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Brad Avy, State Geologist

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ANALYSIS OF EARTHQUAKE AND TSUNAMI IMPACTS FOR PEOPLE AND STRUCTURES INSIDE THE TSUNAMI ZONE FOR FIVE OREGON COASTAL COMMUNITIES:

GEARHART, ROCKAWAY BEACH, LINCOLN CITY, NEWPORT, AND PORT ORFORD

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WHAT'S IN THIS REPORT?

This report evaluates the effects of a great (M_w 9.0) earthquake and tsunami on the Cascadia Subduction Zone for five Oregon coast communities, in order to understand the degree of potential destruction, including: potential building losses, debris generated, fatalities and injuries, and estimated numbers of the displaced populations. The goal is to help coastal communities prepare.

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ACCOMPANYING DATA

See the digital publication folder for file.

Excel Spreadsheet:

DOGAMI Hazus Tsunami Casualty Model Spreadsheet with Sample Data.xlsx

Note: A macro is included, but due to security reasons DOGAMI cannot distribute a macro-enabled Excel file.

EXECUTIVE SUMMARY

This report provides an evaluation of the potential impacts of a Cascadia earthquake and tsunami on five Oregon coastal communities — Gearhart, Rockaway Beach, Lincoln City, Newport, and Port Orford. Each community was selected based on discussions with the Oregon Department of Land Conservation and Development (DLCD) and the respective communities, which were interested to receive tsunami evacuation modeling and Hazus results in order to guide community-based tsunami planning efforts. The analyses include an assessment of the numbers of people, businesses, and critical facilities located in the maximum-considered XXL1 Cascadia tsunami inundation zone; in a few areas we evaluated the L1 tsunami scenario. Importantly, this report evaluates population demographics in each community in order to better understand potential evacuation challenges that could affect different population groups, as well as socioeconomic impacts associated with a Cascadia subduction zone (CSZ) earthquake and resultant tsunami. The results and analyses presented here reflect a comprehensive effort to document the likely effects the next great earthquake and tsunami will have on coastal communities in the state of Oregon.

We used previously developed physical models of a CSZ earthquake and resultant tsunami, previous and concurrent "Beat the Wave" tsunami evacuation modeling, and the recently published FEMA Hazus Tsunami Model to develop standardized loss estimates for each community: injuries, fatalities, and building damage. From the latter we estimated the amount of debris generated from the building damage. To more efficiently quantify and visualize the tsunami evacuation challenges and options for mitigation, we developed an independent tool (Excel spreadsheet) that implements the FEMA Hazus Tsunami casualty model. The tool is included with this report.

Our study is the first structure-level analysis of tsunami impacts in Oregon using the FEMA Hazus methods. Accordingly, much of this report is given to documenting our methods, including the development of population models. Our devised population model improves upon previous studies by providing spatially detailed estimates of permanent and temporary populations — the latter quantifying numbers of visitors and second-home owners, which varies widely throughout the calendar year. The tsunami injury and fatality modeling evaluates a nighttime (2 AM) evacuation scenario, quantifying impacts to permanent and temporary residents. We analyzed two daytime (2 PM) evacuation scenarios, for two settings: a popular state park beach, and the efficacy of the tsunami vertical evacuation structure (TVES) at the Hatfield Marine Science Center in Newport. Results are summarized as follows:

- The total permanent resident population (all coastal communities) present on the Oregon coast within a tsunami zone ranges from ~22,380 (M1), to ~32,630 (L1) or ~56,500 (XXL1). However, these numbers *exclude* the temporary (visitor) population, which could increase the number by 2-3 times. For example, the communities of Rockaway Beach, Lincoln City, and Newport can experience very large (~620–700% increase) influxes of visitors, well exceeding their resident populations;
- The fraction of the total community population inside XXL1 tsunami zone varies widely among the communities, with virtually 100% of the town's population located within the XXL1 zone at Gearhart, Rockaway Beach, and Port Orford, but less than 25% inside XXL1 for Newport and Lincoln City. This reflects different patterns in coastal geomorphology and inundation extents between the communities as well as the distribution of permanent residents within the communities;
- Analyses of population demographics indicate that Newport and Port Orford have more people age ≥65 in the tsunami zone (42% and 37%, respectively for those residents in the XXL zone),

while the other three communities are closer to the coastal average of 27%. Variations in demographics will likely impact ability to evacuate from the tsunami zone;

- Estimated fatalities for an XXL tsunami impacting the five Oregon communities evaluated for a summertime scenario was found to exceed 13,000 people. However, this assumes that all residential, second homes, motels/hotels, and parks are at 100% occupancy.
- Calculated fatalities were especially high at Gearhart and Port Orford. In the case of Gearhart, this is because high ground is in the eastern foothills and the evacuation distances are relatively long. However, fatalities at Gearhart fall significantly (~2%) if the earthquake and tsunami is an L1 (large) event; differences here are due entirely to the fact that there are many more areas of high ground available for the L1 tsunami. In the case of Port Orford, despite an abundance of high ground nearby, there will be very little time to respond: the tsunami will arrive at the beach quickly (~10 minutes) and will inundate the community in 8 more minutes;
- In all situations, fatalities from a tsunami can be minimized if people evacuate on foot toward safety as soon as possible after the earthquake and move as fast as possible;
- Compared with fatalities, injuries from the earthquake and tsunami were found to be relatively low, varying from ~1 to 9% of the affected community. Combined, Hazus calculated ~900 injured from these five communities. However, because our analyses did not include earthquake-related injuries outside of the tsunami zone, the numbers of injured are likely to be higher.
- Estimated damage to buildings in the Cascadia tsunami inundation zone is very high, primarily due to the powerful hydraulic forces associated with the tsunami and the prevalence of wood-frame and other vulnerable light-frame construction used in Oregon coastal communities. Results from the five communities indicate the following:
    - An estimated 8,200 buildings damaged;
    - Total building replacement costs would approach $2.5 billion;
    - Debris generated from damaged buildings is calculated to be ~776,000 tons. This estimate is at the low end because it excludes building content, road rip-ups, vehicles damaged, etc.
- If a Cascadia earthquake were to occur during summertime, the thousands of individuals who successfully evacuated from the tsunami would need short-term shelter and care (~days to a few weeks). Information contained in this report may be used to guide mass-care planning in the examined communities.

For better adaptation into community planning and for communicating more directly with community members, this report contains detailed, individual community profiles. Each community profile is composed of estimates on numbers of people and buildings within the tsunami zone, injuries and fatalities from both the earthquake and tsunami, number of people who successfully escaped the tsunami in need of short-term shelter, and social characteristics of people in the tsunami zone that can better inform planning for tsunamis. Community profiles conclude with tailored recommendations for education, mitigation, response, and recovery options. Although each community in this report has unique circumstances and challenges, as supported by the results of this study, in all communities ***injuries and fatalities from a tsunami can be minimized if people evacuate on foot toward safety as soon as possible and travel as fast as possible.***

1.0 INTRODUCTION

The destructive and life-threatening forces of tsunamis are well known globally, as demonstrated by the 2011 Tōhoku, Japan event that resulted in 15,868 killed and another 2,848 missing (as of August 8, 2012; Goto and others, 2012). Most (92.4%) of these deaths were due to drowning (Government of Japan Cabinet Office, 2011). The Oregon coast is similarly exposed to large megathrust subduction zone earthquakes, capable of generating catastrophic tsunamis (Witter and others, 2011). Geologic verification for such events is recognized in the geologic record, with evidence of at least 19 megathrust earthquakes (>8.5 Mw) over the past 10,000 years (Satake and others, 2003; Priest and others, 2009; Witter and others, 2012; Goldfinger and others, 2017). The most recent tsunami generated by a large megathrust subduction zone earthquake on the Oregon coast occurred on January 26, 1700 (Atwater and others, 2005). Because many communities on the Oregon coast have large numbers of people and assets (residences and businesses) located in the tsunami inundation zone, there is a high potential that next great earthquake and tsunami will result in many fatalities, catastrophic destruction of local infrastructure, and lasting damage to Oregon's economy.

Key to effective disaster response, recovery, and mitigation planning associated with a Cascadia tsunami is an understanding of the numbers of people located in harm's way and the economic costs associated with such an event. To address these concerns, the 2013 Oregon Resilience Plan recommended that tsunami evacuation modeling be undertaken for each coastal community to estimate potential fatalities, develop models to test improvements in evacuation measures, and evaluate if such improvements would reduce fatality levels (OSSPAC, 2013). The Oregon Resilience Plan also noted that economic resilience must address the number of local businesses located in the tsunami zone. In 2015, the Oregon Department of Land Conservation and Development (DLCD) developed a tsunami land use guide (DLCD, 2015), which recommended undertaking estimates of population subject to tsunami evacuation, including the most at-risk populations. The overarching goal was to document the "who," "what," and "where" in terms of population exposure, building damage and socioeconomic impacts. However, standardized estimates for building damage, displaced population, and fatalities were not available until recently.

Following the Tōhoku, Japan tsunami of 2011, the Federal Emergency Management Agency (FEMA) commissioned an effort to standardize quantification of tsunami impacts (FEMA, 2013). This work was refined and incorporated into FEMA's Hazus framework and released in 2017 (FEMA, 2017a). Hazus is a geospatial information system (GIS) software model that produces loss estimates for earthquakes, floods, hurricanes, and tsunamis based on state-of-the-art scientific and engineering risk analyses and knowledge. Critical input data needed by Hazus includes a wide variety of applied research and engineering products (e.g., ground motion, ground deformation, inundation, and coseismic hazard maps).

In Oregon, considerable mapping and modeling has been undertaken by the Oregon Department of Geology and Mineral Industries (DOGAMI) in order to better advise local and state government agencies on the various geologic hazards that could impact the state. For example, DOGAMI and the U.S. Geological Survey (USGS) published ground motion/deformation maps for a magnitude (M_w) 9.0 Cascadia subduction zone (CSZ) earthquake (Madin and Burns, 2013); these data were integral in initial efforts to evaluate impacts from a CSZ event throughout Oregon (OSSPAC, 2013). In parallel, DOGAMI combined high-resolution lidar-derived terrestrial digital elevation models (DEMs) with detailed bathymetry to develop detailed physical descriptions of several locally generated (CSZ) tsunami scenarios (Witter and others, 2011, 2012; Priest and others, 2013e). More recently, DOGAMI pioneered techniques for tsunami evacuation modeling ("Beat the Wave" (BTW)) at Seaside and Gearhart, Oregon (Priest and others, 2015a,b), and has now applied the technique to multiple coastal communities (e.g., Gabel and Allan, 2016, 2017; Gable and others, 2018a,b; Gabel and others, 2019a,b). These BTW studies graphically demonstrate evacuation challenges and mitigation opportunities but do not quantify potential loss of life. Since 2015, Williams and others (Matthew Williams, DOGAMI, written communication, 2019) developed a Hazus-compatible building inventory for all seven Oregon coastal counties, identifying the locations, size, and primary usage (e.g., residential, commercial) of buildings, which is fundamental to addressing fatalities and building damage potential.

