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Projected 21st Century Coastal Flooding in the Southern California Bight. Part 2: Tools for Assessing Climate Change-Driven Coastal Hazards and Socio-Economic Impacts

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Abstract: This paper is the second of two that describes the Coastal Storm Modeling System (CoSMoS) approach for quantifying physical hazards and socio-economic hazard exposure in coastal zones affected by sea-level rise and changing coastal storms. The modelling approach, presented in Part 1, downscales atmospheric global-scale projections to local scale coastal flood impacts by deterministically computing the combined hazards of sea-level rise, waves, storm surges, astronomic tides, fluvial discharges, and changes in shoreline positions. The method is demonstrated through an application to Southern California, United States, where the shoreline is a mix of bluffs, beaches, highly managed coastal communities, and infrastructure of high economic value. Results show that inclusion of 100-year projected coastal storms will increase flooding by 9–350% (an additional average 53.0 ± 16.0 km^2) in addition to a 25–500 cm sea-level rise. The greater flooding extents translate to a 55–110% increase in residential impact and a 40–90% increase in building replacement costs. To communicate hazards and ranges in socio-economic exposures to these hazards, a set of tools were collaboratively designed and tested with stakeholders and policy makers; these tools consist of two web-based mapping and analytic applications as well as virtual reality visualizations. To reach a larger audience and enhance usability of the data, outreach and engagement included workshop-style trainings for targeted end-users and innovative applications of the virtual reality visualizations.

Keywords: coastal hazards; sea-level rise; coastal storms; climate change; exposure; socio-economic vulnerability; data visualization

1. Introduction

Increases in sea-level rise (SLR), nuisance flooding, and changing storm patterns in coastal areas are raising awareness of the need to mitigate, plan, and consider alternatives in construction guidelines for the safety of future and planned construction and human health and safety [1–4]. Varied approaches have been developed to identify and map such coastal hazards for coastal planners and decision-makers [5–12]. However, few studies account for the combined effects of SLR and storm-driven coastal flooding on the local scale across vast geographic expanses; even fewer studies account for non-stationary changes in projected water levels and their resulting exposure hazards and socio-economic impacts [7,8,11,13–15]. To address this void, the Coastal Storm Modeling System (CoSMoS) was developed to provide planners, managers, policy-makers, and engineers with local-scale (approximately 10–100 m) data on probable future coastal exposure hazards across large geographic scales (approximately one hundred to several thousand kilometers) [13–15].

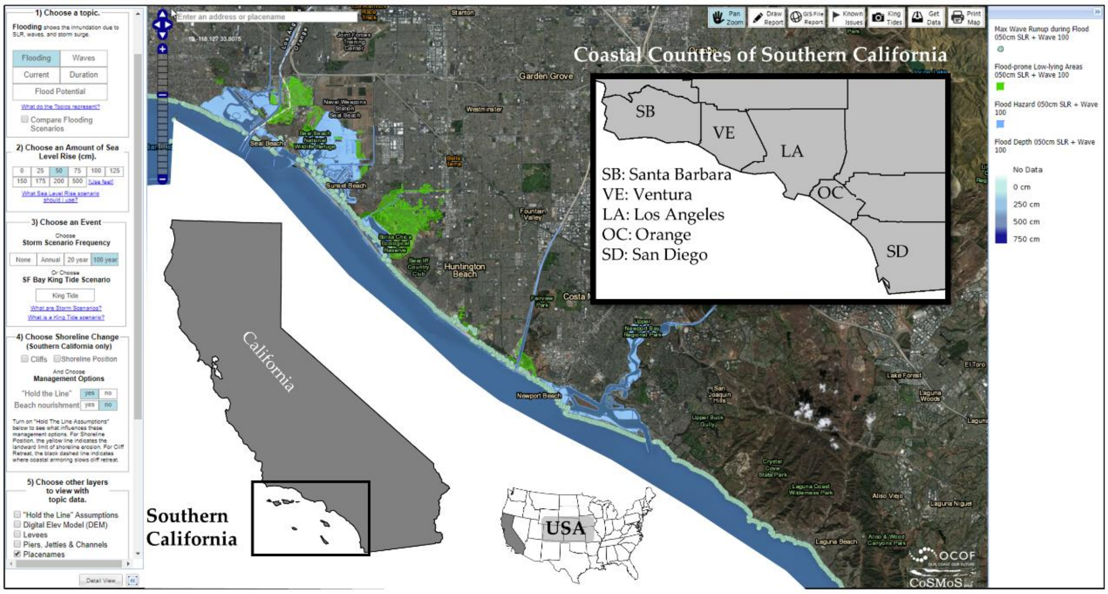
The third-generation CoSMoS model and its application in Southern California (USA), using a mid-emissions climate scenario (representative concentration pathway (RCP) 4.5), are presented in Part 1 [16] of this two-part manuscript. More extreme wave climate conditions are illustrated for California in the RCP 4.5 scenario [17] and, accordingly, it is used for detailed hazard simulations in CoSMoS [16]. The CoSMoS framework projects global changes, which are driven by Global Climate Models (GCMs) to local scales via a suite of regional and local scale models simulating coastal hazards in response to projections of 21st century waves, storm surges, anomalous variations in water levels, river discharge, tides, and SLR. A detailed discussion of the methodology, modeling framework, recent improvements, model validations/limitations, and an incorporation of uncertainty into coastal hazard projections can be found in Part 1 [16].

In this second part of the manuscript, results of the modeled hazards are presented and conjoined with land cover, population statistics, and socio-economic data to provide 21st century hazard-exposure estimates along the largely developed Southern California coastline, a region that thrives on tourism, software, automotive, ports, finance, and biomedical industries, contributing to more than 50% of California's Gross Domestic Product (GDP), ranked the fifth largest worldwide [18].

The *hazards* of interests in this study are coastal erosion and flooding. *Exposure* refers to the presence of various societal elements (e.g., people, buildings, resources, critical facilities, and infrastructure) that are in hazard zones, and therefore susceptible to damage or loss. *Vulnerability* describes the characteristics of individuals and assets as well as larger socioeconomic factors that influence the degree to which an individual, system, or community is susceptible to the damaging effects of a hazard. For example, although a large area of residential housing may be equally exposed to coastal flooding, the vulnerability of individual households will vary due to demographic characteristics of homeowners (which influence one's ability to prepare for and mitigate potential losses) and due to differences in the types of structures (which influence the ability to withstand impacts). In addition, two adjacent towns may have equal hazard exposure, but their overall vulnerability to flooding varies if the number of homes exposed to flooding represents 5% of available housing in one town and 95% of housing in the other town.

To communicate coastal hazards, exposures, and vulnerabilities as well as assess the socio-economic impacts, the data are made available via two publicly accessible web tools (Figure 1). "Our Coast, Our Future" [19] (OCOF; www.ourcoastourfuture.org) is a web application for data visualization, synthesis, and access to all output products from the CoSMoS model. The OCOF mapping interface provides coastal managers and the general public with a user-friendly means to visualize how various SLR scenarios alone and in combination with three different future return-period coastal storms are projected to flood or erode. Users can export summary tables and reports detailing changes in flood extent by scenario on a scale relevant to local planners. The Hazard Exposure Reporting and Analytics [20] (HERA; https://www.usgs.gov/apps/hera/) web tool translates the flooding hazards into community-based exposure statistics and quantifies populations, property, and critical infrastructure at risk in terms of exposure statistics and monetary values on a community level.

