Title: Projecting community changes in hazard exposure to support long-term risk reduction: a case study of tsunami hazards in the U.S. Pacific Northwest

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Abstract

Tsunamis have the potential to cause considerable damage to communities along the U.S. Pacific Northwest coastline. As coastal communities expand over time, the potential societal impact of tsunami inundation changes. To understand how community exposure to tsunami hazards may change in coming decades, we projected future development (i.e. urban, residential, and rural), households, and residents over a 50-year period (2011-2061) along the Washington, Oregon, and northern California coasts. We created a spatially explicit, land use/land cover, state-and-transition simulation model to project future developed land use based on historical development trends. We then compared our development projection results to tsunami-hazard zones associated with a Cascadia subduction zone (CSZ) earthquake. Changes in tsunami-hazard exposure by 2061 were estimated for 50 incorporated cities, 7 tribal reservations, and 17 counties relative to current (2011) estimates. Across the region, 2061 population exposure in tsunami-hazard zones was projected to increase by 3,880 households and 6,940 residents. The top ten communities with highest population exposure to CSZ-related tsunamis in 2011 are projected to remain the areas with the highest population exposure by 2061. The largest net population increases in tsunami-hazard zones were projected in the unincorporated portions of several counties, including Skagit, Coos, and Humboldt. Land-change simulation modeling of projected future development serves as an exploratory tool aimed at helping local governments understand the hazard-exposure implications of community growth and to include this knowledge in risk-reduction planning.

Keywords - tsunami; hazards; exposure; land use projection; Cascadia

1.0 Introduction

There have been an estimated 565,000 tsunami-related deaths throughout recorded history (NOAA National Geophysical Data Center/World Data Center 2016) and tsunami hazards continue to threaten lives and livelihoods in coastal communities throughout the world. Studies to better understand potential losses from future tsunamis and the range of possible risk-reducing strategies have included the distribution of developed land within hazard zones (Wood 2009), population exposure (Morgan 1984; Wood 2007; Post et al. 2009), building integrity (Dall'Osso et al 2009), demographic sensitivity (Wood et al 2010), evacuation potential (Jonkman et al 2008; Wood et al. 2015), economic loss estimation (Dominey-Howes et al. 2010), vertical-evacuation siting (Park et al. 2012; Wood et al. 2014), and institutional resilience (U.S. Indian Ocean Tsunami Warning System Program 2007). Each of these approaches provides practitioners and policymakers with information for developing risk-reduction strategies tailored to local conditions and needs, instead of more generic, regional strategies.

Vulnerability assessments and related risk-reduction efforts are typically based on current landscape conditions, demographic distributions, and development patterns in hazard zones. Extreme events that create significant tsunamis, however, may not occur for many years into the future, while coastal at-risk communities continue to grow. Vulnerability assessments based on current conditions therefore are only static snapshots of existing conditions and fail to capture likely changes in hazard exposure over time. Although these efforts have value for outreach, preparedness, and evacuation planning to help protect lives today, they may be insufficient for long-term mitigation projects (e.g. capital improvement plans, vertical-evacuation refuges) that should anticipate future exposure and related societal risk-reduction needs based on projected development trends.

Numerous studies have used land-use/land-cover (LULC) scenario modeling to explore potential changes in the distribution of human populations and developed lands (e.g., Theobald and Hobbs 1998; Theobald 2005; Sleeter et al., 2012; Radeloff et al. 2012; Sohl et al. 2013; Wilson et al., 2016); however, far less research has integrated LULC scenarios with hazard scenarios to characterize future community exposure. Recent exceptions include studies related to future hazard exposure to tornadoes (Ashley et al. 2014), volcanic lahars (Strader et al. 2015), and sea level rise (Hauer et al. 2016). Vulnerability assessments that recognize potential changes in development provide practitioners and policymakers with the ability to make more informed decisions related to land use planning and capital improvements to infrastructure. These types of assessments may be particularly useful when dealing with tsunami hazards, with long and highly variable recurrence intervals for a given tsunamigenic source.

The objective of this paper is to characterize and compare community changes in population exposure to tsunami hazards between current patterns of development and projected growth. To demonstrate this approach, we focus on coastal counties and communities in the U.S. Pacific Northwest (PNW) that are threatened by local tsunamis associated with a Cascadia subduction zone (CSZ) earthquake, which last occurred in 1700 A.D. (Cascadia Region Earthquake Workgroup 2013). This region is ideal for exploring potential changes in tsunami-hazard exposure as past CSZ earthquakes have shown considerable range in recurrence intervals, from 140 to more than 1,000 years between events and a mean recurrence interval of approximately 500 years for full CSZ rupture (Atwater et al. 1995; Goldfinger et al. 2003; Witter et al. 2003; Frankel and Peterson 2013). Given the wide range in past recurrence intervals, PNW

coastal communities must grapple with how to effectively develop and implement risk-reduction strategies to protect at-risk individuals from a regional catastrophe that could occur tomorrow or several decades from now.

To project changes in developed lands, residential populations, and households, we used the Land Use and Carbon Scenario Simulator (LUCAS) model to project a business-as-usual development scenario spanning the period 2011-2061 (Sleeter et al. 2015; Wilson et al. 2016). The LUCAS model uses a spatially explicit, stochastic state-and-transition-simulation model (Daniel et al. 2016) to project changes in LULC over space and time, based on historical, empirical land change data. Scenario projections were compared with CSZ-related tsunami-hazard zones to determine the change in exposure for each community and to identify regional hotspots for increased community exposure to tsunami hazards. We discuss the implications and application of our analysis for long-term planning to increase community resilience to tsunamis, as well as opportunities for future efforts to integrate LULC modeling with hazard scenarios. Information and methods presented here can be used by elected officials, land-use planners, and emergency managers to better understand how population exposure may change over time and to incorporate these potential changes into long-term risk-reduction efforts.