In 2017, the Oregon Coastal Management Program (OCMP) within DLCD obtained funding from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Resilience Grants program to evaluate tsunami preparedness and recovery in five Oregon coastal communities[1]. Components for each community included evacuation modeling, socioeconomic analysis of tsunami impacts, and evaluation of tsunami land use resilience measures with an overall focus on minimizing loss of life and property. An integral component of this pilot project was devoted to combining these data with the recently released FEMA Hazus tsunami model to quantify building damage, potential loss of life, job losses and lost wages due to destroyed businesses, and vulnerable populations that may be exposed to a tsunami.

Although most of the components for modeling earthquake and tsunami impacts are in place, one key missing element is a spatially explicit population model for the Oregon coast. That is, how many people are located in the tsunami zone, and where are they positioned relative to safety from the tsunami at the time of the CSZ earthquake. Such a model is complicated because many Oregon coastal communities experience large influxes of daytime and overnight visitors throughout the year (Dean Runyan Associates, 2018). In addition, many homes and condominium units located in the tsunami zone are second homes or vacation rentals (Raskin and Wang, 2017). These challenges are further compounded by the fact that many parks and campgrounds on the coast are located in the tsunami zone and potentially host many thousands of overnight visitors (White, 2018). Each of these considerations must be carefully evaluated and accounted for in order to generate meaningful statistics of both local and visitor populations and, ultimately, potential casualties and displaced populations associated with a CSZ earthquake and tsunami. The DLCD Land Use Guide (2015) advises that *population estimates should assume the highest seasonal occupancy so that design capacities will be based on the maximum potential evacuation need*. In addition, the guide recommends identifying vulnerable population groups within the tsunami zone that may present special evacuation challenges.

This study is part of a broader research effort that is being undertaken to develop a comprehensive suite of new tsunami pedestrian evacuation maps and socioeconomic (exposure) data products for five at-risk coastal communities to assist in their overall tsunami preparation. The five Oregon Coast communities chosen for this pilot project are Gearhart (Clatsop County), Rockaway Beach (Tillamook County), Lincoln City and Newport (Lincoln County), and Port Orford (Curry County). This broad objective is accomplished through the following three tasks:

1. Conduct least-cost-distance (LCD) modeling to evaluate local evacuation pathways and challenges;
2. Produce "Beat the Wave" (BTW) evacuation maps; and,
3. Undertake community exposure to tsunami inundation by providing estimates of infrastructure damage and casualty estimates for five communities on the Oregon coast (**Figure 1-1**).

Results for tasks 1 and 2 are fully described by Gabel and Allan (2017) and Gabel and others (2019a, b; unpublished, 2020). The purpose of this report is to describe the methods, analyses, and results associated with task 3, which specifically addresses needed estimates of potential building losses, debris

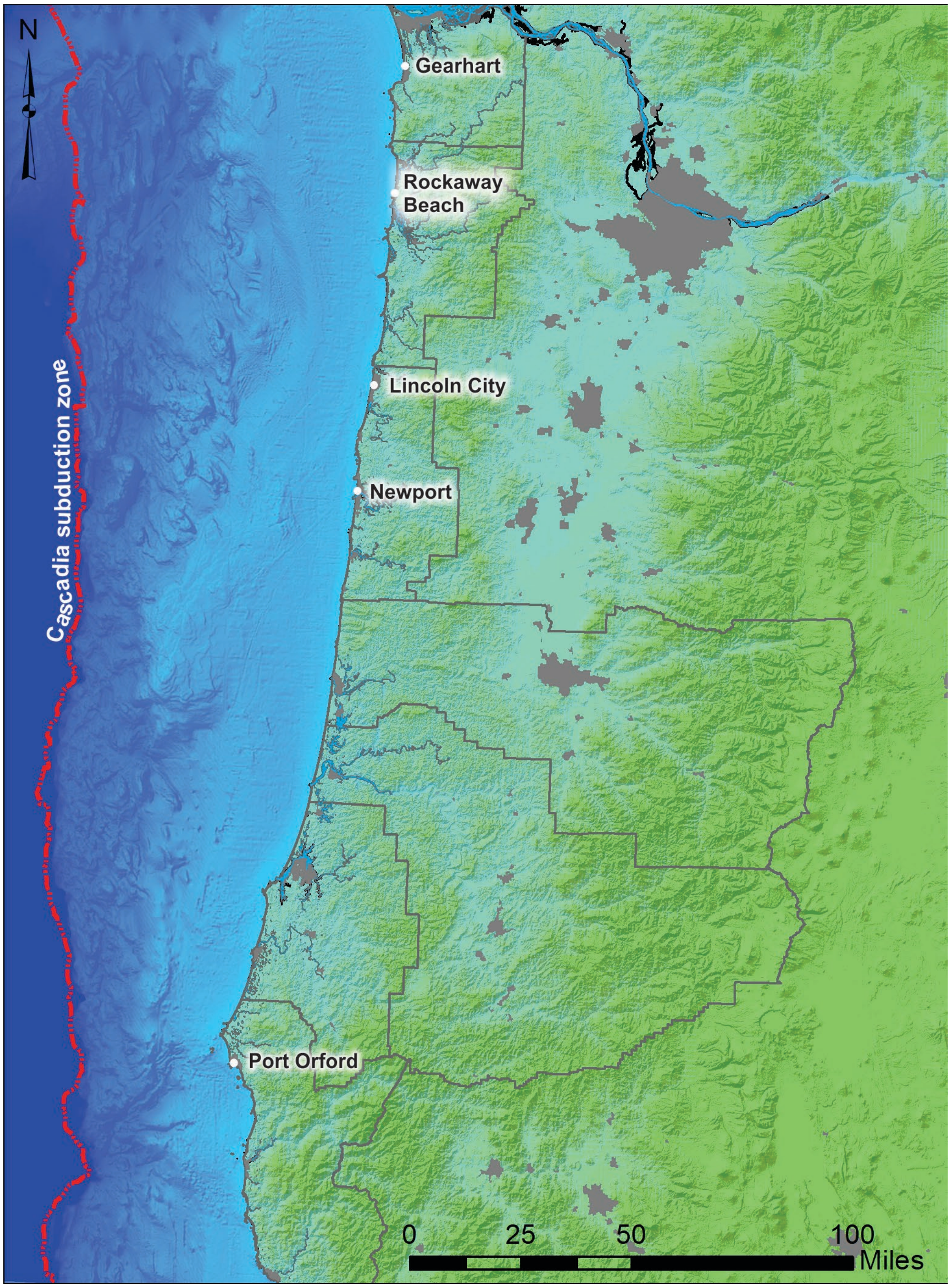
[1] https://www.coast.noaa.gov/resilience-grant/projects/#westcoast

weight, fatality and injuries, as well as estimates of numbers of displaced populations using standardized methods. The study also evaluates vulnerable population groups, essential facilities, and critical infrastructure that are integral to response and recovery. Therefore, this study integrates previous earthquake and tsunami products with a new population model (comprising permanent and temporary people) in order complete the following:

a. To evaluate tsunami evacuation challenges and opportunities on the coast; and,
b. To complete a detailed socioeconomic analysis using several data sources to identify vulnerable communities in the tsunami zone, as well as the number and types of jobs in the tsunami zone that would be impacted by a CSZ event.

Much of this report is given to a detailed account of the overall Hazus approach, especially the development of the population model. This is necessary because this is the first time this approach has been implemented and will thus form the framework for similar analyses in future projects. Our primary purpose in this study was not to perform in-depth comparisons between communities, but to provide useful and actionable data for each individual community. Thus, in addition to a discussion of the overall results in Section 3, with broad conclusions in Section 4, community-specific datasets and results are fully evaluated in Appendix A. Finally, although much of the information presented here is focused on the five communities examined, our results include broader observations that will help all coastal communities consider tsunami preparedness.

Figure 1-1. Map showing the Cascadia subduction zone off the Oregon coast and the locations of Gearhart, Rockaway Beach, Lincoln City, Newport, and Port Orford.



1.1 Study Limitations

Although this study provides loss estimates and community level information at scales and resolution not seen previously, inherent limitations to the overall study approach exist and are explored in more detail in Section **2.10** . Limitations include the following:

- The tsunami risk and vulnerability assessment guidelines (DLCD, 2015) recommend that population estimates in tsunami zones should account for future growth. However, for the purposes of this study we did not consider future urban growth potential. This is because the data available to us to develop the population model do not lend themselves to undertaking future projections of population growth, let alone where these people will eventually be located. Similarly, we did not consider build-out potential of existing vacant lands or redevelopment of currently built lands that could reflect more intensive future land use and higher population densities. The interested reader is directed to Sleeter and others (2017), who developed models to estimate future growth in tsunami zones in Pacific Northwest communities, including the five communities of this study;
- Often, communities are part of a development continuum, such that a city boundary or urban growth boundary is an arbitrary demarcation relative to the potential damage from natural hazards and the resulting human needs. The estimates contained in this report are specific to urban growth boundaries (UGB) and city limits defined for a given community, such that buildings and population clusters adjacent to but outside of these boundaries were not evaluated. As a result, actual damage potential and casualties can be expected to be higher. This points to the need for future evaluations to better account for county-wide damage and casualty potential;
- Although we developed two specific daytime population models for the community of Newport and neighboring South Beach State Park, we were unable to develop similar generalized daytime population models for the other four communities. Such an effort involves considerable research and was beyond the project scope. Furthermore, we did not quantify the number of individuals visiting the communities on day trips. Longwoods International (2018) quantified overnight visitors and economic impact but did not estimate day trips. White (2018) provided total annual day visits for all Oregon state parks but did not provide seasonal variations or estimates of park usage throughout a busy day;
- Although our data may be helpful in estimating the number of individuals who may gather at particular tsunami evacuation assembly areas, and thus be helpful to community planners and first responders with shelter demand planning, we did not pursue such an analysis; such analysis was beyond the project scope;
- Our Hazus modeling did not include impacts of earthquake aftershocks (including aftershocks that could potentially generate smaller tsunamis) or impacts from a distant-source (e.g., Eastern Aleutian Island Arc) tsunami. The latter is unlikely to be significant other than in a few discrete communities where portions of those communities have low elevations and are subject to inundation by a maximum considered distant tsunami;
- Our results are limited to buildings and people within the tsunami zone. Impacts of the earthquake to buildings and people outside of the tsunami zone are not included in this study.

2.0 METHODS

2.1 Overview

Our earthquake and tsunami impact analysis include the following parameters: building damage, injury and fatality, debris, and displaced population estimated using methods established by FEMA (2010, 2011, 2013, 2017a). Baseline information required by Hazus includes:

1. A physical description of the earthquake and tsunami hazard; and,
2. A comprehensive building database, with each building populated with an occupancy estimate derived from our population model.