(a) Our Coast Our Future (OCOF) web-tool



(b) Hazard Exposure Reporting and Analytics (HERA) web-tool

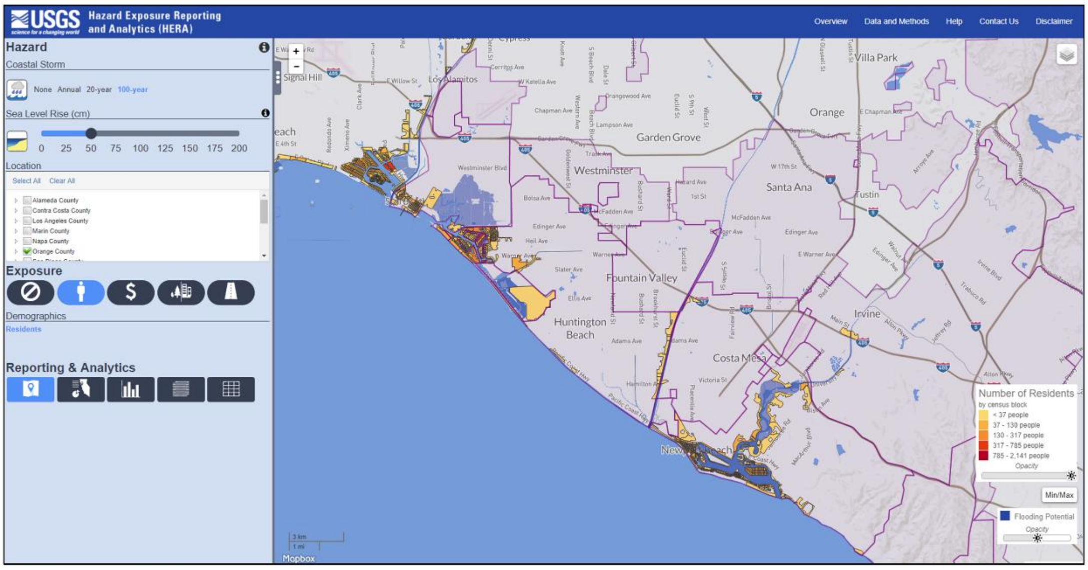


Figure 1. Web applications for visualization, synthesis, socio-economic analyses, and data download. (**a**) Screen-grab from the "Our Coast, Our Future" (OCOF) web tool showing coastal hazards associated with currents, wave heights, flood extents/depths, durations, and shoreline change for each of the modeled sea-level rise (SLR) and storm scenarios (www.ourcoastourfuture.org). Inset shows location of Southern California and the five coastal counties within the Southern California region; (**b**) Screen-grab from the Hazard Exposure and Analytics (HERA) web tool developed to aid in analysis of exposure and socio-economic statistics (https://www.usgs.gov/apps/hera/). Both applications contain a suite of tools and options for visualizing (maps and graphs) and synthesizing the model results. Example screen-grabs are for the Orange County (OC) area.

The scientific methods that underpin the projected hazards are based on state-of-the-art science that includes many of the latest developments and understandings of coastal processes (i.e., non-linear effects of currents and waves, reflection, refraction, and blocking of wave energy due to complex bathymetry; see Barnard et al. and O'Neill et al. [15,16]) making it difficult to communicate assumptions, limitations, as well as the strength and value of the data to non-technical and non-specific science-educated audiences. To address these concerns, both traditional and innovative stakeholder engagement, training, and outreach efforts have been tested. Although the translation of the science remains challenging, we have pinpointed several tactics that are likely to be useful in similar large-region, high-resolution studies elsewhere.

The aim of this paper is to (1) highlight the need to account for dynamic water levels in addition to static SLR for estimating future coastal flood hazards and vulnerabilities along high-energy coastal environments such as Southern California, USA and (2) to present means and introduce innovative approaches for conveying the hazards, socio-economic impacts, and underlying scientific basis to a broad audience including coastal managers, planners, and engineers. The remainder of this manuscript describes the data and methods used to quantify exposures and vulnerabilities along the Southern California coast. Results pertaining to erosion and flood hazards are presented with a particular emphasis on the added risk when storms are accounted for in addition to SLR. Results of the socio-economic impact analyses are then presented for a select set of assets and demographics rather than all available results to illustrate the use and applicability of stakeholder user-tools. The final sections present strategies and innovative outreach activities for dissemination of the information as well as a summary and discussion of findings.

2. Methods

The methods developed for simulating hazards with the latest generation of CoSMoS are outlined in Part 1 of this manuscript [16], which include presentation and discussion on models, selection of storm conditions, model validation/limitations, and uncertainty. The latest iteration of CoSMoS is implemented in Southern California, an active and complex tectonic region spanning over 500 km and five counties (Figure 1). The coastal landscape is generally characterized as beaches backed by semi-resistant bedrock sea-cliffs as well as coastally constrained estuaries and low-lying areas at the foot of coastal mountain ranges (see Part 1 for more details). CoSMoS-modeled hazards for Southern California include outputs of coastal erosion, wave heights, wave runup, total water levels, current speeds, flood extents, and flood depths/durations for 40 'scenarios' consisting of all combinations of 10 SLR elevations (0–200 cm SLR in 25 cm increments, plus 500 cm), three coastal storm intensities (annual, 20-year, and 100-year), and a no-storm condition [16,21,22]. Coastal erosion outputs included management scenarios involving beach nourishment and the existence and maintenance of hard structures (see Section 3.1.1). Low-lying flood-prone areas and uncertainties in flood extents and shoreline change are also generated as part of the model output.

Resulting model data were converted to static GeoTIFF rasters (flood depth, wave height, and current velocity), polygon shapefiles (flood extent, low-lying areas, and uncertainty) or point shapefiles (wave runup and shoreline change) and were processed for the OCOF cyberinfrastructure to display and provide exposure hazard map data. The cyberinfrastructure was built on the Open Source Geospatial Foundation stack of software. Simple raster tiles were first rendered from the GeoTIFF data layers; point and polygon layers were loaded into PostgreSQL (an open-source database; version 9+; available https://www.postgresql.org/)/PostGIS (an open-source, GIS-support software program; version 2+; available https://postgis.net/) database and piped through the GeoServer web service for rendering and display on the map (see Appendix A for a list of terms, acronyms, and software platforms). Initially, the data were provided for download as large zip files but these proved to be too cumbersome for many users; a re-organization of the data tiled by scenario, output product (e.g., flood depth/extent, duration, wave height), and individual counties has improved users' ability to access the data and increased overall user satisfaction.

Geospatial data summarizing various population, business, land cover, and infrastructure were used to estimate community exposure to a given flood hazard zone in HERA [20]. Residential populations were estimated using block-level population counts compiled from the 2010 US Census [23]. Demographic and economic factors, such as age, health, ethnicity, race, and health, and tenancy, can amplify an individual's sensitivity to hazards [24,25]; therefore, the 2010 block-level data were used to estimate demographic attributes related to these socio-economic indicators of sensitivity.

Business populations and regional trends of exposure were estimated in HERA using employee counts organized by North American Industry Classification System (NAICS) codes [23] at individual businesses using a georeferenced, proprietary employer database [26]. Business types based on NAICS codes were generalized in this analysis into five classes: (1) government and critical facilities; (2) manufacturing; (3) services; (4) natural resources; and (5) trade.

Land cover indicators include the amount and type of land in hazard zones based on 30-m-resolution data extracted from the 2011 National Land Cover Database (NLCD) [27]. The HERA application currently focuses on land classified in NLCD as either wetlands or developed.

Hazard exposure of critical facilities and infrastructure was estimated using the length of rail and road networks (infrastructure) and the number of schools, medical facilities, police stations, and fire stations (facilities). These facilities are considered critical because they provide public safety services or house vulnerable populations. Data sources for critical facilities and infrastructure include a wide array of county and federal sources [28].

For each variable, geographic information system (GIS) software was used to overlay data representing community boundaries, the community indicator, and a specified flood hazard zone. Two variables for each asset were estimated at the community level: (1) a total amount (or length, in miles, for road and rail networks) of an asset in a hazard zone and (2) a community percentage. For resident and employee populations in hazard zones, the community percentage reflects the exposed amount compared to the total amount within a community. For the business types, percentages reflect the number of businesses of a certain type divided by the total number of that business type in the community. For the demographic attributes, community percentages reflect the percentage of a specific demographic attribute relative to the total number of residents in the hazard zone, not the community total. Spatial analysis of vector data focused on determining if points (businesses and critical facilities), lines (roads and rails), or polygons (census blocks) were inside hazard zones. If census-block polygons overlapped hazard polygons, final population values were adjusted proportionately using the spatial ratio of each sliver within or outside of a hazard zone.