2.0 Study area

This study focuses on coastal communities in the PNW directly threatened by tsunami waves associated with a CSZ earthquake (fig. 1). Although the study area is susceptible to tsunamis generated by distant earthquakes (e.g., local waves associated with the 2011 Tohoku magnitude 9.0 earthquake in Japan), more catastrophic tsunami threats are associated with local CSZ earthquakes emanating along the interface of the North America and Juan de Fuca tectonic plates. This plate juncture extends more than 1,000 kilometers from northern California to southern British Columbia (Rogers et al. 1996; fig. 1). A future CSZ earthquake (likely magnitude 8 or greater) could generate a series of large tsunami waves potentially arriving in tens of minutes after the initial ground shaking (Cascadia Region Earthquake Workgroup 2013). Wood et al. (2015) estimates that CSZ-related tsunami-hazard zones across coastal communities in this study area collectively contain 94,872 residents, as well as 42,424 employees, 486 public venues, 440 dependent-care facilities, and 2,314 businesses with a significant customer presence. Approximately 23% of residents and 15% of employees in tsunami-hazard zones are in areas where modeled pedestrian-evacuation times are greater than wave-arrival times, suggesting the need for vertical-evacuation refuges or other long-term mitigation strategies to save lives (Wood et al. 2015).

3.0 Methods

The LUCAS model is a customized state-and-transition simulation model (STSM) (Daniel et al., 2016), where states are used to represent LULC classes (e.g. forest, grassland, shrubland, agriculture, developed) and transitions represent common changes in LULC associated with urbanization, agricultural expansion and contraction, harvest, and wildfire (Sleeter et al., 2015; Wilson et al., 2016). The landscape is represented by a raster grid of simulation cells, where each cell is assigned to one LULC type. Transitions between state classes are determined for each simulation cell from a set of spatially explicit, discrete-transition probabilities, based on historical land change data. Stochastic simulations are run at annual time-steps across a predetermined number of Monte Carlo simulations, which is only limited by computational constraints.

Figure 1. Study area map including 2011 NLCD and the incorporated cities, Indian Reservations (IR), and counties in the U.S. Pacific Northwest with land in tsunami-hazard zones associated with Cascadia subduction zone earthquakes, arranged geographically north to south. Inset map shows the regional extent of the Cascadia subduction zone.

The LUCAS model has been used to project various impacts of land-use change, including water use demand (Wilson et al., 2016), ecosystem carbon dynamics (Sleeter et al., in press; Daniel et al., 2016), threats to protected areas (Wilson et al., 2015, Wilson et al. 2014), and ecosystem carbon stocks (Sleeter et al., 2015). Although other general land-change models are available, such as CLUE-S (Verburg et al., 2002), DINAMICA EGO (Soares-Filho et al., 2002) and CA_MARKOV (Pontius and Malanson, 2005), SLEUTH (Chaudhuri and Clarke, 2013) and SERGoM (Theobald, 2005), we chose the LUCAS model due to its stochastic functionality, flexibility in scale, and open and transparent architecture. This functionality allows

modelers the ability to readily modify an existing model with new simulations based on more informed local knowledge, additional parameters, or alternative scenario projections.

For this study, the LUCAS model was developed to produce a business-as-usual (BAU) spatially explicit stochastic projection of changes in development, residential population, and households based on historical (1992-2011) development land change data. We evaluate the footprint of future development in 2061 within CSZ-related tsunami-hazard zones to assess potential changes over time in community exposure to tsunamis. Below we describe the input data and assumptions of the model formulation used to produce the stochastic projection.

3.1 Communities of analysis

The spatial extent of our modeling included coastal counties and communities in the PNW with land in CSZ-related, tsunami-hazard zones. State agencies in California, Oregon, and Washington have varied somewhat in how they have delineated CSZ-related, tsunami-hazard zones. Therefore, we used the following published tsunami-hazard zones with similar earthquake source and modeling assumptions. Tsunami-hazard zones in Oregon and in the Washington counties of Whatcom, Skagit, Island, and San Juan (fig. 1) reflect an M_w 9.0 earthquake with source parameters of the “L1” scenario, which is a deterministic scenario assuming 650-800 years of slip accumulation and a 95% confidence interval (Priest et al. 2013). In Pacific and Grays Harbor counties (Washington), the tsunami-hazard zone is based on a combination of (a) the L1 source parameters described in Priest et al. (2013) and provided as model outputs by the State of Washington Department of Natural Resources (T. Walsh, written communication, August 20, 2014) and (b) earlier work associated with the “1A with asperity” deterministic scenario for an M_w 9.1 earthquake that assumes 450 years of slip accumulation (Walsh et al. 2000). In Clallam and Jefferson counties (also in Washington), hazard zones in populated areas are based on the “1A with asperity” earthquake scenario (Walsh et al. 2002; 2003) and the undeveloped areas reflect a 25-foot contour line (Wood and Soulard 2008). For the two California counties (Humboldt and Del Norte), we used the statewide maximum tsunami-hazard zone (State of California 2009, Wilson et al. 2010) which is considered similar to the L1 CSZ scenario in these counties (Wilson et al. 2010).

Jurisdictional boundaries for incorporated cities, Indian reservations, and counties were based on 2010 administrative boundaries (U.S. Census Bureau, 2011). Any land within a county not classified as an incorporated city or Indian reservation was classified as unincorporated. An overlay of tsunami-hazard zones and jurisdictional boundaries yielded 50 incorporated cities, 7 tribal reservations, and 17 counties from Del Norte County in northern California to Whatcom County in northern Washington for our analysis (fig. 1).

3.2 State variables and scales

Simulations for this study were run at 1 hectare (ha) spatial resolution as a compromise between preserving local-scale landscape patterns and computational requirements of the model. The study region was subdivided into a regular grid of 9,428,208 simulation cells (94,282 km²) and run for 60 years between 2001 and 2061. The historical 2001-2011 period was used for model calibration and validation purposes and the 50-year projection period from 2011-2061 was chosen because that is the typical planning time horizon for capital improvement and infrastructure projects. All simulations were run at an annual timestep and were repeated for 50

Monte Carlo iterations, which is a reasonable number of simulations given available computing resources and captures a broad range of uncertainty in the projections.

Each simulation cell was assigned to a primary and secondary spatial stratum, as well as a LULC type (i.e. state class). The primary spatial stratification was county boundaries and the secondary strata defined the incorporated city, tribal reservation or unincorporated county land of each simulation cell and whether a cell was inside or outside of the tsunami-hazard zone (Table 1). The LULC of each cell was assigned to one of 9 land cover classes, generally corresponding to an Anderson Level 1 classification scheme (Anderson et al. 1976), and included water, developed, barren, forest, grassland, agriculture, wetland, shrubland, and snow/ice (fig. 1). Initial LULC conditions representing the year 2001 were estimated from 30-m resolution LULC data from the 2001 National Land Cover Database (NLCD)(Homer et al., 2007), resampled to 100-m x 100-m cells (1 hectare or ha) using a nearest neighbor algorithm. The combination of the two spatial stratum and assigned LULC state class defined the initial conditions of each cell at model onset (Table 1; fig. 1).