For the earthquake and tsunami hazard, we used a CSZ M_w 9.0 earthquake as defined by the Oregon Resilience Plan (OSSPAC, 2013; Madin and Burns, 2013), and a corresponding T-shirt sized tsunami as defined by Priest and others (2013e). For the purposes of this study, we used the tsunami inundation zone associated with an XXL1 tsunami (Priest and others, 2013e) in order to estimate damage potential, debris weight, and potential casualties; for Gearhart and Port Orford we used the XXL1 and L1 tsunami inundation scenarios. Our analysis is limited to only those buildings within the tsunami zone and to the community's UGB (DLCD, 2017). For injury and fatality estimation we analyzed a "2 AM" scenario for all communities, distinguishing between permanent residents and temporary residents. For Newport, we analyzed two specific "2 PM" scenarios[2]. As noted previously, we did not evaluate earthquake damage potential outside of the tsunami inundation zone.

2.2 Natural Hazard Dataset Development

2.2.1 Earthquake

We used the bedrock ground motions associated with a M_w 9.0 CSZ earthquake (Madin and Burns, 2013) for use in the FEMA Hazus Advanced Engineering Building Module (AEBM, FEMA, 2010). Bedrock ground motions were adjusted for discrete areas in each study area by using NEHRP recommended site amplification factors (FEMA [2015b]; implemented as piecewise linear equations by Bauer and others [2018, Appendix B]). Madin and Burns (2013) NEHRP site classification and Hazus-scale liquefaction susceptibility GIS data were used; the exception is Port Orford, where we used updated NEHRP site classification and liquefaction susceptibility data based on recent geologic mapping undertaken by McClaughry and others (2013). Sites with NEHRP site classification (as defined by FEMA, 2003, Section 3.5) rated as "F" (soils requiring site-specific evaluations) were reclassified as "E" (soft soils) — a commonly implemented assumption for loss estimation purposes (Bauer and others, 2018). For liquefaction modeling, we assumed a water table level of zero (0) feet (fully saturated soil).

Hazus-scale landslide susceptibility data were obtained by processing landslide susceptibility GIS data given by Burns and others (2016). We mapped the 1–4 scale defined by Burns and others to the FEMA Hazus landslide susceptibility scale of 0–10 as follows: "Low" corresponds to 1, "Moderate" corresponds to 4, "High" corresponds to 7, and "Very High" corresponds to 10. The mapping corresponds to the 'WET' scenario described by FEMA (2011, Table 4.15).

[2] South Beach State Park and the Hatfield Marine Science Center in Newport

2.2.2 Tsunami

The earthquake scenarios used to model tsunami inundation for the Oregon coast reflect a full-length rupture of the Cascadia megathrust and the corresponding surface deformation used for tsunami simulations (Witter and others, 2013). This was necessary because the primary purpose of this effort was directed at the development of regional tsunami inundation maps. Four representative slip models were defined and tested, including slip partitioned to a hypothetical splay fault in the accretionary wedge and models that vary the updip limit of slip on the megathrust. Each tsunami scenario was then weighted using a logic tree, the results summarized on maps depicting the percent confidence that the local CSZ tsunami will reach no further inland than each inundation line. Inter-event time intervals that separate the 19 sandy turbidites range from as little as 110 to ~1,150 years (Witter and others, 2011, Table 1). From these data, four time intervals (mean values rounded to the nearest quarter century) were defined as representative of four general earthquake size classes:

- Small (SM), these events have a mean inter-event time of 300 years (range=~110 to 480 years, 5 events);
- Medium (M), 525 years (range=~310 to 660 years, 10 events);
- Large (L), 800 years (range=~680 to 1,000 years, 3 events); and,
- Extra Large (XL), 1,150 years (1 event), rounded to 1,200 years.

The mean inter-event time interval multiplied by the CSZ plate convergence rate at each latitude equates to the amount of slip deficit released in each scenario earthquake. Slip was also reduced progressively from north to south on the CSZ to account for evidence in the paleoseismic record of increasing numbers of partial CSZ ruptures from north to south (Goldfinger and others, 2012; Witter and others, 2013). A fifth scenario termed Extra Extra Large (XXL), which simulated a maximum-considered tsunami, was eventually used to guide evacuation planning (Witter and others, 2013). This last hypothetical scenario assumes 1,200 years of slip deficit release but without any reduction of slip from north to south. According to Witter and others (2013), the defined earthquake size classes correspond to approximate recurrence rates as follows: SM, 1/2000 yr; M, 1/1,000 yr; L, 1/3,333 yr; and XL, <1/10,000 yr. Recurrence for the XXL event is not known.

Maximum flow depths were obtained from Priest and others (2013a,b,c,d) while the maximum momentum flux was derived from Priest and others (2014a,b,c,d). The unstructured computational grid data were converted to raster format for use in Hazus by using the Esri® ArcGIS Spatial Analyst Natural Neighbor tool. We specified a 3-m (~10 ft) grid resolution, noting that the mean distance between points in the terrestrial regions within the XXL1 tsunami zone was ~5 m (~16 ft). The Hazus tsunami building damage and casualty fragility curve parameters (determined by engineers) are based on median rather than the maximum depth and momentum flux values (FEMA, 2017a, section 4.6). To that end, the raster data were subsequently converted to both median depth and median momentum flux using a 0.66 multiplier; the results were also converted to non-SI (English) units.

Wave arrival times at the tsunami runup limit were obtained from data originally developed by Priest and others (2013a,b,c,d). Wave arrival time values for each of the communities examined are also presented by Priest and others (2015a), Gabel and Allan (2017), and Gabel and others (2019a,b; unpublished, 2020). We examined variations in the wave arrival times at the tsunami runup limits for each community (e.g., Gabel and Allan, 2017, **Figure 2-3**) and established an average value typical for each community (**Table 2-1**). We used the same wave arrive time values for two communities (South Beach State Park and the Hatfield Marine Science Center in Newport) where we modeled an L1 tsunami in addition to the XXL1 scenario. The early wave arrivals at Port Orford are indicative of the area being closest to the fault zone. Differences in wave arrivals on the central coast are probably a function of offshore bathymetric features (e.g., Stonewall Bank) that influence the propagation of the tsunami.

Table 2-1. Modeled wave arrival times at the XXL1 tsunami runup limit, in minutes after start of the earthquake.

Community	Wave Arrival Time (minutes)
Gearhart	33
Rockaway Beach	27
Lincoln City	24
Newport	30
Port Orford	17

2.3 Building Database Development

A Hazus-compatible building database contains a record for each distinct building, with each record containing essential information for estimating damage potential to the structure and harm to the building's occupants (**Table 2-2**). Information associated with the building record, commonly referred to as attributes in a GIS context, is populated primarily from county assessor records or, where better data are available, from ancillary datasets such as is provided by Lewis (2007). We followed the methods established by Bauer and others (2018), starting with the incorporation of building records previously developed by Williams and others at DOGAMI (Matthew Williams, written communication, 2019) and modifying or amending records where better information was available.

We used the RSMeans valuation method for estimating a building's replacement cost (Charest, 2017) where:

$$\text{RSMeans} = \text{building square footage X standard cost per ft}^2 \qquad (1)$$

Per-square-foot replacements costs are derived from the Hazus 4.2 database[3] that incorporated the 2014 RSMeans valuation. Adjustments for inflation or regional variation to the tabular data were not incorporated.

Building replacement cost is not the same as a property's assessed value. For analysis purposes, we assume repair or replacement costs to damaged structures will be charged at standard construction rates, independent of a building's age or the land on which the building is placed. Assessed value includes the land's value, which may fluctuate greatly depending on real estate markets, and home improvements, while assessors may also factor in the building's depreciation into the assessed value.

[3] FEMA Hazus SQL tables [dbo].[hzRes1ReplCost] for single-family residential; [dbo].[hzReplacementCost] for all other occupancy types.

Table 2-2. Building information required by Hazus earthquake and tsunami model.

Hazus Attribute	Example	Purpose
Location of building	latitude, longitude	Extract ground motion and ground deformation data
Building usage	Single-family Residential; Retail Commercial	Repair/replacement cost; number of people per building
Building material	wood; steel	Building response to ground motion; debris
Year built	1968	Seismic design level: building response to ground motion
Number of stories	2	Building response to ground motion
Square footage	2,250	Building repair/replacement cost; debris; number of people per building
First floor height	3.0	(in feet) Tsunami non-structural building damage estimate
Daytime occupancy+	2.1	Casualty estimate
Nighttime occupancy+	3.4	Casualty estimate

+*Daytime* and *Nighttime occupancy* are Hazus terminology. For our analysis purposes we populate *Daytime occupancy* with the number of temporary residents in the building at 2 PM and *Nighttime occupancy* with the number of permanent residents in the building at 2 AM.

An abnormal shortage of skilled labor or materials can occur after a large-scale disaster. *Demand surge* is a process resulting in a higher cost to repair building damage after large disasters, compared with the same repair for damage after a small disaster (Olsen and Porter, 2011). Adjusting repair/replacement costs due to a likely demand surge was beyond the scope of this project.

We used street-level imagery to determine the building type of all non–single-family residential buildings, using the guidance provided by FEMA (2015a). Selected records were updated with information from Lewis (2007). We were unable to locate additional building information that might have helped further refine the building type assignment, or of any seismic retrofitting datasets that could be used to update individual building's seismic design level. Our observations from field visits and street-level imagery analysis suggested that the statistical distributions for building types identified in by FEMA (2011, Tables 3.A1–3.A.10) are not applicable on the Oregon coast. This is because the overwhelming majority of commercial and industrial buildings in the Oregon coast communities were wood-frame construction. For single-family residential buildings, our field observations confirmed the FEMA Hazus assumption of 99% wood/1% other (FEMA, 2011, Table 3A.17). For simplicity, we assigned wood frame to all single-family residences except manufactured housing.

2.4 Population Models

2.4.1 Overview

In order to estimate injuries and casualties from damaged buildings, the FEMA Hazus earthquake model requires estimates of individual building occupancy (FEMA, 2010). People occupying tents, yurts, recreational vehicles, and boats, or who happen to be outside of a building at the time of the earthquake are assumed uninjured from the ground motion. To estimate injuries and fatalities from a tsunami, the FEMA Hazus tsunami model requires the user to refine the population model further to include locations, numbers, population demographics (age), and distance to safety outside the tsunami zone (FEMA, 2017a). Typically, people are associated with a building in tsunami modeling, but they can also be placed in temporary lodging, such as in a tent or recreational vehicle, or out on a beach. Given the dynamic human environment the modeler must therefore make several assumptions about each parameter in order to simulate fatalities and injuries.

To minimize the complexity associated with a dynamic human environment, FEMA Hazus documentation recommends modeling be undertaken for two time periods:

- a mid-week "2 PM" scenario, where people are dispersed among work, institutional, and home buildings; and,
- a "2 AM" scenario, where most people are in a residential structure (in the Hazus model, hotels/motels are considered residential structures; temporary structures such as a tent or RV were also accounted for in our model).

However, our initial assessments indicated that such divisions were inadequate to meet the needs of this project. This is because Oregon coastal communities experience large temporal population fluctuations daily, seasonally, and annually, with large visitor influxes occurring on weekends and in the summer months (Dean Runyan Associates, 2018). Community planners expressed strong interest that our population model account for such variations, which could then be used to assist with identifying tsunami evacuation challenges and short-term sheltering needs.