3. Results

3.1. Projected Hazards

3.1.1. Coastline Change

Shoreline management scenarios involving beach nourishment and the existence and maintenance of hard structures to limit erosion were simulated with the cliff recession and sandy shoreline change models (see Section 2.2 of Part 1) [16,29–31]. Two management scenarios were investigated for the cliff recession projections: (1) cliff recession unlimited by cliff armoring; and (2) cliff recession everywhere except where armoring exists (as of 2016). For the sandy shoreline projections, four management scenarios were simulated, representing all four combinations of: (A) no beach nourishment or continued rates of historical beach nourishment; and (B) the existence ("hold-the-line") or non-existence of hard structures that limit erosion. For the "hold-the-line" scenarios, scenario erosion was limited to an 180,000-point polyline digitized from aerial photos (Google Earth™, 2015/2016) that represents the division of beach and urban infrastructure.

Applied and averaged over 2156 transects, the cliff model projects that recession rates will increase by 62%, 92%, 150%, and 220% relative to historical rates for the 50, 93, 150, and 200 cm SLR scenarios, respectively [29]. The highest rates of increase are projected for Santa Barbara, Los Angeles, and southern Ventura counties. A total land loss of 7–82 m for the 25–200 cm SLRs is projected, but this assumes much variability along the coast and increasing uncertainty with the projected greater recession rates. Examples are shown for the 50 and 200 cm SLRs in Figure 2, where it can be seen that the greatest recession rates are in Los Angeles and San Diego counties.

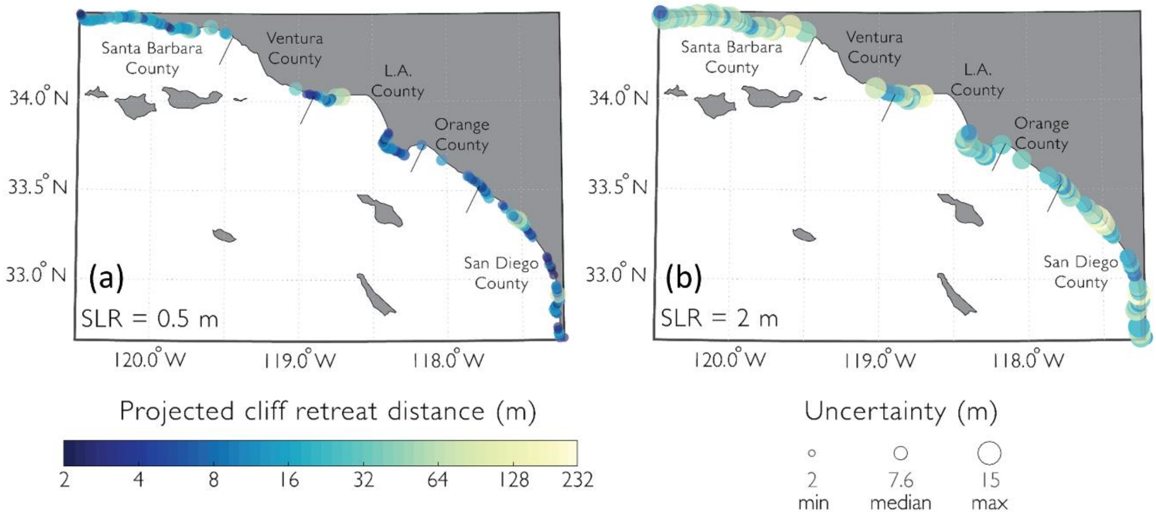


Figure 2. Map of cliff recession model results for two sea-level rise (SLR) scenarios: (**a**) 50 cm SLR and (**b**) 200 cm SLR. The colors represent cliff retreat distance, while the size of the marker represents the amount of uncertainty.

Results of the shoreline change model (sand and gravel beaches) projects average beach losses of 21–68 m for the 100–200 cm SLRs, depending on the management scenario [30] (Figure 3). The inclusion of the additional effect of seasonal[1] erosion (driven by larger-than-average wave conditions) increases this range from 32 m to 106 m of average beach loss by 2100 (Figure 3; see Vitousek et al. [30] for details). This amount of beach recession may result in 31–67% of beaches in Southern California being completely eroded to the landward limit of coastal infrastructure or cliffs by 2100. Furthermore, 25–65% of beaches may erode more than 5 m into existing coastal infrastructure and homes if allowed to migrate landward, unimpeded by seawalls and hardened structures.

The results also indicate that there is little overall difference between the nourished and unnourished management scenarios (scenarios 1 and 2): the continued nourishment scenarios only reduce the extent of erosion compared to the unnourished scenarios by 2–3 m on average (Figure 3). The model only projects any stability or significant decrease in erosion of the shoreline in local cases, where very large nourishments are assumed to continue.

3.1.2. Flood Hazards

Flood hazards, simulated with CoSMoS and evolved coastlines assuming management scenario 1 ("hold-the-line" and no nourishment, Figure 3), indicate that 10–380 km^2 of land along the Southern California coast will be permanently inundated with the 25–500 cm SLR, no storm, scenarios.

Inundation due to SLR alone is summarized for each of five coastal Southern California counties in Figure 4a. Ventura County is consistently the most vulnerable region for SLR scenarios above 1 m, where permanent inundation extents are estimated at 50 and 91 km^2 for the 200 and 500 cm SLR scenarios, respectively. Orange and San Diego Counties are projected to experience slightly less

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[1] average beach loss shorelines are based on a 1 January (mid-winter) time horizon, whereas the max seasonal erosion is based on the upper limit of the 95% confidence interval (2nd standard deviation) using all the model-projected positions.

inundation, while Santa Barbara County is less vulnerable with a maximum flooded area of ~20 km^2 due largely to the high cliffs and bluffs that front this coastline. For the more near-term SLR estimate of 25 cm (approximately by the year 2030) [32], Los Angeles and San Diego will be the most affected, with an estimated 3–4 km^2 of inundation. The susceptibility of each county to the different states of SLR are due to variations in local topography and flood protection infrastructure that hinder or allow inland flow of ocean water.