Table 1. The Land Use and Carbon Scenario Simulator (LUCAS) model variables and parameters used to project changes in development over the 17-county study area.

Primary Strata	Secondary Strata	State Classes	Transition Types		Transition Pathways	Transition Groups	Transition Targets	
			From Class	To Class			Baseline	Projection
N=17 Counties (Washington 8, Oregon 7, California 2)	N=74 Communities repeated for 'in' and 'out' of hazard zone	N=9 Land Use/Land Cover Classes	Forest	Developed	N=85 (Primary Strata * Transition Types)	N=1 Urbanization	Average annual change amounts derived from NLCD	Sampled from a Uniform distribution in each timestep and iteration
			Grassland					
			Shrubland					
			Wetland					
			Agriculture					

3.3 Model formulation

The LUCAS model requires a defined set of state class ‘transition types’, ‘transition groups’, ‘transition pathways’, and ‘transition targets’ in order to simulate change between defined LULC state classes. In this model, the only type of land conversion considered was the unidirectional change into development (e.g. urbanization) as previous work demonstrated a high correlation between developed land and socioeconomic assets in PNW tsunami-hazard zones (Wood 2009). As such, transition parameters in the model were defined as follows (Table 1):

- ‘Transition types’ were defined for each LULC state class which could be converted into development. For this model we allowed transitions into development from forest, grassland, shrubland, wetland, and agriculture. Conversions to development from barren lands, water, and snow/ice were not allowed.
- ‘Transition Pathways’ were defined for each combination of strata (i.e. County and community type in or outside of the hazard zone) and transition type, producing 85 possible combinations. The base probability for each transition pathway was set to 1.0, meaning all state classes eligible for conversion were initially assigned an equal probability of transition.

- A single ‘Transition Group’ called *Urbanization* was defined which included the 5 transition types described above.
- ‘Transition Targets’ were used to specify the amount of *Urbanization* in the model. Transition targets were specified independently for each county, timestep, and Monte Carlo iteration and based on historical land change data described below.

Transition targets for urbanization were derived from the National Land Cover Database spanning the periods 1992-2001, 2001-2006, and 2006-2011. For the 1992 to 2001 period, we used the ‘NLCD Retrofit Change Product’ which allows for comparison of major LULC classes between two datasets developed using differing methods (Fry et al., 2009). For the 2001-2006 and 2006-2011 periods, we used the published NLCD change products (Homer et al., 2007; Xian et al., 2009; Fry et al., 2009; Jin et al., 2013). Road networks were removed from all LULC datasets by applying a spatial filtering algorithm using geographic information system (GIS) software. First, the 30-m NLCD data were resampled to 100m cell size using a nearest neighbor algorithm. Second, a focal filter was applied to the 100-m map to calculate the median value for each cell based on a 5x5 moving window, resulting in a generalized neighborhood map. Lastly, we merged the original 100-m NLCD map with the generalized neighborhood map. All cells classified as developed in the original 100-m map were reassigned the LULC class from the generalized neighborhood map; all non-developed cells were retained from the original 100-m classification. The objective was to capture only changes in development which corresponded to an increase in settlements while removing the impact of road network expansion (e.g., construction of logging roads), which are not indicative of increased population. Table 2 shows the transition targets used for this study.

Within the LUCAS model, the baseline period (2001-2011) was simulated using annualized county urbanization rates derived from the 2001-2006 and 2006-2011 NLCD change datasets. Rates were derived by running zonal statistics on the amount of developed cells in each of the NLCD change products (1992-2001, 2001-2006, and 2006-2011) and dividing this amount by the length of the NLCD interval to derive annual transition targets. For the projection period (2011-2061), transition targets were independently sampled for each county, timestep, and Monte Carlo iteration from a uniform distribution fitted to the minimum and maximum values from the full temporal range of historical data (i.e. 1992-2011 NLCD data). To constrain the spatial location of urbanization transitions, two types of spatial multipliers (Daniel et al., 2016) were used. First, urbanization was restricted from occurring on lands dedicated for conservation purposes. These lands were identified as areas with a defined conservation management plan categorized as GAP Status 1, 2, and 3 lands within the U.S. Geological Survey’s Protected Areas Database (U.S. Geological Survey, 2016). Protected lands were considered fixed and the potential for additional or fewer lands dedicated for conservation purposes in the future was not considered (Wilson et al. 2014). All cells located within conservation lands were assigned a transition probability of zero. Second, urbanization was distributed across the landscape using adjacency multipliers, which were calculated for each cell and Monte Carlo iteration, to prioritize new development as extensions of current development. Adjacency multipliers were calculated as a linear function (0-1) based on the number of adjacent cells (8 neighbors) classified as developed. Cells with no neighbors classified as developed were assigned a zero probability of change while cells completely surrounded by development were assigned a probability multiplier of 1.0. Adjacency multipliers were updated and calculated at 5-year

intervals during the model run.

Table 2. County-scale developed change area and transition targets used within the model calculated from the 1992 National Land Cover Dataset (Retrofit product) and the 2001, 2006, and 2011 National Land Cover Database.

	Total Transition Area (ha)			Baseline Period		Projection Period (2011-2061)		
				Target Area (ha/yr)		Target Area (ha/yr)		
	1992-2001	2001-2006	2006-2011	2001-2006	2006-2011	Min	Max	Avg
Whatcom Co.	487	515	188	103	38	38	103	65
San Juan Co.	11	0	1	0	0	0	1	1
Skagit Co.	363	285	230	57	46	40	57	48
Island Co.	234	114	42	23	8	8	26	19
Clallam Co.	94	101	75	20	15	10	20	15
Jefferson Co.	91	20	9	4	2	2	10	5
Grays Harbor Co.	159	29	23	6	5	5	18	9
Pacific Co.	35	9	3	2	1	1	4	2
Washington (total)	1473	1072	569	214	114	104	239	164
Clatsop Co.	93	8	20	2	4	2	10	5
Tillamook Co.	92	4	3	1	1	1	10	4
Lincoln Co.	114	13	34	3	7	3	13	7
Lane Co.	497	456	239	91	48	48	91	65
Douglas Co.	141	182	42	36	8	8	36	20
Coos Co.	264	50	5	10	1	1	29	14
Curry Co.	100	29	2	6	0	0	11	6
Oregon (total)	1298	742	344	363	183	62	201	121
Del Norte Co.	104	2	3	1	1	1	12	4
Humboldt Co.	556	72	10	14	2	2	62	26
California (total)	660	74	13	524	250	3	73	30
Regional (total)	3431	1888	926	1101	546	168	513	315