To better understand these effects, we distinguish two broad population groups: *permanent residents* who have established residence within the tsunami zone, and *temporary residents* who are visiting the community. We chose not to refer to the latter residents as *seasonal*, as large influxes can occur on weekends throughout the year, nor do we refer to the latter residents as *transient*, as the term is commonly associated with people experiencing homelessness. At night, temporary residents occupy residential facilities such as second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds. Conversely, permanent residents typically occupy residential structures at night, though some permanent residents may be at work in round-the-clock operations. During the day permanent and temporary residents may occupy institutional, educational, commercial, and industrial buildings, along with residential buildings, or may be dispersed throughout the tsunami zone (e.g., at the beach) and thus may not be directly associated with any particular building.

Development of a detailed temporary population model was motivated by several important factors:

1. Simply computing an overall injury/fatality ratio for the permanent population (total number of tsunami injuries and fatalities divided by the total exposed permanent population) and assuming that the ratio could be applied to the temporary population could lead to significantly underestimating the casualties and injuries. For example, analysis of U.S. Census data and observation of real estate dynamics in several Oregon coastal communities indicate a strong spatial correlation between the temporary population's preference to be as close to the ocean,

and thus farther away from tsunami safety, when compared to the permanent population (Raskin and Wang, 2017; illustrated with 2010 U.S. Census data in **Figure 2-1**);

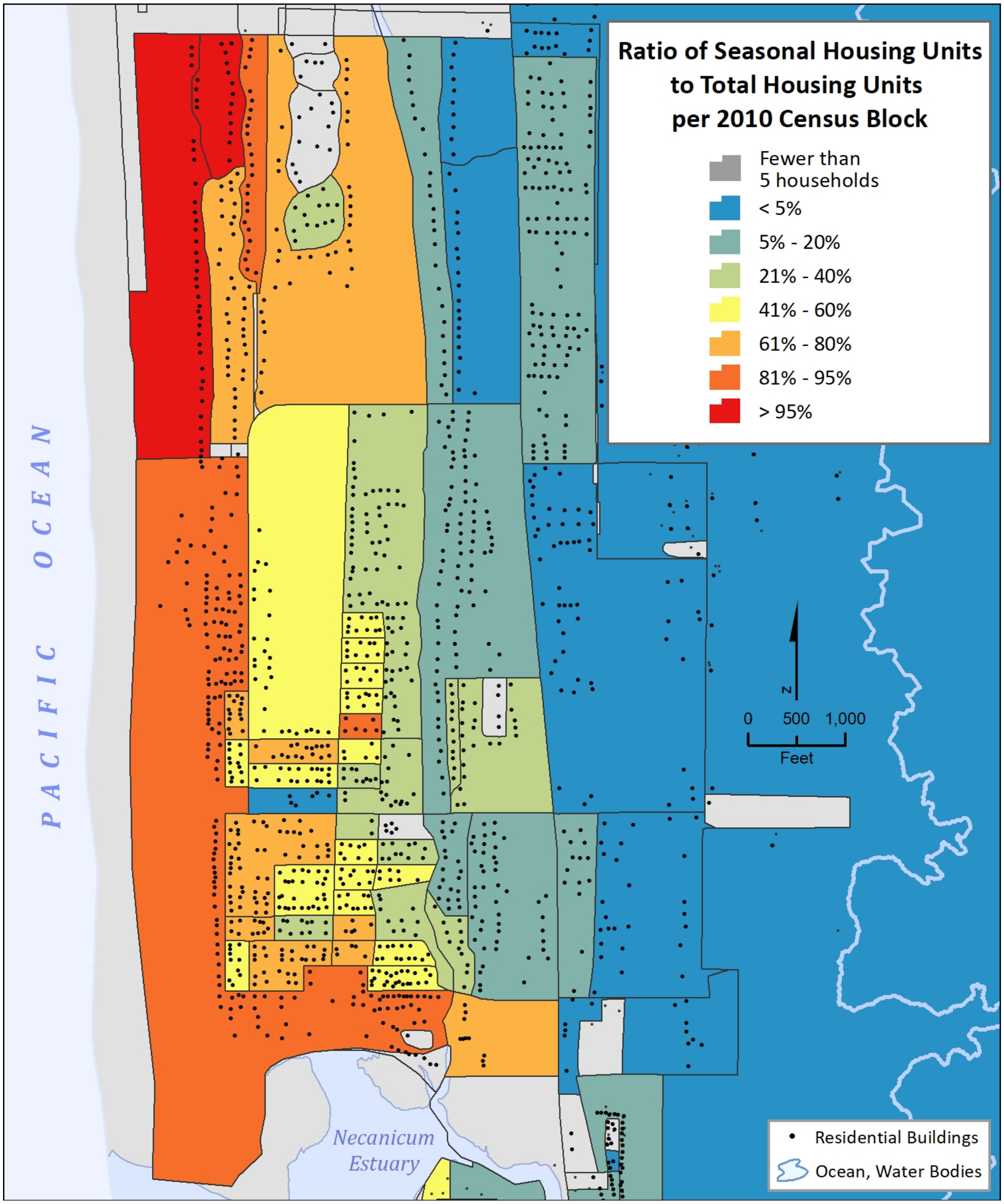
2. It is reasonable to assume that the temporary population may be less aware of tsunami risk, locations of tsunami safe zones, signage, understanding of temporal urgency (e.g., if you feel strong ground shaking, evacuate immediately), and local evacuation routes when compared with permanent residents; and,
3. Community planners expressed a need for detailed estimates of tsunami injuries and fatalities, as well as potential numbers of displaced population. These data are essential for effective mass care planning. Our modeling of tsunami-caused injuries and fatalities is thus done at maximum occupancy, combining permanent and temporary residents, and distinguishing injuries and fatalities between the respective population groups. By doing so, we established a range that planners can use and apply educated judgment to estimate impacts at non-maximum occupancy periods.

Given project scope constraints and discussions with community members we focused our attention on developing a summer weekend "2 AM" population model for all communities, in order to maximize estimates of the temporary population and thus provide a more realistic worst-case tsunami evacuation scenario for those communities. In addition to the 2 AM population model, we developed two location-specific (South Beach State Park and Hatfield Marine Science Center) mid-day "2 PM" scenarios — one as a pilot study for modeling evacuation from a popular beach, the other based on strong community interest in an ongoing tsunami vertical evacuation structure.

Researchers have recognized that demographic factors can be an important factor in tsunami casualties (summarized by González-Riancho and others, 2015). This is because specific age groups have been recognized as having different evacuation speeds, which affects their evacuation potential. Accordingly, FEMA (2013, 2017a) incorporated population demographics into the FEMA Hazus casualty model. This is accomplished by accounting for those people under 65 years of age and those aged 65 and older in the Hazus tsunami casualty model (FEMA, 2017a), with the latter group assumed to evacuate at slower walking speeds. Hence, for our tsunami casualty modeling purposes, an individual is identified as 1) either permanent or temporary, and 2) either under 65 years of age or 65 years of age or older.

Although our summer weekend "2 AM" population scenario does not account for day trippers to the coast, the injury and fatality estimates derived from this scenario, along with the displaced population, can be considered an upper bound. This is because the population model assumes maximum occupancy. Conversely, planners can use the permanent resident casualty estimates as a baseline. With this baseline, planners can estimate the number of temporary residents present in their communities at other times of year and assume the injury and fatality estimates will scale proportionally. Furthermore, the Oregon coast is increasingly becoming a year-round destination for many tourists, such that the mid-winter temporary residential population may also be significant. For example, mid-winter/mid-week spots checks of the South Beach Newport recreational vehicle parks by the authors suggested occupancies on the order of ~10% of total capacity. Here we provide a brief overview of our two population models, while additional details are presented in Appendix B.

Figure 2-1. Example of "seasonally occupied households" relative to the ocean compared to the total households per census block in Gearhart, Oregon. XXL1 tsunami inundation zone shown as a light blue line on the far right. Census blocks with fewer than five households as of 2010 are shown in grey. Residential buildings shown as dots and include residential buildings constructed since 2010 that were not captured in the 2010 census. Census block data source: U.S. Census Bureau (2010).



2.4.2 2 AM Summer weekend scenario

Our summer 2 AM weekend scenario assumes permanent residents are at their homes, and that all available designated temporary lodging such as vacation rentals, second homes, vacation condominiums, campsites, marina boat slips, and recreational vehicle spots are fully occupied (i.e., 100% occupancy). Institutions and businesses, with certain exceptions, are considered to be unoccupied.

For permanent resident occupancy we established locations, numbers of individuals, and age group using geocoded Oregon Department of Motor Vehicle (DMV) driver license registration records as of September 2017. Most DMV records were spatially associated with a single-family residential home. After populating the buildings, or in the case of multi-family residential structures, units, with permanent residents, we then assumed the residential buildings or units that are not occupied by a permanent resident are occupied on a temporary basis by out-of-town residents. For single-family residential houses, we used the number of bedrooms to determine temporary occupancy. We populated motels, campgrounds, recreational vehicle parks, and marinas using the number of rooms, tent or RV sites, or boat slips as a baseline, and multiplying by a people-per-unit occupancy assumption.

Homeless encampments may be present within the tsunami zone in Oregon coastal communities. A January 2019 Lincoln County Project Homeless Connect served 135 individuals (Rachel Cotton, verbal communication, February 2019). Although the number of individuals experiencing homelessness and occupying sites within a tsunami zone is currently unknown, the group should not be ignored in tsunami awareness outreach programs.

To reiterate, we limited our population model to permanent and temporary people within the tsunami zone. We did not include motels, second homes, campgrounds, and recreational vehicle parks located outside the tsunami zone. As a result, the total number of temporary visitors in the communities could be larger than the estimates provided here, especially for the communities of Lincoln City and Newport, where many motels and second homes are not located in the tsunami zone. These additional temporary visitors will likely be impacted by the earthquake as well and thus are likely to be an important consideration when planning post disaster mass-care. However, quantifying these additional numbers was beyond the scope of this pilot study.

2.4.3 2 PM population models

FEMA Hazus-based risk assessments often include a “2 PM” population scenario, where people are dispersed between work, education, and residences. In practice this can be challenging, given the dynamic nature of people in commercial and recreational settings, especially in Oregon coastal communities. Bauer and others (2018) observed that application of guidelines provided by FEMA (2012b, Table 3.1) can result in unreasonably high overall population estimates for an area based on this particular population model. The FEMA guidelines (FEMA, 2012b, p. 3-6) note that full occupancy at the individual building level happens only occasionally, and that “point-in-time population models can be used to develop a better understanding of the uncertainty in casualties associated with time, but it is necessary to perform a large number of realizations (*on the order of several thousand*) to do this in a meaningful way” [italics added]. Such extensive modeling for all communities was beyond the scope of this project.