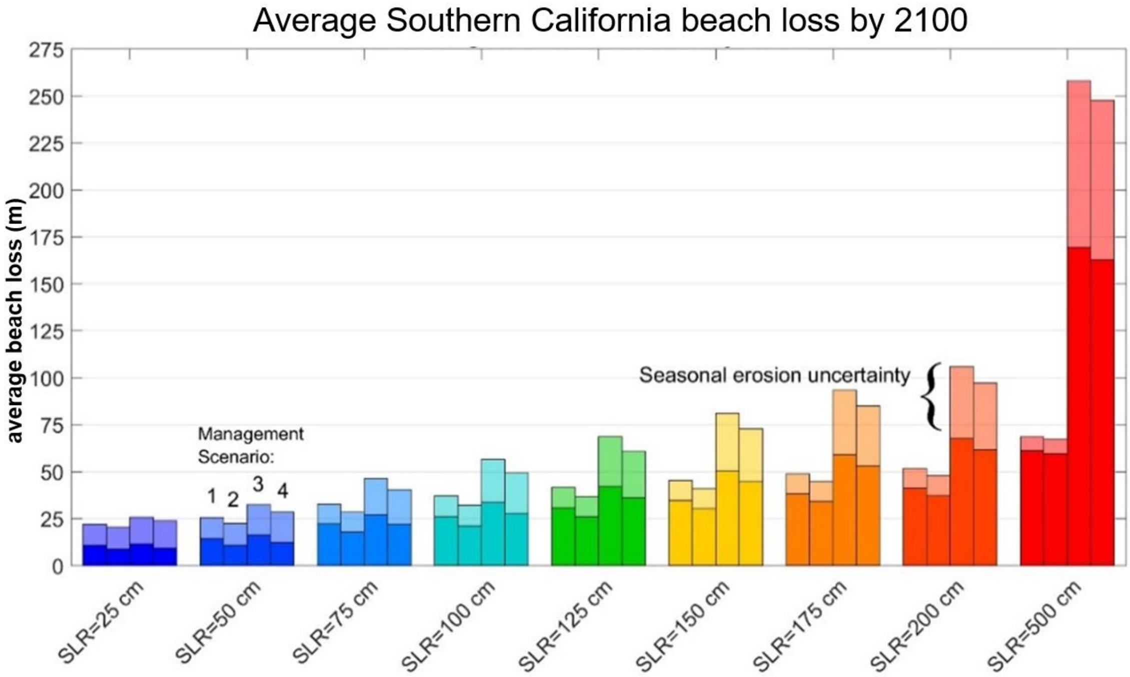

Figure 3. Average beach loss in Southern California derived from the shoreline change model under different management and sea-level rise (SLR) scenarios (see O'Neill et al. and Vitousek et al. [16,30] for model details). The four management scenarios are (1) "hold-the-line" (hard structure to limit erosion) with no continued nourishment; (2) "hold-the-line" with continued nourishment; (3) no structures/limit on erosion and no continued nourishment; and (4) no structures/limit on erosion and continued nourishment. Figure modified from Vitousek et al. [30].

Inclusion of storms (and the combined effects of associated waves, surge, and discharge) in the model simulations significantly increases the flood extents across all counties. For example, the 100-year coastal storm floods, on average, an additional 4.5 ± 2.0, 16.0 ± 5.5, 9.0 ± 6.0, 12.0 ± 8.0, and 11.5 ± 4.0 km^2 of land in Santa Barbara, Ventura, Los Angeles, Orange, and San Diego Counties, respectively (Figure 4b–f; Table 1). These extents predominantly include the coastally constrained estuaries and low-lying areas in each county as well as hundreds of kilometers of impacted cliff- and infrastructure-backed shoreline. Viewed from a perspective of percentages, the inclusion of storms represents substantial increases for the lower-end SLRs, whereas, for the higher SLRs, the percentages are smaller because the total areas inundated by SLR alone increases and dominates the flood signal. For example, flood extents increase >10-fold (from 1.2 to 15.5 km^2, an increase of 14.5 km^2) when the 100-year coastal storm in Ventura County is included for the low-end 25 cm SLR, but 'only' by 26% (from 49.5 km^2 to 62.5 km^2) for the 200 cm SLR, although the areal increase is similar (13.0 km^2 compared to 14.5 km^2). Taking the entirety of Southern California into consideration, percentages of increased flood-area due to storms decrease from ~350% for the 25 cm SLR scenario to 9% for the 500 cm SLR scenarios (last column in Table 1).

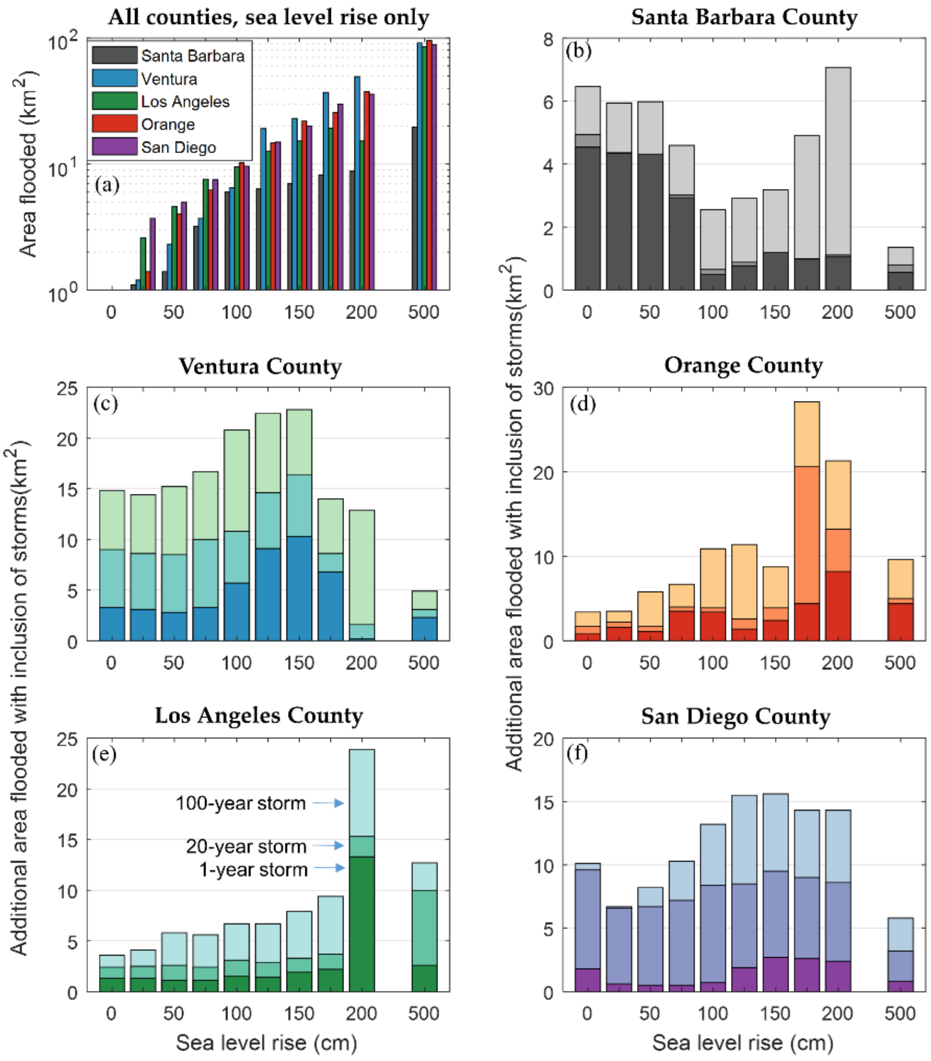

Figure 4. Areas projected to flood within each of the five coastal counties in Southern California due to sea-level rise (SLR) alone and in combination with coastal storms. (**a**) Total extents of flooded areas in each county for the SLR only scenario (no storm). Note the logarithmic vertical axis to capture the large differences between the 25 cm and 500 cm SLR scenarios; (**b**–**f**) Areas flooded beyond the SLR-only scenario, when the annual (darker color), 20-year, and 100-year (lightest color) costal storms are simulated in combination with SLR.

3.2. Projected Exposures and Vulnerabilities

Integration of modeled shoreline retreat and flood hazards with geospatial demographic and socio-economic data shows that 20,000–164,000 residents, 150–1330 km of road, and as much as 22 km^2 of agricultural land are at risk of being permanently flooded in Southern California with a 25–200 cm SLR. Building replacement values are estimated to be between \$3.65 billion and \$26.10 billion (2006 value, unadjusted for inflation). Inclusion of the 100-year coastal storm increases hazard exposures to 30,800–256,000 residents (a 55–110% increase), 340–2300 km of road (a 50–115% increase), and building replacement costs to \$6.95–\$38.25 billion (up by 42–91%).

Table 1. Area (km^2) flooded due to sea-level rise (SLR) alone and SLR in combination with the 100-year coastal storm (SLR only/SLR plus 100-year coastal storm). Bottom row shows increase in flood area from impact of 100-year coastal storm (average across all SLR values) for each county and across all counties.