3.4 Demographic attributes

Projected changes in the number of households and residents (population) in current CSZ-related, tsunami-hazard zones were used as an indicator of tsunami-hazard exposure change for each community. Although the numbers of households and numbers of residents are typically highly correlated, we present results for both indicators given their utility for different end users. Emergency managers typically develop risk-reduction strategies that address the number and type of people in hazard zones while household estimates provide less utility, except for some outreach efforts (e.g., a household-based, outreach campaign). The land-change research community has typically focused on projecting changes in households due to the fact that the number of people in a household is difficult to project over time (e.g., aging children that leave a household at some point but parents remain).

The model was parameterized to track population and households at the community scale, with the assumption that ratios of population and housing density per unit area of development remained constant over the simulation period. Residential population and household estimates in tsunami-hazard zones for each community were generated by disaggregating population and housing counts from 2010 Census block data (U.S. Census Bureau 2011) to residence points in tsunami-hazard zones manually interpreted from National Agriculture Imagery Program (NAIP) 1-meter resolution ortho-rectified imagery acquired between 2009 and 2012 (U.S. Department of Agriculture 2014)(Wood et al. 2015). Total population and household counts in each community or county (regardless of hazard zones) came from the 2010 Census decennial count (U.S. Census Bureau 2011).

4.0 Results

4.1 Model validation

To validate the results of the model, we conducted a series of comparisons using the baseline period (2001-2011) included in our simulation. The primary validation was to ensure that transition targets derived from data contained in NLCD change products were being accurately implemented in the model simulations. For each of the 17 counties, we compared transition targets from NLCD (Table 2) for the 2001-2006 and 2006-2011 periods with the projections produced across 50 Monte Carlo realizations of the model (fig. 2). A comparison of mean projected area resulted in a statistically significant correlation ($r^2 = 0.99$) between the NLCD targets and the average simulation model output, indicating the model was, on average, capable of reliably reproducing the targeted area. However, it is important to note that due to the stochastic nature of the model, the projected change in any timestep and/or Monte Carlo realization could be different from the NLCD targets (e.g. as indicated by the range of values in modeled data depicted by the error bars in Figure 2).

Figure 2. Comparison of county-scale urbanization targets derived from NLCD data for the period 2001-2006 and 2006-2011 (gray shaded area) with model output over the same period. Circles represent the mean estimate and error bars represent minimum and maximum values across 50 Monte Carlo realization of the model.

We also compared the spatial distribution of developed cells at the community scale. To do this, we summarized the total area converted to developed from the two NLCD change products and calculated an average annual rate across the 2001-2011 period. NLCD data reveal that changes into development occurred in only 49% of the communities within the study region. Similarly, the modeled results projected 98% of the developed change within the same 34 communities; on average 5 ha/yr was projected in communities where NLCD did not capture any change. Additionally, the majority of conversion into development was located in the

unincorporated portions of counties, such as Lane, Whatcom, Skagit and Douglas (fig. 3). NLCD data show between 74% (2006-2011) and 84% (2001-2006) of new developed lands were within unincorporated areas compared to 84% (2001-2011 average) from the modeled results. Figure 3 shows a comparison between average annual change rates from NLCD and the modeled output for each jurisdiction where increased development was captured in the reference data.

Figure 3. Comparison of jurisdictional-scale changes in development between NLCD and model simulations. Bars represent the average annual rate of change over the 2001-2011 period from NLCD (2001-2006 and 2006-2011 annual average). Points (Red dots) represent the mean modeled estimate and error bars show the minimum and maximum values across 50 Monte Carlo realizations.

Due to the stochastic simulations produced for this study (e.g. 50 Monte Carlo realizations), it was not possible to conduct a complete pixel-to-pixel comparison between NLCD and LUCAS model simulations. However, for illustrative purposes we generated a pixel-scale validation based on a single randomly selected Monte Carlo realization. Results of this validation show that the LUCAS model had a 95.9% agreement (98.1% producers accuracy, 97.8% users accuracy) with the reference NLCD map in the year 2011. The vast majority of this agreement can be explained by the persistence and uni-directionality of the developed class and

the relatively low amounts of net change imposed over this baseline period (i.e. less than 0.1% of the study area was projected to experience change).

4.2 Urbanization projections across regional, state, county, and community scales

Across the entire 17-county study area, developed lands represented approximately 1% of the 2011 landscape (121,647 ha), with the largest areas classified as developed in Washington (49% of the study area), followed by Oregon (39%) and California (12%). The average annual rate of urbanization across the study area between 2011 and 2061 was projected to be 340 ha/yr^{-1} , based on mean estimates across the Monte Carlo simulations. Results reported throughout the remainder of the manuscript reflect the mean estimates across the Monte Carlo simulations as well, unless otherwise noted. On average, 48% of new development across the entire study area originated from forest cover, followed by agricultural land (29%), grasslands (9%), wetlands (8%), and shrublands (3%) (fig. 4a). In total, developed lands increased by 14% to 138,666 ha in 2061, in which Washington was projected to experience the largest net increase in developed area (50% of the study area increase) followed by Oregon (39%) and California (11%) (fig. 5a).

Figure 4. Whisker plots showing sources of new developed lands between 2001 and 2061 and summarized as hectare per year across (a) the entire study area and (b) within the hazard zone. Whiskers represent the minimum and maximum values, and boxes represent 25% and 75% confidence intervals across 50 Monte Carlo realizations of the model.

Within the hazard zone, we estimated 7% (14 ha) of the land in 2011 was classified as developed and projected to increase by 1,050 ha or 7% by 2061, representing an average annual increase of 21 ha/yr^{-1} . Wetlands were the most common converted class (43% of regional totals) within tsunami-hazard zones, followed by forest (21%), grasslands (16%), agriculture (11%) and shrubland (9%) (fig. 4b). Washington had the largest amount of developed land in 2011 within the tsunami-hazard zone (7,514 ha), followed by Oregon and California (Table 3). However, the highest projected increase in developed land within the hazard zone was in Oregon (472 ha), followed by Washington and California (Table 3, fig. 5a). Expressed as a percent change over 2011 estimates, the largest increase was in California (12%), followed by Oregon (7%) and Washington (4%).