While a “2 PM” population model was not possible for all communities, we developed two focused “2 PM” daytime population scenarios, based on strong community interests:

1. A summer weekend model for recreationalists dispersed at South Beach State Park beach; and,
2. A summer weekday model wherein we quantified the efficacy for the surrounding community of the under-construction tsunami vertical evacuation structure (TVES) associated with the Gladys Valley Marine Studies Building at Oregon State University’s Hatfield Marine Science Center (HMSC).

To better understand the TVES impact on life safety we chose summer mid-week to maximize the number of people who may use it, including employees occupying the HMSC buildings and recreationalists and staff at the Port of Newport RV Park and Marina located in South Beach. During evening hours and weekends, building occupancy at HMSC is very low. We obtained weekday population estimates for each HMSC building (Cinamon Moffett, written communication, December 2018). We assumed that the Port of Newport Recreational Vehicle Park is at full capacity and that during a summer weekday 40% of the recreational vehicles in the park are occupied.

In response to concerns raised by staff from the Oregon Parks and Recreation Department (OPRD) regarding the volume of day-use visitors at the South Beach State Park beach, we developed a “2 PM summer weekend” population distribution model. We dispersed the occupants of 40 vehicles at South Jetty parking area and 128 vehicles at South Beach State Park Day Use Area by using an exponential decay distribution model and the occupant and age group estimates per vehicle summarized by Bergerson and Rushing (2017). Further details are provided in Appendix B.

2.5 Building Damage and Building Debris Estimation

2.5.1 Earthquake

To calculate combined building losses from an earthquake and tsunami the Hazus model requires the user first to model earthquake damages using the Hazus User-Defined Facilities (UDF) earthquake model (FEMA, 2017a; FEMA, 2011). In the Hazus earthquake simulation we modeled a fully saturated soil scenario, with groundwater level at the surface, thereby incorporating the potential impacts of liquefaction. We believe this is a reasonable assumption for low-lying coastal areas. For our analysis, we used Hazus 4.2 Service Pack 1, which corrected an overestimation of building damage due to earthquake-induced ground deformation including liquefaction and earthquake-induced landslides (FEMA, 2018b).

The XXL1 tsunami model data described by Witter and others (2011) and Priest and others (2013e) were based on a moment magnitude (M_w) 9.1 CSZ earthquake, whereas the terrestrial ground motion data from Madin and Burns (2013) assumed a moment magnitude (M_w) 9.0 CSZ earthquake. For Hazus loss estimation purposes we determined that the 0.1 difference in moment magnitude was minor and accounted for by our choice of the “default betas” in the Hazus Advanced Engineering Building Model (probability of damage state, Kircher and others, 2006; Kircher, 2002). The default betas (also referred to as relaxed betas) were crafted by the Hazus earthquake model developers to account for greater uncertainties in the ground motion for an earthquake scenario compared to an instrumented earthquake event.

Building repair cost estimates were obtained by using the probability of damage state (PDS) values for each building[4]. The Hazus UDF earthquake model currently overestimates repair costs for UDFs by using overly conservative PDS multipliers for determining a building loss ratio (Bauer, 2016). Using corrected PDS multipliers (described by Bauer [2016]), we calculated per-building repair cost estimates, and then summarized building repair costs due to earthquake ground motion and earthquake-induced ground deformation by community.

[4] Hazus SQL table [dbo].[eqUserDefinedFlty].

2.5.2 Tsunami

The XXL1 median depth and momentum flux grids were input data to the Hazus tsunami tool as "Level 3" tsunami data (FEMA 2017b), which reflect advanced level user-provided tsunami model scenarios. We summarized building repair costs for the XXL1 tsunami event by community[5].

2.5.3 Combined earthquake and tsunami

The Hazus tool combines the per-building damages state probabilities from the earthquake and tsunami into an overall damage state probability and then calculates per-building repair cost estimates (FEMA, 2017a, Section 5.7). We summarized the combined building repair costs for the earthquake and the XXL1 tsunami by community[6].

Building recovery times are provided in the FEMA Hazus methods (FEMA, 2017a, Table 7.10), but we chose not to report them, as we believe the assumptions behind the tabular entries are overly optimistic given the spatial scale of a M_w 9.0 CSZ earthquake and tsunami and the likely catastrophic nature of the event on core infrastructure. Thus, access to labor, material, and investment capital may be constrained for prolonged periods during recovery, in large part due to the anticipated damage to western Oregon's transportation network, infrastructure, and fuel supply (OSSPAC, 2013; ODOT, 2014; ODOE, 2017).

2.5.4 Building debris

The Hazus version 4.2 model (FEMA, 2017a, 2018a) presently does not provide support for debris estimation from a tsunami event, due in part to the challenges of accounting for debris redistribution from advection, including debris washed out to sea, sediment transport, and uprooted vegetation. While recognizing the complexities associated with estimating debris caused by the earthquake and tsunami, we contend that estimates of debris tonnage derived from damaged buildings are valuable for community planners to better understand the scale of the disaster and, importantly, to develop post-disaster community debris plans. Timely recovery from a major earthquake and tsunami will depend not only on the localized damage in each community, but also on the ability of communities to stage and dispose of earthquake- and tsunami-generated debris. To that end, we provide estimates summarized by community of debris generated by the earthquake and the XXL1 tsunami (Appendix A).

Estimates of the amount of debris (expressed as tonnage) generated by the earthquake can be obtained using guidelines provided by FEMA (2010). Our building debris estimates combine the guidelines provided in Chapter 7 of FEMA (2013) and Chapter 12 of FEMA (2011). The Hazus tsunami model, when run in conjunction with the Hazus earthquake model, provides combined probability of damage states for a building's structural and nonstructural components. We first calculated the weight of the building based on the model building type using the values provided in Table 12.1 by FEMA (2011). Using the building weight together with the probability of damage states estimate for each building (Section **2.5.3**), we then estimated the debris tonnage using the FEMA (2011) equation 12-3.

2.6 Injury and Fatality Estimation

We independently evaluated injuries and fatalities resulting from a CSZ earthquake and tsunami, using, respectively, the Hazus AEBM model (FEMA, 2010) and the Hazus tsunami model (FEMA, 2017a). Unlike

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[5] Per-building repair cost estimates from the tsunami event by itself were obtained by exporting the Hazus SQL table [dbo].[tsUserDefinedFlty].

[6] Per-building repair costs that combine earthquake and tsunami events were obtained by exporting the Hazus SQL table [dbo].[tsCombUserDefinedFlty]. The table also contains structural and nonstructural probability of damage state (PDS) data for each building.

the building damage estimates described previously, the FEMA Hazus methods currently do not provide a method for combining injury and fatality estimates from the two events (FEMA 2017a, Section 6.4). The approach we used is described in more detail in the next two sections.

2.6.1 Injuries and fatalities from earthquake

We used the Hazus AEBM model (FEMA, 2010) to calculate injuries and fatalities, populating the individual buildings with the permanent and temporary population "2 AM" summer weekend occupancy estimates. The `DayOccupants` and `NightOccupants` fields were used as Hazus AEBM inputs for the two population groups. We note that the `DayOccupants` and `NightOccupants` are simply Hazus field names, and their usage does not suggest we modeled a daytime building occupancy.

The Hazus AEBM model first calculates a building's structural and nonstructural probability of damage state (PDS) values from the ground motion and liquefaction/landslide data provided to the model. It then uses the PDS values to calculate injuries and fatalities based on the number of user-specified people occupying the building and the building type. The methodology assumes a strong correlation between building damage and the number and severity (injury level) of casualties (FEMA, 2011). According to FEMA (2011), casualties (both injuries and fatalities) are classified into four levels: minor injuries, injuries requiring hospitalization, life-threatening injuries, and deaths (**Table 2-3**).

Earthquake-induced casualties have been summarized by community, by casualty level, and by resident status (permanent versus temporary). For comparison with the Hazus tsunami casualty model we summarized earthquake casualty levels 1 through 3 as *injuries*, while casualty level 4 reflected *fatalities*. We note that in Oregon coastal communities, most residents occupy wood-frame structures at 2 AM, and such structures are much less likely to be severely damaged in an earthquake compared to other building types (FEMA, 2011). We reiterate that we constrained our earthquake-induced injury and fatality estimates to people occupying buildings in the community's XXL1 tsunami zone at 2 AM. As a result, it is important to recognize that earthquake-induced injuries and fatalities will inevitably occur to occupants of buildings outside the tsunami zone. However, these latter estimates were not quantified as part of this study. Nevertheless, the proportion of casualties defined for the tsunami zone may be used as guidance for casualties occurring outside the zone.

2.6.2 Injuries and fatalities from tsunami

The Hazus tsunami casualty model estimates are based on a rational actor pedestrian evacuation model in which all persons in the tsunami zone have acute awareness of the impending tsunami, that they possess knowledge of or can quickly determine the most optimal route to a tsunami safety area, and that all individuals seek safety as pedestrians and not by vehicles. The model assumes a group average (median) departure time and travel (walking) speed and accounts for individual variations from the group average using a lognormal distribution (FEMA, 2017a).

While human behavior in an emergency situation is highly variable, we believe the results from the Hazus tsunami casualty model provide critically important data for planners that will help assess the status quo, identifying areas in their communities where injury and fatality rates will likely be higher, while also providing the ability to quantify the efficacy of proposed mitigation solutions such as tsunami vertical evacuation structures where needed. The following sections define in more detail the overall approach and assumptions used to define injuries and fatalities from a CSZ tsunami.

Table 2-3. Hazus earthquake casualty level descriptions (FEMA, 2011).

Injury Severity Level	Injury Level Description
Level 1: Minor Injuries	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Examples: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of lesser severity that could be self-treated are not estimated by Hazus.
Level 2: Injuries Requiring Hospitalization	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life-threatening status. Examples: third-degree burns or second-degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration, or exposure.
Level 3: Life-Threatening Injuries	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. Examples: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
Level 4: Deaths	Instantaneously killed or mortally injured.

2.6.2.1 Model implementation

We implemented the Hazus tsunami casualty model as a standalone Excel spreadsheet in which we estimate the likelihood of a casualty for every person, incorporating their particular distance to a tsunami safety destination, assumptions on group median departure time, and median travel (walking) speed. A travel dispersion coefficient (C_{STD}) was also implemented in the spreadsheet to account for variations (uncertainty) within the group's departure time and evacuation travel (walking) speed. Motivations for developing the standalone spreadsheet versus using the dedicated Hazus tsunami tool are:

1. Our existing tsunami BTW evacuation modeling (e.g., Priest and others, 2015a,b) already provided the needed path distance to safety data needed by the Hazus tsunami casualty model; the Hazus tsunami casualty model includes the USGS Pedestrian Evacuation Analyst Tool (PEAT) (Jones and others, 2014), which performs the same calculations as the DOGAMI approach. Thus, rerunning this capability within Hazus is not warranted;
2. Our project requires a model with considerable flexibility for evaluating alternative population and evacuation scenarios (including distinguishing temporary and permanent residents), and, crucially, for testing population assumptions and model parameter settings; and,
3. Importantly, the Hazus tsunami model currently estimates casualties at the census block level, not at the building level, and thus uses a worst-case assumption of time-to-safety for all occupants within a particular census block (D. Bausch, written communication, July 2018). The Hazus approach is thus too coarse for our objective, which includes a more refined population model disbursed across individual buildings and campground sites.