SLR (cm)	**County**					**All Counties**		
	Santa Barbara	**Ventura**	**Los Angeles**	**Orange**	**San Diego**	**Total**	**Increased Flooding**	
							km^2	**Percent**
25	1.1/7.0	1.2/15.6	2.6/6.8	1.4/4.8	3.7/10.5	10/45	35	347%
50	1.4/7.4	2.3/17.5	4.6/10.4	4.0/10.4	5.0/13.2	17/58	41	237%
75	3.2/7.8	3.7/20.4	7.6/13.2	6.2/12.9	7.5/17.8	28/72	44	155%
100	6.0/8.6	6.5/27.2	9.5/16.3	10.2/21.1	9.6/22.8	42/96	54	129%
125	6.4/9.3	19.1/41.5	12.6/19.2	14.8/26.2	14.9/30.4	68/127	59	87%
150	7.0/10.1	23.0/45.8	15.2/23.1	21.9/30.7	20.1/35.7	87/145	58	67%
175	8.2/13.1	37.0/51.0	19.2/28.6	25.6/54.0	29.9/44.3	120/191	71	59%
200	8.8/15.9	49.4/62.4	15.2/39.0	37.5/58.8	35.8/50.1	147/226	79	54%
500	19.6/21.0	91.3/96.1	85.0/97.7	95.5/105.1	88.9/94.7	380/415	34	9%
Increase in flooding with 100-year storm (average across all SLRs) *								
km^2	4.5 ± 2.0	16.0 ± 5.5	9.0 ± 6.0	12 ± 8.0	11.5 ± 4.0		53.0 ± 16.0	
percent	157%	327%	84%	101%	99%			

* rounded to 0.5 km$^{2.}$

3.2.1. County Level

From a county perspective, residents within Los Angeles, Orange, and San Diego counties are at a greater risk to coastal flooding compared to the other two counties (Ventura and Santa Barbara) within coastal Southern California (Figure 5a). Overall, 80–90% of residents exposed to flooding for any combination of SLR and coastal storm in Southern California, reside within Los Angeles, Orange, or San Diego counties. More than 18,000 residents are at risk of being permanently flooded in these three counties for the lowest modeled 25 cm SLR and no coastal storm. Inclusion of the 100-year coastal storm increases residential flood exposure by 176% (from 5170 to 14,270 residents), 62% (from 5970 to 9650 residents), and 57% (from 7150 to 11,250 residents) in Los Angeles, Orange, and San Diego Counties, respectively.

Replacement costs of buildings (residential and commercial) are projected to be highest in the same three counties: Los Angeles, Orange, and San Diego. Together, these three counties will experience more than 85% of the cost burden associated with coastal flooding in Southern California (Figure 5b). Replacement values range from $0.95–$4.54 billion in Los Angeles, $4.28–$5.62 billion in San Diego, and $1.17–$6.62 billion in Orange counties for the 25–200 cm SLR. Including coastal storms increases the cost burden by 6–450%. In Los Angeles, Orange, and San Diego counties, replacement values approximately double from approximately $1 billion to $2 billion when storms are included with the 25 cm SLR.

3.2.2. Community Level

Identification of the most vulnerable communities within each of the counties was performed with the HERA tool, which provides graphs and maps of (1) magnitudes (e.g., total number of residents, length of road, or replacement values) and (2) percentages of an asset that fall within the hazard zone and within each community. For example, the number of residents and percent of total residents in Orange County communities that are projected to be affected by a 50 cm SLR exclusive and inclusive of the 100-year storm are shown in Figure 6. The bar plot indicates that residents within Newport, Huntington, and Seal Beach areas are most vulnerable and that the 100-year coastal storm floods additional residential areas within these communities. Similar plots and assessments are provided on the web-tool for infrastructure, developed and undeveloped land areas, and employees.

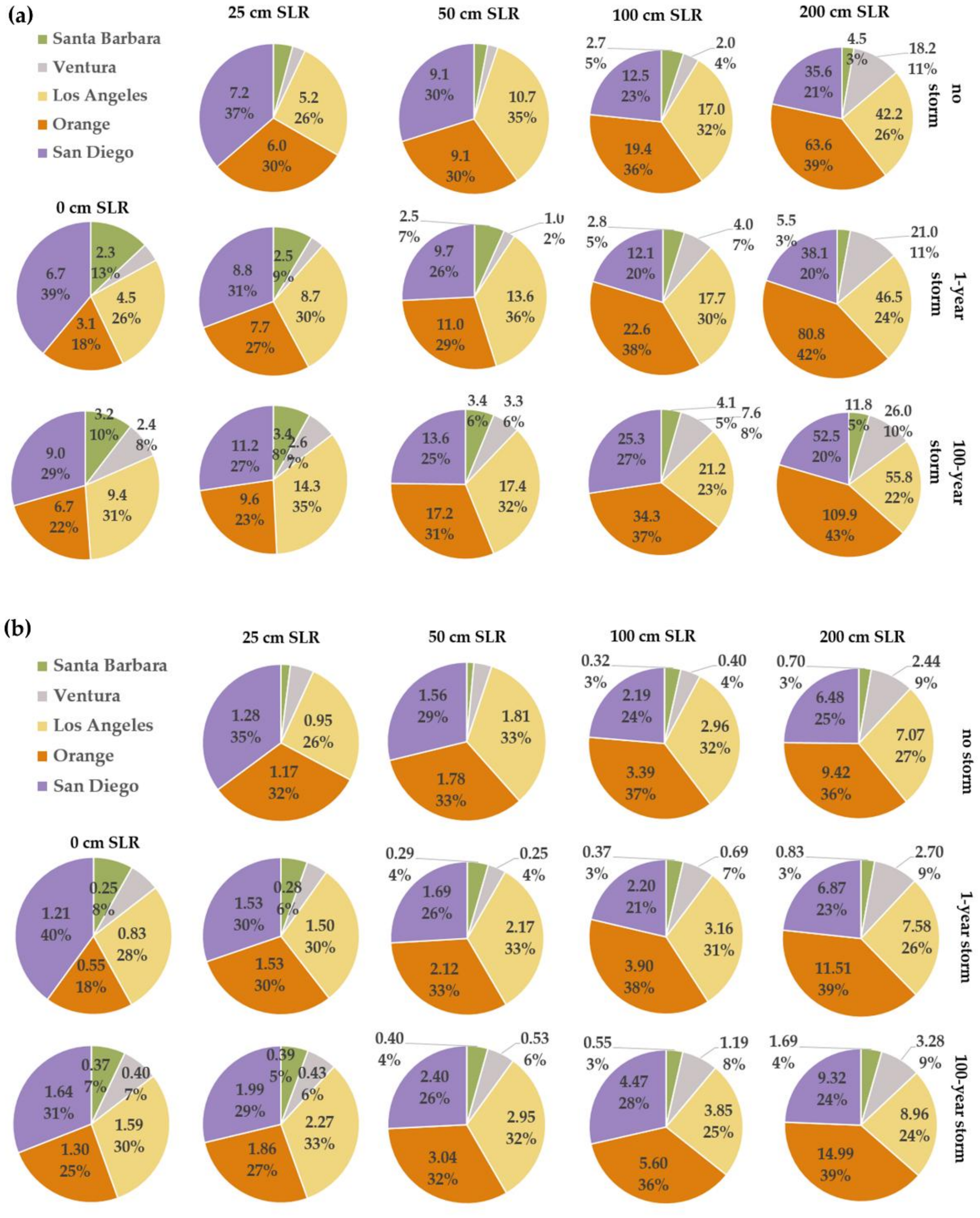

Figure 5. Example of socio-economic impacts resulting from flood hazards modeled for sea-level rise (SLR) scenarios of 25, 50, 100, and 200 cm without storms and in combination the annual and 100-year projected storms. (**a**) County residents (1000) and (**b**) building replacement values in billions of dollars. Pie charts show the proportion of residents affected and cost burdens within each of the five Southern California coastal counties (number of residents, cost of building replacements, and percent of totals with respect to impacts to all of Southern California). Results for the 75, 125, 125, 150, 175, and 500 cm SLR scenarios and 20-year return period storms are not shown but are commensurate with the trends shown.