Figure 5. Bar graphs showing the net change in developed land (thousands of hectares), households (thousands of units), and population (thousands of persons) for (a) the entire study area, and (b) for land in tsunami-hazard zones for Washington, Oregon, and California. Error bars represent the minimum and maximum estimates across 50 Monte Carlo realizations.

Grays Harbor County had the largest absolute net increase in development (196 ha) in the hazard zone, followed by Humboldt County and Clatsop County (Table 3; fig. 6a). Expressed as a percent change over 2011 levels, Skagit (26%), Lane (23%) and Island counties (20%) had the highest projected net change in developed area (fig. 6a). At the community level, the majority of new developed land in the tsunami-hazard zone was projected to occur on unincorporated county land (62% of regional totals), followed by incorporated cities (37%) and Indian reservations (less than 1%). The city of Ocean Shores and the unincorporated portions of Pacific County had the largest amount of developed areas within the tsunami-hazard zone in 2011 (1,479 ha and 1,389 ha, respectively) and were projected to continue to have the largest amount by 2061 (1,522 ha and 1,451 ha, respectively)(fig. 7). Other areas with large amounts of development in hazard zones in 2011 and projected to have large areas by 2061 include the unincorporated portions of Grays Harbor and Humboldt counties, along with the cities of Aberdeen and Hoquiam. The largest net change in developed area in tsunami-hazard zones was projected to be in the unincorporated portions of Humboldt (127 ha), Grays Harbor (105 ha), Coos (69 ha) and Pacific (62 ha) counties (Table 3, fig. 7). The largest increase in development as a percentage over 2011 estimates were projected for Lakeside (67%) and Skagit County (60%).

Figure 6. County projections of net change and percent change between 2011 and 2061 in (a) developed land, (b) households, and (c) in tsunami-hazard zones. Bars represent mean estimates and error bars represent minimum and maximum estimates across 50 Monte Carlo realizations of the model.

4.3 Projected changes in community exposure to tsunami hazards

We estimate 53,230 households and 101,421 residents will be in CSZ tsunami-hazard zones by 2061, representing an increase of 3,880 households (an 8% increase) and 6,940 residents (a 7% increase) over 2011 estimates (fig. 5b, c; Table 3). Oregon had the largest

increase in exposure (Table 3; fig. 5b, c), with a projected increase of 1,983 households and 2,819 residents, followed by Washington and California.

Table 3. Modeled changes in developed area, households, and residential population between 2011 and 2061 in the tsunami-hazard zone for each county and state in the study area. Projected changes and totals by 2016 are mean values calculated over 50 Monte Carlo simulations.

	Developed land (ha)			Households			Residents		
	2011 total	Change by 2061	2061 total	2011 total	Change by 2061	2061 total	2011 total	Change by 2061	2061 total
Clallam Co.	279	18	297	868	75	943	2,019	155	2,174
Grays Harbor Co.	4,703	196	4,899	14,012	514	14,526	32,918	995	33,913
Island Co.	24	5	29	328	65	393	328	66	394
Jefferson Co.	274	20	294	1,066	118	1,184	1,998	210	2,208
Pacific Co.	1,989	75	2,064	8,040	324	8,364	12,434	471	12,905
San Juan Co.	25	0	25	224	3	227	323	4	327
Skagit Co.	49	13	62	584	294	878	1,059	522	1,580
Whatcom Co.	171	21	192	824	197	1,021	1,637	384	2,021
Washington (total)	7,514	348	7,862	25,944	1,592	27,536	52,716	2,806	55,521
Clatsop Co.	1,668	139	1,807	7,930	653	8,583	15,258	1,226	16,484
Coos Co.	785	109	894	1,461	308	1,769	3,494	598	4,092
Curry Co.	567	58	625	1,521	163	1,684	3,160	314	3,474
Douglas Co.	294	22	316	618	46	663	1,632	119	1,752
Lane Co.	67	16	83	338	96	433	649	170	819
Lincoln Co.	829	60	889	4,250	283	4,532	5,039	336	5,375
Tillamook Co.	744	69	813	4,972	436	5,408	3,919	362	4,281
Oregon (total)	4,954	472	5,426	21,089	1,983	23,072	33,152	3,125	36,277
Del Norte Co.	471	51	521	605	70	675	2,249	193	2,442
Humboldt Co.	1,431	179	1,610	1,712	235	1,947	6,365	815	7,180
California (total)	1,901	230	2,131	2,317	306	2,622	8,614	1,009	9,622
Study area (total)	14,369	1,050	15,419	49,350	3,880	53,230	94,481	6,940	101,421

At the county level, Grays Harbor County had the largest number of households (14,012) and residents (32,918) located within the hazard zone in 2011 and is projected to continue to have the largest numbers of households (14,526) and residents (33,913) in tsunami-hazard zones by 2061. The largest net increase by 2061 in households and residents was in Clatsop County (653 households and 1,226 residents), followed by Grays Harbor County (Table 3, fig. 6b,c). Although Clatsop and Grays Harbor counties are projected to have the largest increases in households and residents in tsunami-hazard zones, these increases do not represent high percentages over their current exposure in 2011 (+8% and +3%, respectively). The largest percentage increases were projected in counties that currently have low residential exposures, including Skagit (49% increase over 2011), Lane (26% increase), Whatcom (23% increase), and Island (20% increase) counties (fig. 6, Table 3).

Figure 7. Mean projected changes between 2011 and 2061 in (a) developed land, (b) households, and (c) in tsunami-hazard zones at the community level.

At the community scale, unincorporated portions of Pacific County currently have the largest number of households in tsunami-hazard zones (6,362), followed by Ocean Shores (4,161), Aberdeen (3,652), unincorporated Tillamook County (2,984), and Seaside (2,597). The largest numbers of residents in the tsunami-hazard zone in 2011 are estimated to be in Aberdeen (12,313), unincorporated Pacific County (8,687), Hoquiam (7,768), Ocean Shores (5,559), and Seaside (5,556) (fig. 7). By 2061, this group and ordering of communities for the largest number of households and residents in hazard zones does not change, except for Seaside having more residents in hazard zones than Ocean Shores (5,772 and 5,719, respectively). Between 2011 and 2061 projections, the net change in households in tsunami-hazard zones for these communities or unincorporated county areas ranged from 38 (Aberdeen) to 289 (Tillamook County). The net

change in residents in tsunami-hazard zones was also relatively low for these communities, ranging from 108 residents in Hoquiam to 390 residents in unincorporated Pacific County (fig. 7).

