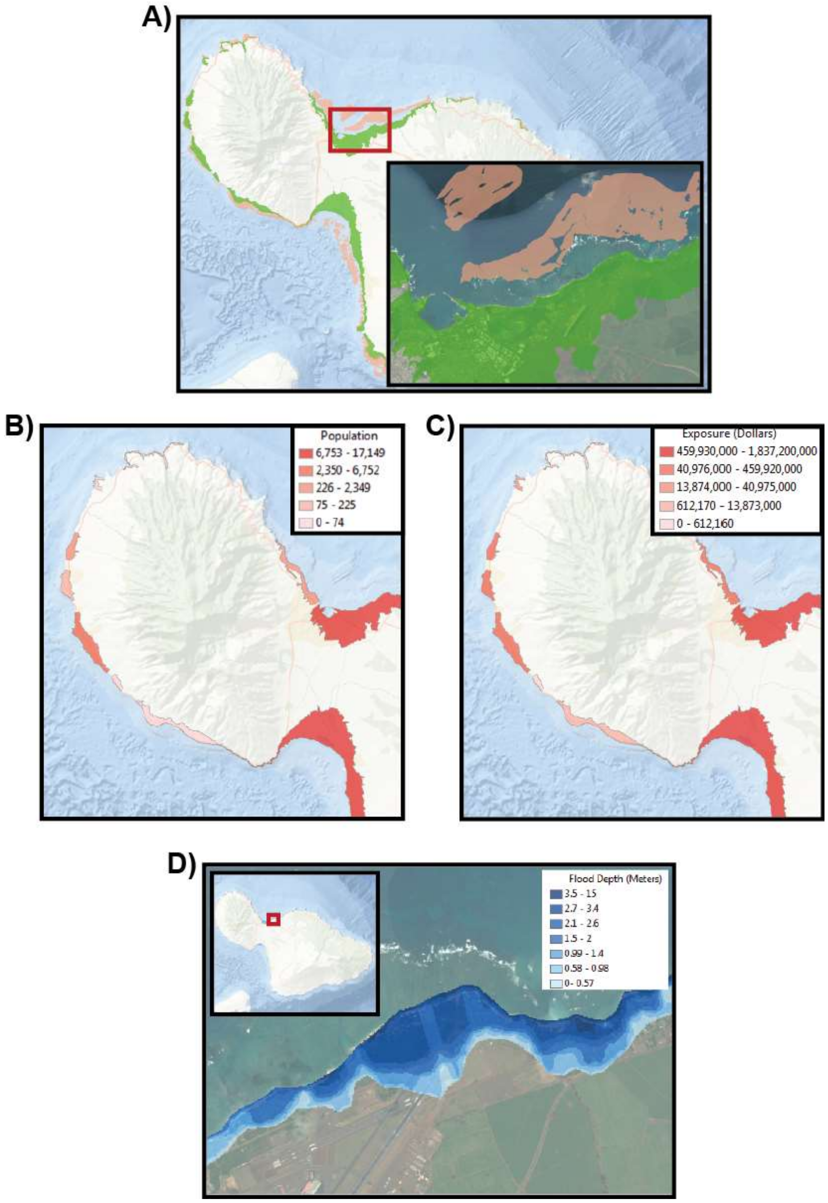

Figure 3 – Example data layers showing example model inputs and outputs for Maui. A) Coral reefs (tan) and adjacent reef-influenced zones (green) extending to the 20-m elevation contour. B) Population in the reef-influenced zones from CENSUS data. C) Value of infrastructure in reef-influenced zones from HAZUS data. D) Example 100-year wave-driven flood depths. Red boxes in A and D denote the location of the higher resolution images displaying data.

report, scientific papers, and the on-line interactive decision support tool *Coastal Resilience* (http://maps.coastalresilience.org). This on-line platform, developed through a public-private partnership led by The Nature Conservancy, includes an approach and decision support tool for climate adaptation and resilience planning, as well as information to support disaster response, coastal habitat restoration and climate change policy efforts. The *Coastal Resilience* platform works globally to assess risk and identify risk reduction solutions.

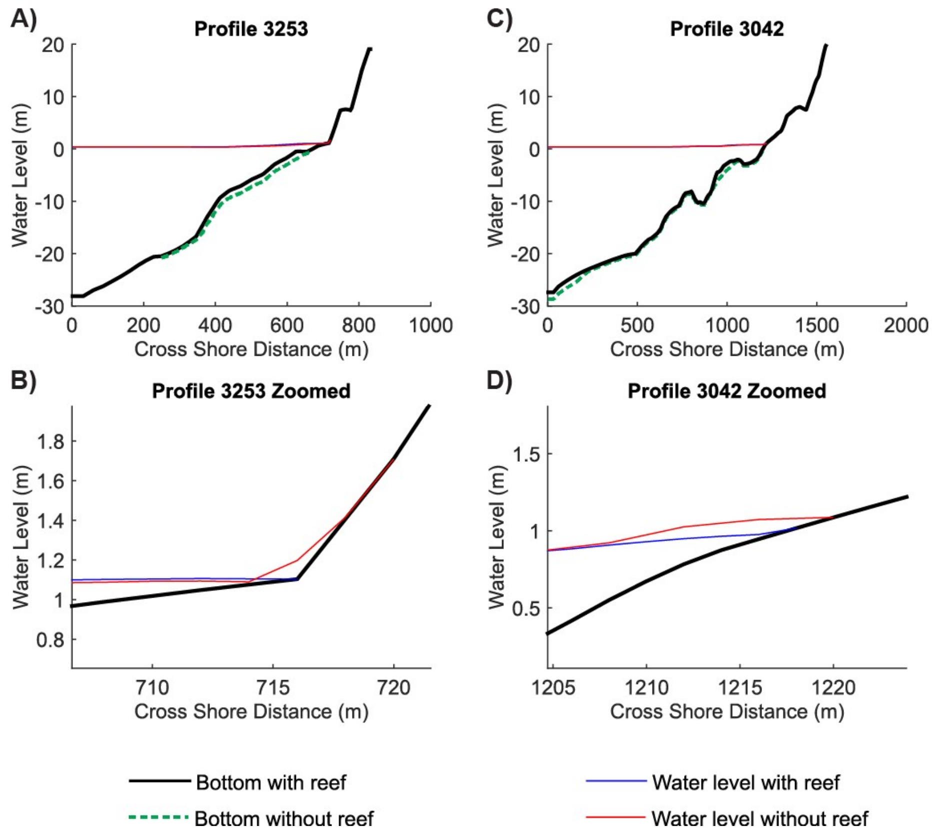

Figure 4 – Example Maui topographic-bathymetric cross-sections and XBEACH wave-driven total water levels with and without the presence of coral reefs. A) Cross-shore profile 3253 with a continuous fringing reef offshore. B) Zoomed-in view of profile 3253. C) Profile 3042 with patch reefs offshore. D) Zoomed-in view of profile 3042. The black line denotes bathymetry and the blue line total water levels (set-up plus run-up) with coral reefs; the green line denotes the bathymetry and the red line total water levels without coral reefs.

Acknowledgements
This work was funded by the U.S. Office of Insular Affairs, the U.S. Geological Survey's Coastal and Marine Geology Program, and The Nature Conservancy's Global Oceans Program. Use of trademark names does not imply USGS endorsement of products.

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