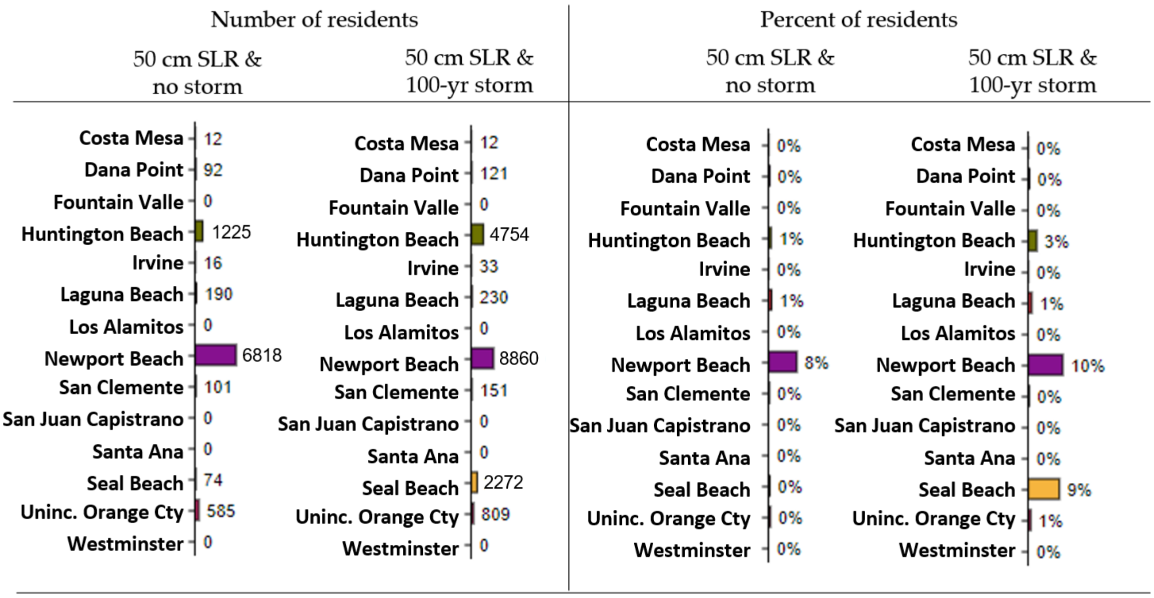

Figure 6. Example outputs (screen-grab: https://www.usgs.gov/apps/hera/) from the Hazard Exposure and Analytics (HERA) web tool comparing the number and percent of persons in each community that reside within the flood hazard zone for the 50 cm SLR with and without the projected 100-year coastal storm. Example is for Orange County.

In addition to comparing statistics between communities, HERA provides a means to evaluate exposures and vulnerabilities within each community. Magnitudes and percentages of affected demographics (over the age of 65, under the age of 5, ethnicity, race, renter versus owner residents, and head of household), land cover types (barren land, developed land, forest, pasture crops, shrub grass, and wetlands), infrastructure (highways, secondary streets and roads, railroads, critical facilities), economic assets (parcel values, building replacement values by occupancy class such as commercial, government, industrial, educational), and employee sectors (e.g., manufacturing, services, trade) are itemized and displayed spatially and summarized in graphs according to modeled hazards. An example of the spatial distribution and number of residents, including a breakdown of affected ethnicities, is shown in Figure 7b–d for Huntington Beach in Orange County. The data in Figure 7d indicates that this particular community hosts a fairly diverse population and that residents of all ethnicities will be affected by a 50 cm SLR; moreover, additional populations across all ethnicities will be exposed in case of the 100-year storm in combination with the 50 cm SLR. For the 50 cm SLR inclusive and exclusive of the 100-year storm, the greatest building replacement cost burden will be on the community's residents (Figure 7f). The lowest cost burden is expected to be for government structures, of which there is only one identified within the flood hazard zone (not shown). The data also indicate that government and education infrastructure are prone to damage by SLR and less by future coastal storms, as indicated by the equal or nearly equal cost-burden for the no storm and 100-year storm scenarios.

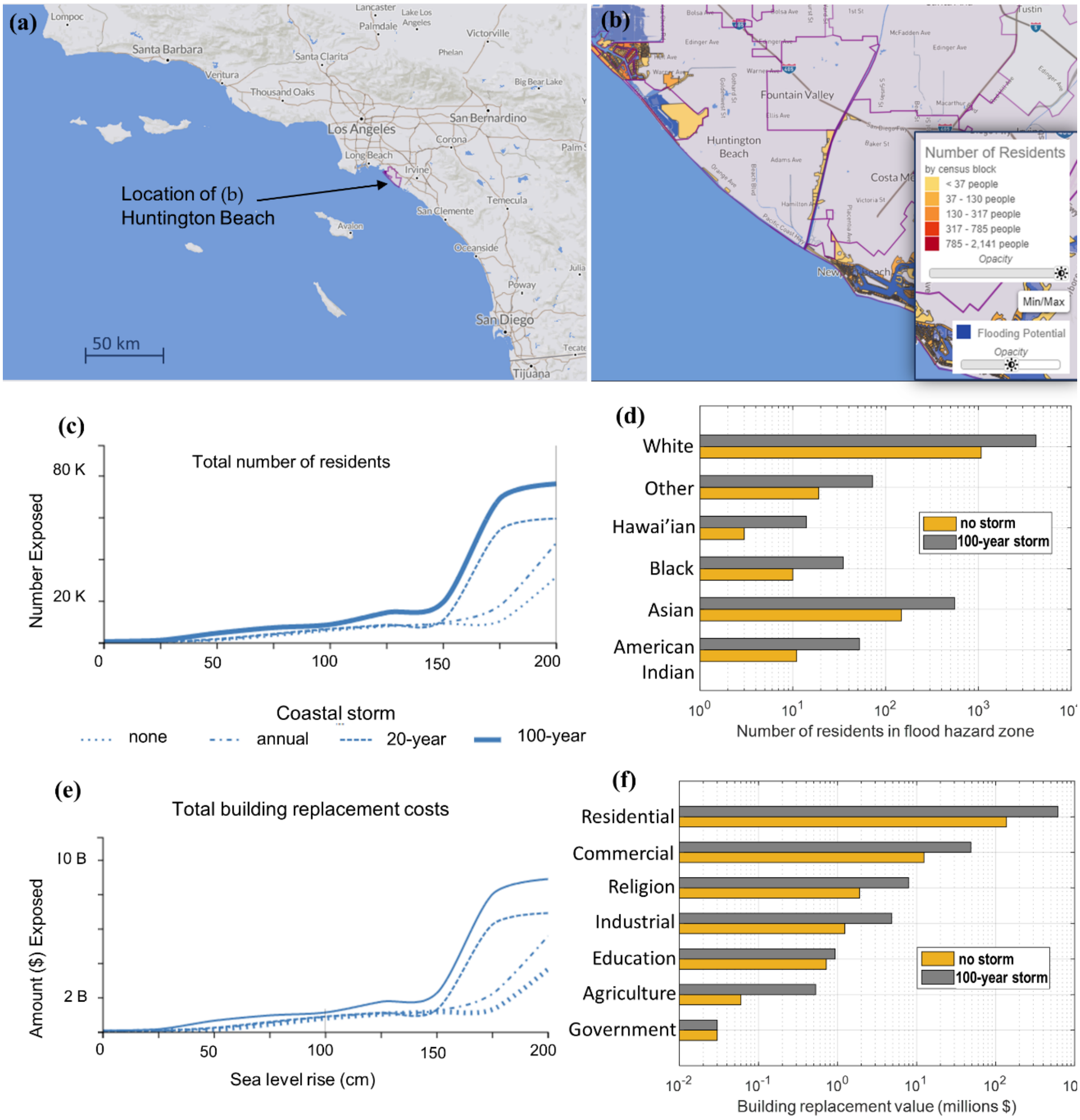

Figure 7. Example outputs from the Hazard Exposure and Analytics (HERA) web tool showing populations affected and building replacement costs within the Huntington Beach community in Orange County because of CoSMoS-modeled sea-level rise (SLR) and coastal storms. (**a**) Screen grab of HERA map showing Huntington Beach in Southern California; (**b**) Screen grab of spatial display in HERA showing the number of Huntington Beach residents exposed with 50 cm SLR in combination with a 100-year coastal storm (same as Figure 1b); (**c**) Total number of community residents exposed for all combinations of SLR (up through the 200 cm SLR) and coastal storms; (**d**) The number of community residents, grouped by ethnicity, exposed to the 50 cm SLR inclusive and exclusive of the 100-year storm; (**e**) Total building replacement costs within the community for all combinations of SLR (up through the 200 cm SLR) and coastal storms; (**f**) Building replacement costs, grouped by occupancy class, exposed to the 50 cm SLR inclusive and exclusive of the 100-year storm.