More detail on our spreadsheet casualty model is described in Appendix C. There we demonstrate functional equivalence of the spreadsheet with the FEMA Hazus tsunami Level 2 casualty tool. To minimize confusion, we use the term "Hazus tsunami casualty model" to refer to the FEMA-established methods of estimating injuries and fatalities resulting from a tsunami, and not a specific tool or spreadsheet.

A local source tsunami provides no warning — the ground shaking itself is the signal to evacuate (OEM, 2011, 2017; DOGAMI, 2012; and stated on all Oregon tsunami evacuation maps, e.g., OEM, 2012). Thus, the warning time (T_W) discussed by FEMA (2017c, Table 6.3) is assumed to be zero for a CSZ tsunami. Furthermore, previous modeling by DOGAMI (Witter and others, 2011) indicates that the maximum tsunami runup from a CSZ earthquake is associated with the first wave arrival[7].

2.6.2.2 Distance to safety

The Hazus tsunami casualty model requires the user provide a GIS file that specifies the distance to tsunami safety at all points along the established evacuation routes. Previous "Beat the Wave" efforts undertaken by DOGAMI (e.g., Priest and others, 2015a,b; Gabel and Allan, 2017; Gabel and others, 2019a,b) have used the anisotropic least-cost distance approach established by Wood and Schmidtlein (2012) to calculate a distance to safety at all locations along evacuation routes. The distance to safety (referred to as *path distance* by Priest and others, 2015a,b) is adjusted to account for the slope of the ground as well as the type of terrain (e.g., soft versus hard sand versus travel on roads) that may influence (slow down) a person's ability to evacuate. Given that tsunami evacuation nearly always requires the evacuee to move up elevation, this adjusted distance to tsunami safety is always greater than the distance as measured on a two-dimensional map. In this report, our usage of *distance to safety* reflects the combined slope and adjusted walking distance.

We associate each building and its occupants with the tsunami evacuation network that specifies the distance to tsunami safety using the Esri® ArcGIS® Near function. The linear distance from the building footprint's centroid to the evacuation network is then added to the distance to safety from the GIS file to derive an overall distance to tsunami safety.

A community often has more than one tsunami evacuation scenario defined, which can include the impact of damaged bridges and/or the inclusion of a tsunami vertical evacuation structure (e.g., Gabel and Allan, 2017). Each scenario has a unique distance to safety GIS dataset, which we captured separately, where applicable.

We did not implement the methods of Wood and others (2016), which has pedestrians evacuating via driveways typically generated on paths perpendicular to the road network. Visual inspection suggested the distance from the building centroid to the evacuation network was minor relative to the overall distance to safety, and such a refinement would only marginally improve the accuracy of the model's results.

2.6.2.3 Departure time

The Hazus tsunami casualty model uses the term *Community Preparedness Level*, which reflects the time required between the tsunami warning (i.e., earthquake shaking) and the actual evacuation of the community (FEMA, 2017a). The degree of preparedness is classified according to three categories: *Good*, *Fair*, or *Poor*. According to FEMA (2017a), these categories are a function of, for example, education level for tsunami awareness, preparation of evacuation routes and signage, a community's risk management level, and, where available, emergency loudspeakers and tsunami sirens. FEMA (2017a) notes that a community with a "good" rating, for example, could be one that is designated "Tsunami Ready" by the

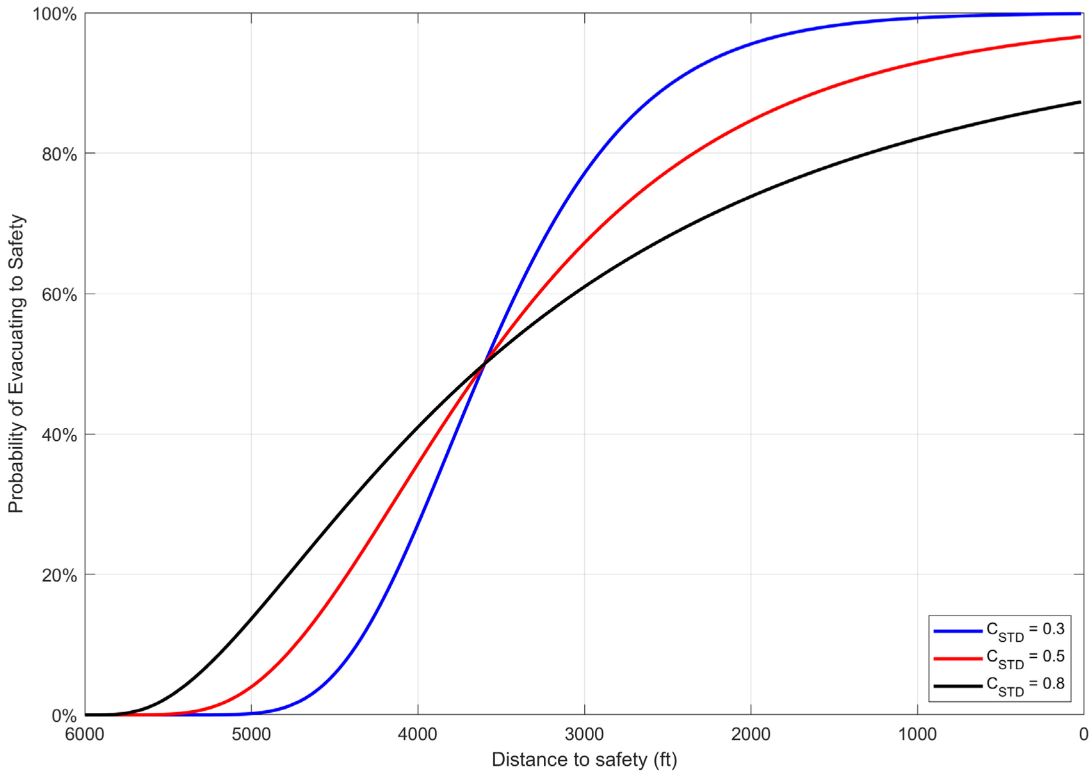
[7] The Hazus tsunami casualty model is one-dimensional and does not incorporate time-sensitive inundation information en route to safety; it simply assumes an evacuee arrived at the tsunami runup (tsunami safety) in time (T_{MAX}). Complex topographic situations, such as those encountered in Seaside, Oregon, require additional analyses. Our analysis of the five communities did not uncover any en route time-sensitive evacuation situations for evacuees (such as first needing to reach a critical juncture (e.g., bridge) before continuing, ascending, and arriving at the designated destination).

NOAA National Weather Service. However, we contend that such designations do not truly reflect a community's level of preparedness given the large uncertainty in people's hazard awareness, knowledge of evacuation routes, their actual response at the time of the event, and the degree of pre-disaster preparation undertaken by communities to prepare for such an event. Thus, for the purposes of this report we chose not to use the *Community Preparedness* terminology, instead focusing our efforts on the importance of group departure times.

It is essential that our injury and fatality estimates quantify the impact of delays in departure times, often referred to as *milling time* in the literature (Wood and others, 2016; Wood and Schmidtlein, 2013; Mostafizi and others, 2017; Buylova, 2018). In this study we provide injury and fatality estimates for 10-, 15-, and 20-minute group departure times. For a 2 AM scenario we use the minimum 10-minute departure time assumptions listed by Priest and others (2015a,b). The 10-minute departure time refers to the time elapsed since the beginning of the earthquake. It accounts for up to five minutes in which the earthquake shaking takes place, followed by five minutes of individual preparation — donning shoes and outdoor clothing, gathering immediate family, collecting a go-bag, and then leaving the building. We also model 15- and 20-minute departure times to represent milling times of an additional 5 and 10 minutes, respectively.

The departure time is assumed to be the group median value. In reality, some individuals may leave earlier, others later, while some may walk faster or slower than the group median evacuation speed. The Hazus tsunami casualty model accounts for these variations by adopting a dispersion factor (defined by a lognormal distribution), which can be accounted for by specifying a standard deviation (or *beta*) value (referred to as C_{STD} by FEMA, 2017a). For the purposes of our study, we used the Hazus tsunami casualty model defaults of 0.3, 0.5, and 0.8 for 10-, 15-, and 20-minute departure times, respectively, corresponding to the Good/Fair/Poor community preparedness levels noted above and the standard deviation (C_{STD}) recommendations provided by FEMA (2017a, Table 6.3). **Figure 2-2** illustrates the probabilistic nature of the lognormal distribution model. It assumes a group departure time of 10 minutes, a walking speed of 4.0 feet per second, and a wave arrival time of 25 minutes. An individual departing at those specifications can cover 1,097 m (3,600 feet). The standard deviation term, C_{STD}, models the dispersion in individual evacuation times and evacuation walking speeds. The model effectively assigns a probability of evacuating to safety that ranges between 0 and 1. As a result, an individual having traveled 1,097 m (3,600 feet) is not assumed to have safely evacuated but instead is assigned a probability of 0.5 of evacuating safely. As previously discussed, this value accounts for dispersion in departure times and walking speeds. Note the asymmetric nature of the lognormal distribution: it implements a conservative assumption regarding a tendency for humans to delay their departure times.

Figure 2-2. Hazus tsunami casualty model predictions for a hypothetical wave arrival time of 25 minutes (with no warning time), a group departure time of 10 minutes, an evacuation walking speed of 4 feet per second, and variations in the lognormal standard deviation term (C_{STD}).



For the South Beach State Park daytime evacuation scenario analyzed in this report we specify a 5-minute departure time, as people on the beach can be assumed to be appropriately clothed and can evacuate to safety with minimal delay (i.e., there is no additional time needed to exit a building).

We currently are unable to quantify how earthquake-induced building damages may inhibit rapid evacuation from a building prior to the arrival of a tsunami. This understudied concern may be important in older manufactured housing units that may slip off their foundation supports, warping framing and possibly jamming doorframes and windows (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014). The situation can also arise due to unsecured nonstructural elements such as large bookcases that are likely to tip over during the ground motion and block potential exits. FEMA (2012a, Section D) provides guidelines on minimizing potential constraints to egress, including advice on storing large crowbars and sledgehammers near primary door(s) to facilitate emergency exiting.

2.6.2.4 Evacuation speed

Using community feedback and DOGAMI's previous BTW work (Priest and others, 2015a,b), we assume a standard 4 feet per second (fps) (2.7 miles per hour, which equates to a "walk" speed) evacuation speed as a baseline for estimating tsunami injuries and casualties. Variations in individuals' walking speeds is incorporated into the C_{STD} standard deviation value discussed previously (FEMA, 2017a).