For the remaining communities, projected changes in residential exposure ranged from no change in five communities (Bellingham, Coquille, Trinidad, Friday Harbor, and Anacortes) and three Indian Reservations (Jamestown S'Klallam, Lower Elwha, and Hoh Indian Reservations) to several hundred additional residents. Changes on the order of less than 100 additional residents were projected for 44 communities or unincorporated county lands and 100 to 500 residents for the remaining 22 areas of interest. The largest net changes in residential exposure to tsunami-hazard zones were projected in the unincorporated portions of several counties, including Skagit (521 residents representing a 60% increase over 2011 estimates), Coos (463 residents, 30% increase), and Humboldt (453, 15% increase) (fig. 8). The largest net changes in household exposure were also projected in unincorporated portions of counties, including Skagit (294 households, 60% increase over 2011 estimates), Tillamook (289 households, 10%), Pacific (285 households, 4%) and Grays Harbor (261 households, 11%). Except for Skagit County, the largest net increases as a percentage over 2011 estimates were primarily in small communities where small increases over low initial exposure estimates yielded high relative percentages, such as the communities of Lakeside (+9 residents, 67% increase), Dunes City, City of Tillamook, and Coquille (increases of 9, 2, and 17 residents, respectively, and each representing a 40% increase) (fig. 8).

Although almost all communities, tribal reservations, and unincorporated county lands are projected to experience some level of increased exposure to tsunami-hazard zones, the relative impact of this exposure to an entire community does not change dramatically, or at all, for many communities. For example, 100% of the residents in Ocean Shores, Long Beach, Westport, and Shoalwater Bay Indian Reservation are in tsunami-hazard zones in 2011 and these community percentages do not change with the additional 160, 36, 4, and 104 residents, respectively, in hazard zones by 2061 (fig. 9). Therefore, while there may be increasing numbers of residents in tsunami-hazard zones, the relative impact of tsunamis in these communities does not change. Across the study area, the percentage of a community's residents in tsunami-hazard zones does not vary substantially between 2011 and 2061, ranging from a 5% decrease in residential exposure for the Makah Indian Reservation (55% of residents in hazard zones in 2011 down to 50% by 2061) to a 1% increase in Arcata (from 7% to 8% by 2061). Sixty-five of the areas experience a change of plus or minus of 1% in the percentage of their residents in hazard zones, with the remaining 9 areas projected to see a 1% to 5% decrease in their relative community percentages (fig. 9).

Figure 8. Jurisdiction comparison of the mean estimated number of additional residents in tsunami-hazard zones in 2061 with the percentage increase in exposure relative to 2010 residential exposure.

5. Discussion

Previous efforts to gauge community vulnerability to tsunamis have been typically based on current landscape conditions and the distribution of human development. While vulnerability assessments based on current conditions may be adequate for preparing communities today, they may not be sufficient for long-term mitigation projects. To support long-term, risk-reduction planning for tsunami hazards, we projected changes in developed lands, population, and households in CSZ-related, tsunami-hazard zones for a BAU development scenario spanning the period 2011-2061. In this section, we discuss the implications of our results on tsunami risk-reduction planning in the PNW and on future efforts to integrate land-change simulation modeling scenarios with hazard scenarios.

5.1 Use of results in tsunami risk-reduction planning

By 2061, we project an additional 3,880 households and 6,940 residents within CSZ-related, tsunami-hazard zones along the PNW coastline, representing a 7-8% increase over 2011 estimates. Increases in population exposure are not consistent throughout the study area. Oregon coastal communities collectively represent 51% of the projected increases in households in tsunami-hazard zones (fig. 5b) and at the local level, some communities are projected to experience no change while other areas are projected to have hundreds of new at-risk individuals.

Although the region is projected to have thousands of additional residents in tsunami-hazard zones, these increases are not primarily in areas already considered to have high community exposure. The top ten areas in terms of population exposure to CSZ-related, tsunamis in 2011 are projected to remain the areas with the highest population exposure by 2061. In these

top-ten areas, 2061 projections represent a less than 5% increase over 2011 estimates (e.g., Aberdeen, Hoquiam, Seaside, Ocean Shores, and unincorporated Pacific County) or a 10-16% increase (Warrenton and unincorporated portions of Grays Harbor, Humboldt, Clatsop, and Tillamook counties). In addition, results across the entire study area indicate that 2061 projections do not significantly alter the relative impact in terms of community percentages of residents in hazard zones, ranging from a 5% decrease to a 1% increase between 2011 and 2061 (fig. 9). A decrease in community percentages suggests that although land in tsunami-hazard zones may become developed, the amount of this development is less than what is occurring outside of tsunami-hazard zones. Given the historical development of coastal communities along low-lying, riverfront banks of an estuary or along the coast, it makes sense that larger amounts of new development in the next 50 years are more likely to occur in upland areas and out of tsunami-hazard zones.

Figure 9. Comparison between 2011 estimates and 2061 mean projections of the percentage of total residents in tsunami-hazards for each community. Communities with the highest percentages in 2011 and 2061 are labelled.

From a regional perspective, our results do not indicate a significant change in the areas with already high numbers or high percentage of residents or households within the tsunami-hazard zone. Any attempt to reduce future hazard exposure in these communities would require changes in local land-use planning to shift existing development in hazard zones and any future development to areas outside of hazard zones. In communities like Ocean Shores, Long Beach, and Shoalwater Bay Indian Reservation where 100% of the communities are currently in tsunami-hazard zones, land-use planning changes would be needed to expand jurisdictional limits for accommodating growth elsewhere, which may be difficult depending on the ownership of adjacent lands.

Barring any significant changes in local land-use planning to reduce development in hazard zones, our results may warrant follow-up studies within specific communities to determine any needed shifts in local risk-reduction planning. For example, several coastal communities along the Washington coast have initiated community-based processes for siting vertical-evacuation (VE) refuges to provide new high ground during a local tsunami (e.g., Engstfeld 2010). Understanding the magnitude and spatial distribution of in-hazard population projections across a community may influence which VE options would best serve the largest number of at-risk individuals or even suggest the need for VE in areas not initially considered based on the current population distributions. Wood et al. (2014) demonstrate the application of multi-criteria decision analysis for siting VE refuges in Ocean Shores, WA, and future efforts could benefit from including population projections, both in terms of the location and potential evacuee demand of a given VE site. Projections would also be beneficial when calculating population demand at assembly areas outside of tsunami-hazard zones (e.g., Wood et al. 2016).