4. Stakeholder Engagement and Outreach

Outreach and engagement with planners, engineers, emergency managers, and environmental scientists from coastal cities, counties, utilities, state agencies, non-governmental organizations, and the private sector were conducted both in advance of and following the release of model results.

Outreach was designed and delivered in collaboration with established and trusted regional partners or networks to ensure local relevance. Workshops were held prior to the development of web tools to gain an understanding of what type of data, formats, and displays might be most suitable for end-users. Once model results were complete and incorporated into the web tools, high-level trainings and demonstrations of the OCOF and HERA web tools were conducted. To bolster interest and use, trainings were tailored to the specific needs and interests of local stakeholders and immediate access to the data in their respective areas was provided. For instance, the San Diego County workshop included a panel highlighting local projects engaged in SLR planning as well as a separate session that focused on model details, assumptions, and limitations for more technical end-users. For the Los Angeles County workshop, community planning exercises were conducted where attendees could view the SLR and erosion projections on paper maps and brainstorm adaptation ideas. Over the course of the Southern California project, we participated in eight workshops over three years, reaching over 500 participants across all Southern California counties.

In addition to the more traditional outreach and engagement strategies, virtual reality (VR) and 360-degree 3-D videos were used for communicating future coastal flood hazards. For instance, in the city of Santa Monica, California, projected flood extents were used to create virtual images of the beach under different states of SLR, both with and without the effects of coastal storms (see mobileowl.co/samo; Figure 8a–c). Possible adaptation strategies were also presented in some locales. Residents and visitors were guided through a series of images in a virtual-reality viewer that showed the beach

(1) in its present state (Figure 8a),
(2) flooded due to a 100-year storm modeled with CoSMoS,
(3) in the future with 2 m of SLR (Figure 8b),
(4) in the future with 2 m of SLR and the 100-year coastal storm, and potentially
(5) modified with a possible adaptation strategy (Figure 8c).

As users moved through the images, they were asked a series of questions on demographics and levels of concern as the flood hazards increase. These images were available via an in situ platform, nicknamed the "owl" (by Owlized™, see Figure 8a inset), that was placed on Santa Monica Pier from November 2016 to January 2017; the "owls" were used to support Santa Monica's local coastal planning and outreach efforts. The augmented images within the viewer provided visceral opportunities to visualize the complex scientific information used by the Santa Monica community in its planning. The visualizations are still available via the online mobile viewer (mobileowl.co/samo) and continue to be viewed by interested stakeholders.

A second innovative technology and approach using VR allows users to visualize how coastal areas may be effected everyday under future SLR conditions. A video system developed in partnership with Google™ and consisting of 16 GoPro™ cameras (the GoPro Odyssey™) was used to film 360-degree videos that show beaches during the highest ('King') tides of the year (Figure 8d–f). The videos were uploaded to YouTube and, using VR headsets, residents can explore and observe their local beach during these extreme conditions, visualizing how it might appear under normal tide conditions in the coming century if sea level continues to rise. Both sets of VR visualizations ("owl" and King tide videos) have been used for education and outreach purposes to help make complex scientific information more accessible. They can both be accessed via mobile platforms as well as via home computers with sophisticated VR headsets (such as any Google™ VR viewer).

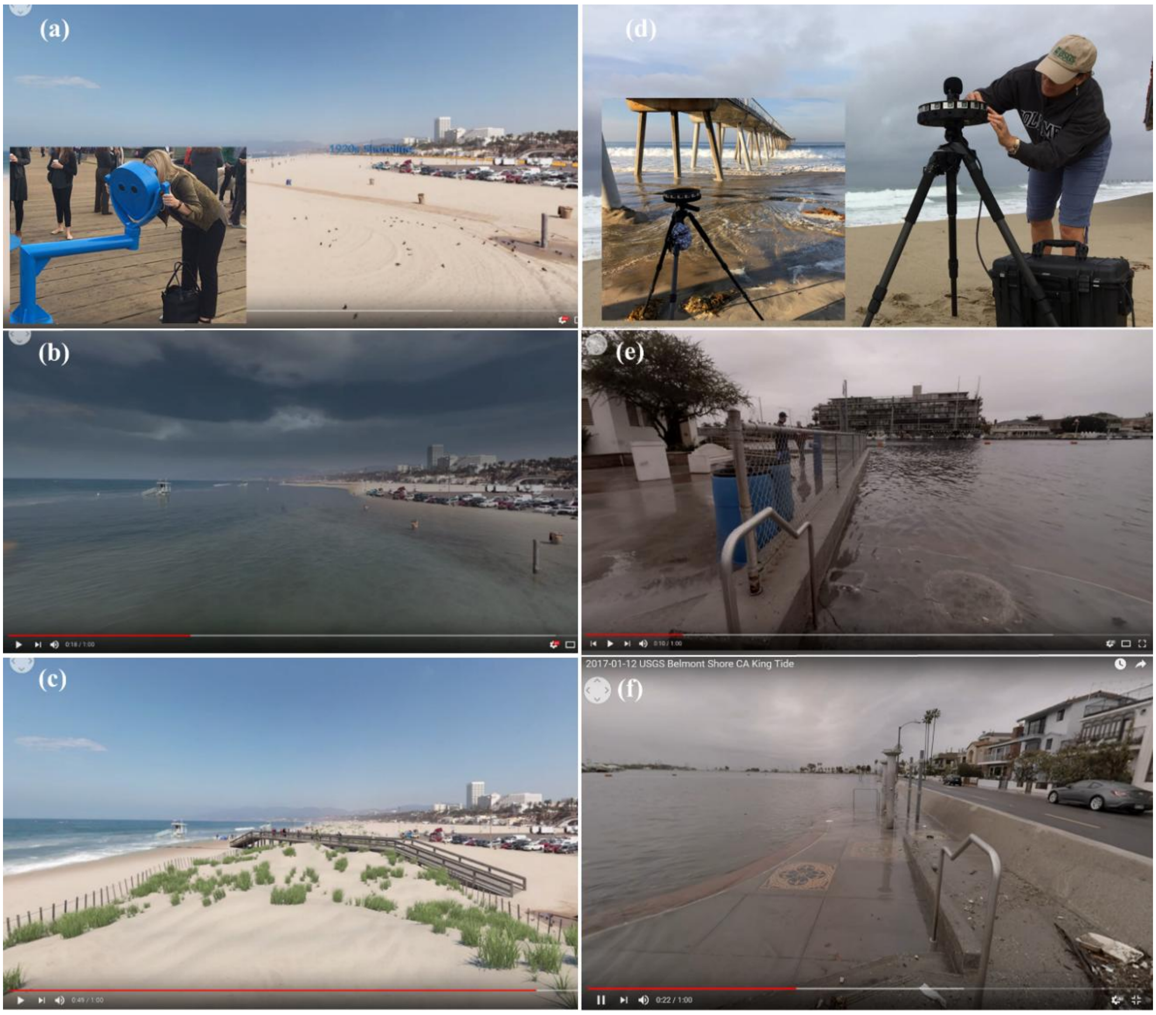

Figure 8. Images showing stills from virtual reality simulations of sea-level rise (SLR) potentials. (**a**–**c**) Example images (screen-grabs: mobileowl.co/samo) from the virtual reality (VR) viewer shown in (**a**). (**a**) Present day conditions and the 1920's shoreline position at Santa Monica Beach in Los Angeles County, California (CA). Inset photo shows use of the viewfinder for observing and scanning the VR images; (**b**) VR image of CoSMoS-modeled shoreline position with a 2 m SLR; (**c**) VR image of a possible adaptation option employing vegetated dunes; (**d**–**f**) Example images (screen-grabs: https://www.youtube.com/watch?v=FQl93W469vI) from the 360-degree 3-D viewer and video. Videos of annual high tides are filmed to serve as proxies for future sea levels under everyday normal tide conditions; the videos are viewed in 3-D by users using any VR headset. Inset photos in (**d**) show the 16 GoPro™ camera system used to capture the 360-degree view.