The Hazus tsunami casualty model incorporates a travel (walking) speed reduction factor for persons aged 65 and over (FEMA, 2017a). This assumption is based on analyses of fatalities in recent tsunamis (e.g., Koyama and others, 2012; Suppasri and others, 2016; González-Riancho and others, 2015). Accordingly, we used a 0.8 walking speed reduction factor based on recommendations documented by FEMA (2017a) to account for travel speeds used by persons ≥65; for this demographic group, people ≥65 are thus assumed to evacuate at 3.2 fps (2.2 miles per hour). It is important to emphasize that travel speed is modeled for the group average (median) and is applicable for the *entire* evacuation route, which can commonly exceed 4,000 feet.

The distance covered by an evacuee can be calculated as follows:

$$\text{Distance Covered} = (T_{\text{ARRIVE}} - T_{\text{DEPART}}) * \text{WalkSpeed} \quad (2)$$

where T_{ARRIVE} is the time interval between the earthquake start and the tsunami first wave arrival, T_{DEPART} is the time interval between the start of the earthquake and when the population begins evacuating, and WalkSpeed is the specified travel (walking) speed. For reference, we calculate the distance an individual could travel prior to a tsunami arriving based on a range of evacuation speeds and wave arrival times (**Table 2-4**). While the group average (median) departure time may be 10 minutes, the Hazus tsunami casualty model accounts for individual variations from the group average using the cumulative lognormal distribution and dispersion factor noted previously in **Section 2.6.2.3** .

Table 2-4. Distance walked (in feet) for several departure times and tsunami wave arrival times at the tsunami runup limit. No warning time is assumed. Departure time is the time after earthquake ground motion begins.

Tsunami First Wave Arrival Time (minutes)	Walking Speed Category	Walking Speed		Distance Walked (in feet) for Various Departure Times (in minutes)			
		Feet per Second	Miles per Hour	5 min	10 min	15 min	20 min
15	Slow Walk	2	1.4	1,200	600	—	—
	Moderate Walk	4	2.7	2,400	1,200	—	—
	Fast Walk	6	4.1	3,600	1,800	—	—
	Jog	8	5.5	4,800	2,400	—	—
	Run	10	6.8	6,000	3,000	—	—
20	Slow Walk	2	1.4	1,800	1,200	600	—
	Moderate Walk	4	2.7	3,600	2,400	1,200	—
	Fast Walk	6	4.1	5,400	3,600	1,800	—
	Jog	8	5.5	7,200	4,800	2,400	—
	Run	10	6.8	9,000	6,000	3,000	—
25	Slow Walk	2	1.4	2,400	1,800	1,200	600
	Moderate Walk	4	2.7	4,800	3,600	2,400	1,200
	Fast Walk	6	4.1	7,200	5,400	3,600	1,800
	Jog	8	5.5	9,600	7,200	4,800	2,400
	Run	10	6.8	12,000	9,000	6,000	3,000
30	Slow Walk	2	1.4	3,000	2,400	1,800	1,200
	Moderate Walk	4	2.7	6,000	4,800	3,600	2,400
	Fast Walk	6	4.1	9,000	7,200	5,400	3,600
	Jog	8	5.5	12,000	9,600	7,200	4,800
	Run	10	6.8	15,000	12,000	9,000	6,000

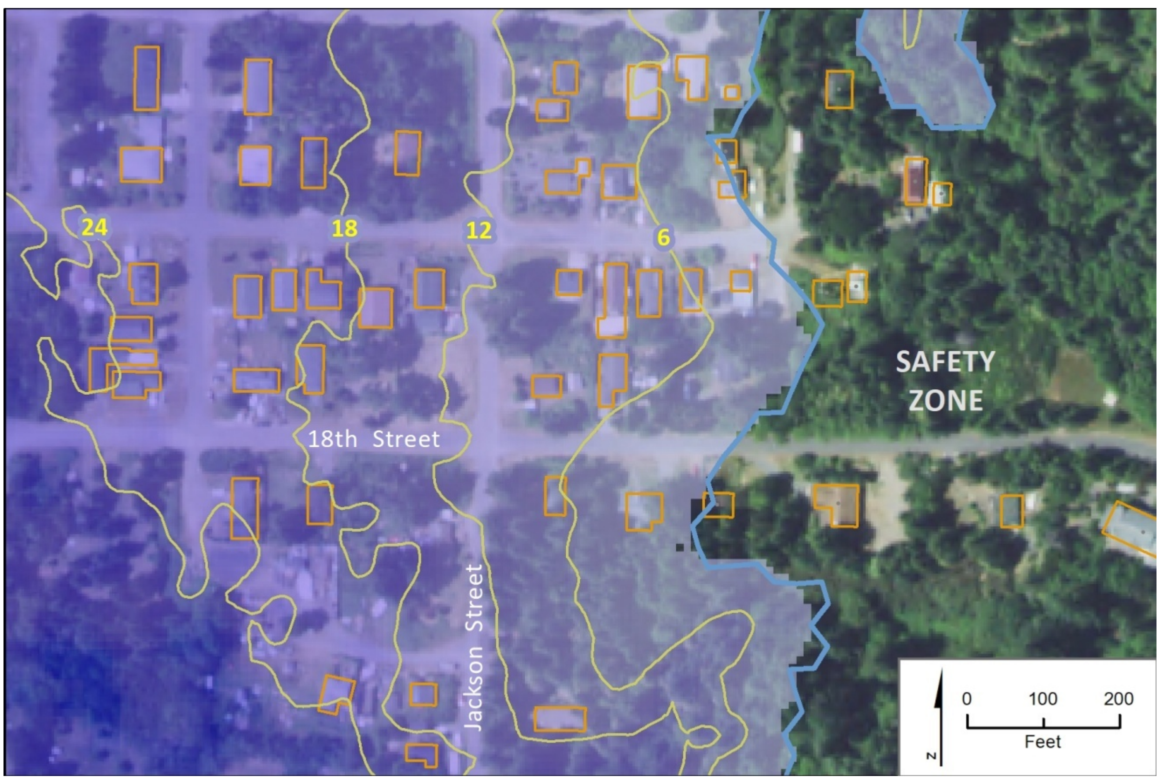
Note: "—" denotes individuals traveling at the designated speed would not reach safety before tsunami arrival.

2.6.2.5 Tsunami injury and fatality estimation

The Hazus tsunami casualty model assumes a 99% likelihood of fatality and 1% likelihood of injury to an individual caught up in a tsunami where the wave depth exceeds 1.8 m (6 feet, FEMA, 2017a). As a result, for individuals caught where the tsunami wave depth is <1.8 m (6 ft), the model assumes a likelihood of 50% fatality/50% injury. In practice, because the topography of many Oregon coastal communities is relatively steep, the horizontal distance between the 1.8 m (6 ft) and 0 elevation contour (tsunami safety) is generally small compared to the typical distance to safety an individual needs to travel. Our analyses indicate that these distances range from ~30 to 90 m (100 to 300 feet, **Figure 2-3**). In the DOGAMI implementation of the Hazus tsunami casualty model, the user specifies the distance as a fixed value for a given community (Appendix C); this is adjusted for each community by averaging all distance to safety values at the 1.8 m (6 ft) depth contour.

The Hazus tsunami casualty model provides injury and fatality estimates for each individual with a likelihood between 0 and 1. We summarize the individual injury and fatality likelihoods to obtain overall injury and fatality estimates at the community level (Appendix A).

Figure 2-3. Example of modeled tsunami wave depth near the tsunami inundation limit (blue line), Port Orford, Oregon. The contours in yellow represent the median tsunami depth value (in feet), per Hazus methods (Section 2.2.2) for an XXL1 tsunami (Priest and others, 2013a). Building outlines in orange. Imagery: National Agricultural Imagery Program (2016).



2.6.2.6 Sensitivity testing

We varied evacuation speeds (2 to 8 fps in 1-fps increments) and departure times (5 minutes to 20 minutes in 1-minute increments) in a manner similar to that of Wang and others (2016), calculating overall injuries and fatalities for each community. Such data can assist in gaining a better understanding of evacuation challenges facing communities. Furthermore, when presented in graphical form these data can be used in education and outreach material to reinforce existing tsunami evacuation messaging, stressing key points such as the need to evacuate immediately and, importantly, to travel as fast as possible in order to reach safety in time. We adjusted the dispersion factor (C_{STD}) as specified in section **2.6.2.3** proportionally for 10-, 15-, and 20-minute departure times. For example, at 17-minute departure time, C_{STD} was set to 0.62 (using C_{STD} = 0.5 at 15 minutes + 0.3 * 40% to adjust for the 0.3 C_{STD} difference between 15 minutes and 20 minutes).

2.6.3 Combining earthquake and tsunami casualty estimates

The Hazus approach does not provide a method for combining injury and fatality estimates derived from the earthquake and tsunami modules. Some portion of the injured people due to the earthquake may not be able to evacuate in a timely manner as they may be disoriented, tend to their own injuries or injuries sustained by another household member, or sustain injuries that prevent or constrain an on-foot evacuation. We report both sets of casualty numbers to provide planners with a more complete accounting of the potential situation.

We note once again that injury and fatality estimates are limited to the people in the community's tsunami zone at the time of the earthquake. The estimates do not include injuries or fatalities arising from for example, heart attacks, bridge failures, automobile or maritime accidents, electrocutions from downed power lines, exposure to released hazardous materials, upstream dam failures, ground failures such as earthquake-induced landslides, or fires. Furthermore, large-scale natural disasters are known to contribute to illness, injury, or death from other factors such as lack of access to clean water or medicine, interruption of power to life-sustaining medical equipment, exposure due to lack of shelter, disease outbreak, domestic violence, and civil unrest. Quantifying these latter causes of injury or death were beyond the scope of the present investigation.

2.6.4 Displaced population

For mass care planning purposes, we calculated the number of uninjured individuals likely to have safely evacuated from the tsunami zone. Those individuals will need shelter, as their homes, motels, recreational vehicles, boats, and tents are assumed to be destroyed by the tsunami. The temporary population that happens to be visiting when the earthquake and tsunami strike will also require shelter needs extending well beyond a week(s), as arrangements for transportation out of the disaster zone and ultimately home may be delayed (OSSPAC, 2013; ODOT, 2014; ODOE, 2017), and their personal vehicles are likely to be destroyed.

2.7 Essential Facilities and Key Infrastructure

We provide the names of essential facilities, special facilities, and key infrastructure that are located within each city's tsunami zone. For this report we use the *essential facility* definition provided in Oregon Revised Statute 455.447, Regulation of certain structures vulnerable to earthquakes and tsunamis; rules. (2017[8]):

"Essential facility" means:

(A) Hospitals and other medical facilities having surgery and emergency treatment areas;

(B) Fire and police stations;

[8] https://www.oregonlegislature.gov/bills_laws/ors/ors455.html

(C) Tanks or other structures containing, housing or supporting water or fire-suppression materials or equipment required for the protection of essential or hazardous facilities or special occupancy structures;
(D) Emergency vehicle shelters and garages;
(E) Structures and equipment in emergency-preparedness centers;
(F) Standby power generating equipment for essential facilities; and,
(G) Structures and equipment in government communication centers and other facilities required for emergency response.