The largest net increases in residential and household exposure are projected primarily in unincorporated portions of counties, including Skagit, Coos, Humboldt, Whatcom, Clatsop, and Tillamook, Grays Harbor and Pacific (fig. 7). Non-county areas projected to have large increases include the cities of Warrenton and Arcata. Collectively, these ten areas are projected to add 3,948 residents to tsunami-hazard zones or 57% of the regional total. Tsunami exposure is well known in Grays Harbor and Pacific counties, as evidenced by the vertical-evacuation siting efforts across these two counties (Engstfeld et al. 2010). Where these large projected increases may have more impact on tsunami risk-reduction planning are in the other areas not typically considered to have high population exposure, such as the unincorporated areas of Skagit County (an increase of 521 residents) and Coos County (an increase of 463 residents). These projections represent a 60% and 29% increase in Skagit County and Coos County, respectively, which are substantial increases compared to the rest of the study area where 65 of the 75 communities, Indian Reservations, and counties are projected to increase residential exposure by less than 20% of 2011 estimates.

The potential impact of new development in tsunami-hazard zones is not uniform along the coastal study area and is tempered by the estimated arrival times of CSZ-related tsunami waves. Wave-arrival times are shortest along the northern California and Oregon coast (10-15 minutes) and longest for northern Washington coastal communities (e.g., 2.5 hours for Whatcom County) (Wood et al. 2015). As a result, projected increases in at-risk residents may be less of an issue for Skagit County emergency managers than in Coos County because predicted arrival times for CSZ-related tsunamis in Skagit County are on the order of two hours after the initial earthquake (Walsh et al. 2004) and individuals in tsunami-hazard zones will have sufficient time to evacuate (Wood et al. 2015). However, in Coos County, predicted wave arrival times are on the order of 15 minutes (Wood et al. 2015) and the addition of 598 residents to tsunami-hazard zones here may introduce new life-safety issues. This issue also applies to the additional 815 residents projected in Humboldt County and 193 residents in Del Norte County of northern California, where CSZ tsunami-arrival times are also approximately 10-15 minutes.

5.2 Limitations of the results

All models are simplified representations of reality; therefore, we discuss here some limitations of results for tsunami risk-reduction planning. The first limitation centers on the utility of NLCD land-cover data, based on moderate resolution (30m) satellite imagery, to

estimate and project the magnitude and distribution of households and residents. We found that developed cells in NLCD products contain most, but not all, resident/household locations in our study area. To provide some context on the ability of NLCD to capture household and resident distributions, we compared the number of developed cells from 2011 NLCD data with residential points manually interpreted from 1-meter imagery collected between 2009 and 2012 (U.S. Department of Agriculture 2014) and merged with 2010 Census block-level population counts. Results indicate that approximately 81% of the estimated residents in tsunami-hazard zones were located on cells classified as developed by NLCD and the remaining populations were in areas classified as grassland or shrubs (5%), wetlands (4%), pasture or cultivated crops (3%), forest (3%), barren (2%) and open water (1%). Therefore, developed pixels in NLCD can be considered to be an adequate indicator for human populations, but should not be interpreted as a definitive measure of the number of people in tsunami-hazard zones. Furthermore, there are uncertainties introduced given the accuracy of land cover map generation. For example, Wickham et al. (2013) report an overall accuracy of the 2001 NLCD map at 79% for the developed class. Despite limitations, our NLCD-based approach is an improvement over others that do not include historical, empirical land change information which provide a landscape-scale perspective of future growth.

The second limitation focuses on the potential for future land use changes that differ from “business as usual”, which may include local actions taken by practitioners and planners to contend with perceived tsunami threats along the PNW coast. Our modeling projects future development based on current population densities and development patterns in the recent past; however, this may not be completely realistic for all coastal communities for several reasons. First, results indicate that the primary source for projected development conversion in tsunami-hazard zones is from land classified as wetlands (fig. 4). Converting wetlands to development may be difficult and contentious, given existing levels of protection and conservation of wetlands across the region. The extent to which wetland-to-developed conversions are allowed will likely occur on a case-by-case basis in each jurisdiction, therefore making it difficult to make regional assertions or assumptions regarding likelihood.

Another possible limitation of business-as-usual development scenarios is that it assumes no differences or changes in risk perceptions and tolerances among the various coastal communities. Low-growth and high-growth scenarios could be implemented but doing so still assumes a consistent philosophy of land development across a region, which is a 700-km long shoreline including land-use planning in 50 incorporated cities, 7 tribal reservations, and 17 counties. In reality, local land use planners may vary in their risk tolerance to threats posed by CSZ tsunamis. For example, discussions are underway within the Quileute Indian Tribe (site 14 in figure 1) for moving to higher ground and out of tsunami-hazard zones after the tribe was granted access in 2011 to land within Olympic National Park for future development (Walker 2012; United States Code 2012). In addition, risk perceptions may change over time. For example, Goldfinger et al. (2012) asserts that if no CSZ earthquake has occurred by 2060, then the region has exceeded 85% of past recurrence intervals for the southern CSZ margin. Therefore, as time passes and coastal communities get closer to 2060, the perceived threat posed by CSZ earthquakes and tsunamis may increase and local planners in various coastal communities may become less inclined to allow development in tsunami-hazard zones. Quantifying these potential variations in development uniformly across a region without local input and including them in a simulation model would likely be fraught with errors, given the local variability in risk tolerance,

willingness to implement or pay for mitigation, and the likely difference between expressed preferences (i.e., what people would say now regarding future growth) versus revealed preferences (i.e., what a person actually implements when confronted with a land-use decision).