5. Discussion and Summary of Findings

The overarching concept of CoSMoS is to leverage projections of global climate patterns over the 21st century from recent Global Climate Models (GCMs). Coarse resolution GCM projections are downscaled to the local level and used as boundary conditions to sophisticated ocean modeling tools that simulate complex physics to accurately predict local coastal water levels and flooding for the full range of expected SLR ($n = 10$: 0–2 m in 0.25 m increments and 5 m) and storm scenarios ($n = 4$: average daily/background conditions, annual, 20-year, and 100-year). Resulting model projections include spatially explicit estimates of flood extent, depth, duration, uncertainty, water elevation, wave run-up, maximum wave height, maximum current velocity, and long-term shoreline change and cliff retreat.

The model system produces coastal hazard projections suitable to aid local climate adaptation planning. The results are provided to the public via two heavily vetted and user-tested web tools, one that presents the hazards in a map-style interface, ("Our Coast, Our Future" (OCOF): www.ourcoastourfuture.org) and a second one that integrates the hazards with geospatial demographic and socio-economic data to provide information on exposures and vulnerabilities (Hazard Exposure Reporting and Analytics (HERA): https://www.usgs.gov/apps/hera/). Both tools have the dual benefit of providing user-friendly web tools that allow the interested public to explore complex scientific information, similar to how they would use a web browser to explore a local map, as well as providing robust scientific information that can be used by municipal, county, and statewide planners and managers in their coastal adaptation and local hazard mitigation plans. Additionally, the web applications can be used by diverse audiences for multiple purposes. For those coastal communities that do not have access to geographical information system (GIS) specialists, OCOF and HERA allow these communities to explore the full suite of SLR and storm hazards and impacts to incorporate into their planning efforts. For communities with access to technical GIS capabilities, web applications are used as a public outreach tool that allows interested residents and community members to explore the scientific information to supplement their own understanding. Thus, they play an important education/outreach function supporting local coastal adaptation planning.

Using a continuous time series of nearshore wave conditions as well as storm surge and sea level anomaly levels in combination with SLR, the coastline change models developed for this study indicate a spatial average of ~25–40 m of beach erosion and ~10–85 m cliff retreat in Southern California [30,31] (rounded to the nearest 5 m). This amount of shoreline retreat would completely erode as much as 67% of the beaches in Southern California [30]. Lower SLR scenarios result in less but not insignificant erosion; for example, 50 cm of SLR results in an average of 15 m of beach loss and 10 m of cliff retreat.

Flood hazards modeled with the deterministic, dynamic CoSMoS model and including projected coastline change, show that, across Southern California, 100 to 200 cm of SLR will inundate 40–150 km^2 of land. It also shows that the effects of a 100-year coastal storm would flood an additional 54% (150–230 km^2) to 129% (40–340 km^2) of land area. More near-term projections of 25 cm SLR (by approximately the year 2030) [32] are estimated to permanently flood ~10 km^2, with an intermittent flood extent increasing the area affected by nearly 350% (10–45 km^2) when the 100-year storm is also taken into consideration. The results demonstrate that, if sea level continues to rise, many areas will be impacted by flooding in both the long- and short-term, and that storm conditions, combined with even small amounts of SLR expected within just a few decades, will substantially increase the exposure hazard.

Translated to socio-economic impacts, 25–200 cm of SLR places ~20,000–164,000 residents at risk of being permanently flooded along the Southern California shores. Building replacement values are estimated to be between $3.64 billion and $26.10 billion (2006 value, unadjusted for inflation). Accounting for the 100-year storm exposes an additional 56–109% of residents and increases building replacement costs by 46% to $38.2 billion, thus highlighting the importance of including storms in vulnerability assessments.

For actual implementation of hazard mitigation or climate adaptation actions, quantified projections of impacts at the community level are invaluable. The HERA tool provides analytics summarized in the form of maps and graphs for evaluation of vulnerable areas, populations, infrastructure, and economic sectors as well as the ability to download all the data for off-line in-depth local-scale analysis and planning. Using this tool, social vulnerability at the community level can be evaluated according to relative distribution of income, race, age, access to resources, viability of critical infrastructure (e.g., hospitals, roads), building replacement costs, and diversity of economic assets [24,33].

To communicate the availability, uses, and implications of the modeled hazards, exposures, and vulnerabilities, numerous workshops and outreach activities, tailored to the specific needs and interests of local stakeholders and delivered through existing, trusted networks and partnerships have been and continue to be held in regions where the model system has been applied. At each workshop, an overview of the CoSMoS model and regional results are provided, demonstrations and hands-on trainings of the web tools are conducted, and access to data specific to the region is highlighted and discussed. In addition to the more traditional outreach and engagement strategies, virtual reality technology and activities are being developed and applied to reach greater audiences and to better communicate future coastal flood hazards. CoSMoS, and the associated web tools OCOF and HERA, are used for local and state-level coastal planning as well as hazard mitigation planning by approximately 30 coastal cities and counties in California. It is also utilized by many of the state agencies, such as the California Coastal Commission, California Department of Emergency Services and the California Department of Transportation, nongovernmental organizations, and regional-scale collaborations. Although both the modeling methods and outreach activities continue to evolve, the success of providing useful information for coastal planners, engineers, and other stakeholders is underpinned by close relationships and ties with regional partners and local stakeholders who help envision, build, and develop effective products and tools for the critical end-user.

Author Contributions: All authors contributed writing to the paper. P.B. conceived the modeling system and coupling to web-tools. L.E. led model development, implemented parts of the model, and compiled and led the writing of the paper. A.O. developed and implemented SoCal CoSMoS; J.L. assisted with model development and application. A.F. led the GIS components of CoSMoS. S.V. and P.L. developed and implemented the coastal change models. J.F.-H. led the virtual reality and stakeholder outreach activities including innovative technology developments. N.W. and J.J. developed the HERA tool. M.F. led the development of the "Our Coast, Our Future" tool. M.H. led outreach and updates of the "Our Coast, Our Future" tool.

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Appendix

List of terms, acronyms, and software platforms used in the text

3-D	Three-dimensional
360-degree	Image collection and display in a continuous 360-degree arc
CoSMoS	Coastal Storm Modeling System
GCM	Global Climate Model
GIS	Geographic Information System
GeoTIFF	Common raster file format with georeferencing information
Google	Technology company with applicable expertise in internet, mapping, and image sharing services; Mountain View, CA, USA
Google Earth	Program that renders a three-dimensional view of Earth and imagery; version 6+; Google: Mountain View, CA, USA
GoPro	A commercial camera company; San Mateo, CA, USA
HERA	Hazard Exposure Reporting and Analytics
NAICS	North American Industry Classification System
NLCD	National Land Cover Database
LA	Los Angeles County

OC	Orange County
OCOF	"Our Coast, Our Future"
Open Source Geospatial Foundation	Non-profit organization that supports open-source GIS formats and technology; https://www.osgeo.org/
"owl"	Virtual reality viewer used to communicate 21st century flood impacts
Owlized	A commercial virtual-reality company; San Francisco, CA, USA
PostGIS	An open-source, GIS-support software program; version 2+; available https://postgis.net/
PostgreSQL	An open-source relational database; version 9+; available https://www.postgresql.org/
SB	Santa Barbara County
SD	San Diego County
SLR	Sea-level Rise
RCP	Representative Concentration Pathway
VE	Ventura County
VR	Virtual Reality

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