5.3 Areas for future research

The current study highlights several areas for future research on both land change modeling and its integration with hazard scenarios. This study uses a time series of historical measurements of land change to derive an empirical foundation for projecting urbanization into the future, where historical variability is used to represent stochastic uncertainty around a ‘business-as-usual’ scenario projection. The BAU scenario represents a logical extension of recent historical rates of change, however, future conditions may evolve in such a way that result in a large deviation from historical conditions. Such deviations could arise from a sustained change in economic conditions, societal preferences and attitudes, or even a future extreme event. The LUCAS modeling framework developed for this study can be used to explore additional “what-if” scenarios and important parameter uncertainties. For example, this study assumed housing and population densities were non-time varying attributes; however, one could explore changes in projected development related to decreases in population density due to concerns of tsunamis or other coastal hazards (e.g., sea level rise) or increases to meet potential housing demands.

It is important to note that the BAU projection used for this study was based on a limited number of historical data points, namely using national-scale land-cover change data for the years 1992, 2001, 2006, and 2011. These three intervals reflect a reasonably long temporal period (19 years) and capture periods of both high and low growth (e.g. economic recession of the late 2000’s). However, due to the length of the temporal periods (5 and 9 year intervals), the true range of annual variability in urbanization may not be fully represented in the future projections. Furthermore, because a meaningful statistical distribution cannot be derived from the limited number of data points, sampling in future years and Monte Carlo iterations was independent for each county, resulting in a lack of covariance across space. Increasing the temporal density of historical data would improve our ability to characterize the true temporal distribution of change. For example, using the LUCAS model, Wilson et al. (2016) used land change data spanning 1992-2012, collected at 2-year intervals, to project changes in land and water use for the State of California while preserving covariance in change rates across counties and other transition types. Efforts are underway to produce national-scale annual land cover products for the U.S. based on the Landsat data archive spanning 1985-present (Zhu and Woodcock, 2014). As new land change data products become available, they can be used to improve empirical projection capabilities for studies such as this.

Empirical-based projections can serve as a useful source of calibration and validation data for other modeling efforts. For example, the Integrated Climate and Land Use Scenarios (ICLUS) program developed by the U.S. Environmental Protection Agency (Bierwagen et al., 2010) used county-scale population projections to model changes in housing and impervious cover for four global climate change storylines (Nakicenovic and Swart, eds., 2000) and a base case scenario. Similarly, researchers of the U.S. Geological Survey (USGS) developed 4

spatially explicit projections of land use and land cover based on the same 4 global change storylines (Sleeter et al., 2012; Sohl et al., 2013). A regional comparison between these projections and our empirical simulation results reveals significant differences. While we project a 14% increase in households and a 15% increase in residents over the 17-county study area, ICLUS projects an average 5% increase in households, a 11% decline in residents, no substantial change in the majority of counties, and projected increases concentrated in Skagit and Whatcom counties under a base case scenario. Population projections varied even more significantly among ICLUS scenarios. For example, within the A1 scenario, ICLUS population change was projected to range between an 83% loss in Curry County and a gain of 15% in Skagit County, with most counties projected to decline in the number of residents over time.

Compared to ICLUS and our empirical projections, the USGS efforts projected significantly more change in developed area across the study region. All USGS scenarios resulted in an increase in development with projections ranging from 30-124%, with an average increase of 78% between 2006 (the last year of their baseline) and 2061. Based on the analysis of historical data used for this study, these rates of change are nearly 5 times higher than recent historical rates. Results such as these suggest that large area projection efforts, such as those often associated with global change research, could benefit from having an empirical foundation from which to calibrate models.

LULC change projections can be used to assess future, community-scale exposure to tsunami hazards across a wide range of scenarios, but do have their limitations. Given the absence of local-scale land use scenarios, we used available LULC change data derived from NLCD to drive community-level change into the future. This empirical approach may be effective in linking remotely sensed change metrics to local scale analyses and producing plausible maps of the future developed lands. However, this historically-derived BAU scenario was not developed with localized storylines describing regionally unique coastal development dynamics. The design of bottom-up scenarios at the community-scale would capture local knowledge of anticipated population growth (rates and patterns), population projections and density, zoning and urban growth boundaries, locally adopted comprehensive plans, the capacity of infrastructure to support growth, and a range of possible hazard mitigation alternatives. This type of approach can also foster collaboration with other regional groups working on climate adaptation and resilience plans (e.g., Oregon Global Warming Commission 2010). A bottom-up approach may better represent localized processes, drivers, and limitations to LULC change, enabling more effective assessments of future hazard exposure and hazard mitigation options. This information may help guide land use planners as they continue to manage growth in coastal communities threatened by natural hazards.

6. Conclusion

This study of projected changes in community exposure to tsunami hazards focuses on the use of spatially explicit LULC state-and-transition modeling to project changes in developed

land, households, and residents. Based on our analysis, we reach several conclusions that bear on future land change modeling and community-exposure studies related to sudden-onset hazards, such as tsunamis.

- Land-change simulation modeling serves as an exploratory tool aimed at helping local governments characterize and visualize the hazard-exposure implications of business-as-usual development and to recognize future growth in current hazard-mitigation planning.
- Projected new development in tsunami-hazard zones is not equally distributed along the study area, where 15% of jurisdictions are projected to have no additional development, 46% are projected to have less than 10 ha, and 39% are projected to have more than 10 ha.
- Tsunami-hazard zones associated with a Cascadia subduction zone earthquake in the Pacific Northwest are projected to increase by 3,880 households and 6,940 residents by 2061, over 2011 estimates. Oregon had the largest increase in exposure (51% of new households and 45% of new residents), followed by Washington (41% and 40%, respectively) and California (8% and 15%, respectively).
- The top ten communities in 2011 in terms of population exposure to CSZ-related, tsunamis are projected to remain the same areas with the highest population exposure by 2061.
- The largest net increases in residential exposure to tsunami-hazard zones are projected in the unincorporated portions of several counties, including Skagit, Coos, and Humboldt. These increases may represent greater life-safety issues in Humboldt and Coos counties than in Skagit due to substantial differences in tsunami wave-arrival times across the region.
- Land-simulation projections provide insight on implications of future land-use decisions but increases may be tempered by changes in risk tolerance and the ability to convert certain land cover classes (e.g., wetlands) to developed.

These conclusions support the notion that future land change should be considered in population-exposure assessments for sudden-onset hazards with long recurrence intervals. Vulnerability assessments based on current landscape conditions and demographic distributions may be appropriate for short-term efforts to educate and prepare at-risk communities. However, such efforts are likely insufficient and may miss significant landscape change over time. Recognizing the potential for new development in tsunami-hazard zones is critical if practitioners and policymakers are to develop effective long-term mitigation strategies and policies for reducing risk and increasing the resilience of coastal communities.

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