We define a *special facility* as one that is likely to contain population segments that may present additional tsunami evacuation challenges. This builds on, but is not limited to, the “special occupancy structure” definition provided in Oregon Revised Statute 455.447. Examples include assisted living facilities, detention facilities, facilities where groups of children are placed in the care of non–family-member adults, and facilities with particular focus on persons with a disability. Facilities with incidental usage by persons with disabilities are not included. The Quarterly Census of Employment and Wages (QCEW) (described in Section **2.8** below) was one of the sources used to identify such facilities. We created a lookup table wherein we identified a subset of employer types based on their 6-digit North American Industrial Classification System code (Office of Management and Budget, 2017) that may host a population that may face additional tsunami evacuation challenges. The table was joined to the QCEW data, which identified specific businesses that could be considered a special facility. We evaluated the business, and if warranted, we included the specific business in the named facilities section of the community profiles (Appendix A).

Although great care was taken to develop as complete a list of special facilities in the tsunami zone as feasible, it is acknowledged that not all businesses may have been included. This is mainly because of the provisional nature of the QCEW data, such that some business locations may not have been captured in our overlay analysis. Furthermore, it is important to note that the designation of a building as a “special facility” should not be interpreted as any statement on the building owner or operator’s level of tsunami preparedness. The analysis simply identifies those businesses located in the tsunami zone.

The *key infrastructure* list includes facilities necessary for community recovery but not covered in the essential facilities list and includes such facilities as water treatment plants and electrical substations. We constructed this latter list based on visual inspections of orthoimagery and other ancillary geospatial data sources such as Homeland Infrastructure Foundation-Level Data (U.S. Department of Homeland Security, 2018). As with the essential facilities and special facilities list, every effort was taken to develop as complete a list as possible.

2.8 Employment

We obtained a geocoded Quarterly Census of Employment and Wages (QCEW) dataset, dated September 2018, from the Oregon Employment Division. We summarized the number of businesses, employees, and annual wages paid for the entire community (defined by its urban growth boundary), and within the community’s XXL1 tsunami zone. For businesses within the tsunami zone, we identified the highest employment sectors by number of jobs, using the employer’s North American Industrial Classification System (NAICS) 2-digit code. We chose not to aggregate the QCEW data by finer tsunami zone divisions, as such divisions often compromised the employer privacy restrictions outlined in the DOGAMI QCEW data sharing agreement (Oregon Employment Department [OED], 2018b). It is important to note that the release notes that accompany the QCEW data (OED, 2018b) that state that due to several factors, “users are cautioned to consider carefully the provisional nature of these data and information before using them for decisions that concern personal or public safety or the conduct of business that involves substantial monetary or operational consequences." Such factors include:

- geocoding errors that can incorrectly define the location of employment; for example, employers may have satellite operations with employees working in other buildings, yet account for all employment at a main office; and,
- the NAICS code may be in error, thus misstating the type of business.

Thus, despite great care in using these data it is possible our employment data profiles may be incomplete.

2.9 Social Characteristics

DLCD guidelines (2015) recommend that a tsunami risk and vulnerability assessment include an analysis of the characteristics and locations of populations that may have specific additional needs or requirements for evacuations. Our population model enabled us to provide demographic information classified into two broad age groups: <65 years of age, and ≥65 years (described in further detail in Appendix B) and by T-shirt size tsunami zone as defined by Priest and others (2013e).

After reviewing the type of population and housing data contained in the American Community Survey (ACS) data products (U.S. Census Bureau, 2018, Table 1.1), we determined the following ACS tables were most useful for informing community tsunami education and evacuation planning:

- S0101 Age and Sex
- S1601 Limited English Speaking Households
- S1810 Disability Characteristics

We obtained the selected ACS tables at the city ("community" in ACS terminology), county, and state level. The 2013–2017 ACS 5-year estimates were based on data collected between January 1, 2013 and December 31, 2017. We chose the ACS 5-year estimates based on U.S. Census guidance for smaller geographies (U.S. Census Bureau, 2018, Table 3.1). We note that the ACS estimates are for the city jurisdiction and not its UGB, and that the ACS data are not available by tsunami zone or at any unit finer than the city. We include the ACS-provided margin of error (MOE) to emphasize the sampling nature and uncertainty of the survey. The U.S. Census Bureau sets a 90% confidence level, where the estimate and the actual population value will differ by no more than the value of the MOE.

Excepting the Oregon state park usage data provided by Bergerson and Rushing (2017) and Longwoods International (2018), we were not aware of any data sources that offered detailed demographic insights into Oregon coastal community temporary populations.

2.10 Model and Data Limitations

2.10.1 Earthquake

Our earthquake ground motion and deformation model is based on various assumptions about the Cascadia rupture zone (Madin and Burns, 2013). Soil amplification, liquefaction susceptibility, and landslide susceptibility values for the five communities were assigned on the basis of the best available local geologic data, much of which was mapped prior to the availability of lidar imagery. As a result, information provided by Madin and Burns (2013) may include generalizations about local conditions that could be better refined in the future with more detailed community or site-specific mapping efforts.

2.10.2 Debris

The weight of damaged building contents such as refrigerators and furniture, and where applicable, business inventory such as groceries, were not included in our estimates of debris. Furthermore, we do not quantify the amount of buoyant debris from damaged buildings that may be washed out to sea, nor do we estimate the weight of concrete and asphalt that would be produced from damaged roads and bridges. Debris from damaged automobiles, trucks, recreational vehicles, shipping containers, boats, and logs in staging areas are not included, but an estimate can be obtained using the weights provided by FEMA (2013, Table 7.6). Estimates of the weight of sediment redistributed across the landscape or vegetation removed and transported by the tsunami were also excluded from our analyses. Lastly, debris resulting from earthquake ground shaking and ground deformation outside the tsunami zone is not accounted for in this study. Such debris will inevitably include additional damaged buildings, landslide deposits, damaged bridges, buckled roads, sand and silt ejecta caused by liquefaction (Villemure and others, 2012), and damaged nonbuilding structures.

Commercial movers provide guidelines for estimating the weight of a typical household content (https://www.move.mil/resources/weight-estimator). The content of a three-bedroom house is generally estimated at around 5 tons. Although we do not report on content damage in this study, a reasonable assumption is that nearly all of the content of a house in the tsunami zone will be destroyed and will be added to the total debris. The building database developed for this study could be used to calculate the added weight of debris associated with household content.

2.10.3 Economic losses

Our economic loss estimates are limited to the direct cost of repairing a damaged building or replacing a severely damaged building with an equivalent structure. Our model assumes standard labor and material costs and availability of capital and credit. It does not factor in demand surge, which is a process resulting in a higher cost to repair building damage after large disasters compared with repair costs (same damage) caused by a small disaster (described previously in section **2.3**). Olsen and Porter (2011) reported demand surges ranging from 10% to 40% from several large-scale disasters. Adjusting repair/replacement costs due to a likely demand surge was beyond the scope of this project. Further, we do not quantify permanent loss of use, and thus value, of the land due to ground failure, presence of spilled hazardous materials, loss of buildable land due to scour and erosion from the tsunami, or loss of use from tidal flooding due to co-seismic subsidence.

2.10.4 Population models

As discussed in Appendix B, our estimates of the permanent population in the tsunami zone used Oregon Department of Motor Vehicles records. We recognize the DMV data used for the assignment may underestimate the number of permanent residents in some locations. Further, our assignment of 0.318 children for every adult between 18 and 64 years of age (described in Appendix B) may either overestimate or underestimate actual numbers. Temporary resident estimates and age demographics were based on several key assumptions outlined in Appendix B.

Our model does not account for populations living in the tsunami zone who are experiencing homelessness. Homeless encampments are likely present within the tsunami zone of many Oregon coastal communities. A January 2019 Lincoln County Project Homeless Connect served 135 individuals (Rachel Cotton, verbal communication, February 2019). Tillamook County emergency officials have established communication procedures with unsheltered individuals when flooding is imminent, as encampments are often in low-lying areas including next to sloughs or under bridges, many of which are in the tsunami zone (Erin Skaar, verbal communication, February 2019).

2.10.5 Hazus tsunami casualty model

The FEMA (2017a) Hazus pedestrian evacuation model makes several key assumptions: 1) all people in the tsunami zone will attempt to evacuate by foot at some time after the ground stops shaking; 2) their exit from the building and the route to safety is unimpeded; 3) they take the most optimal route to safety; and 4) their walking speed is not limited by congestion from fellow evacuees or vehicles or the presence of debris and barriers that may be present on roads. Furthermore, it does not account for certain human behaviors and other factors that could result in higher fatality rates. For example, some portion of the population may be unaware of the impending threat and thus do nothing. Others may be fully aware of the threat but for various reasons, including a fatalistic outlook (Johnson and others, 2013), choose not to evacuate. Some may tend to a person with disabilities or a person who sustained injuries during the earthquake and thus fail to leave in a timely manner or are greatly limited in their travel speeds. Still others may spend time checking on neighbors. Fatigue may impact a portion of the population over longer travel distances, especially individuals with limited mobility or health-related problems. Delay introduced by descending multiple flights of stairs in multi-story structures is also not considered.

Other non-behavior factors that the model does not account for include structural failures in a building leading to jammed doorways, and blocked hallways and doorways, all of which may limit egress. Evacuation on roadways and pedestrian paths is likely to be impacted by several factors: in more developed areas, building debris produced by the ground shaking strewn onto roadways and sidewalks; sections deformed due to lateral spreading caused by liquefaction; the presence of sand boils (a product of liquefaction); and downed power lines, especially in areas where power lines crisscross roads. Depending on the number of evacuees, pedestrian and vehicle congestion at choke points could also influence evacuation travel speeds.

Occupants of boats docked in marinas are assumed to recognize the signs of a major earthquake and be able to safely leave their vessels and exit to high ground via an intact docks and dock ramps. Seiching within enclosed marinas is not modeled, nor is potential damage to the dock or its walkway to dry land.

Although the Hazus earthquake model estimates earthquake-induced building damage, the Hazus tsunami casualty model does not factor in how damage to a building from the earthquake itself may restrict egress and thus possibly impede a rapid evacuation of a damaged building prior the arrival of a tsunami. This understudied concern may be especially pronounced in older manufactured housing units that may slip off their foundation supports, warping framing and possibly jamming doorframes and windows (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014). The situation can be further compounded due to the presence of unsecured nonstructural elements such as large bookcases that tip over during the ground motion, potentially blocking exits. FEMA (2012, Section D) provides guidelines on minimizing potential constraints to egress, including advice on having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting.

Although one can identify several shortcomings with the FEMA Hazus tsunami casualty model, given its assumptions of ideal behavior on the part of evacuees and intact, unimpeded evacuation routes, the injury and casualty results from the model should be perceived, as Wood and Schmidtlein (2013, p1625) noted, “as starting points and not an end point for tsunami risk-reduction discussions.”

3.0 RESULTS

This section presents results of the Hazus analysis used to quantify earthquake and tsunami related impacts (building damage, debris weights, injuries, fatalities etc.) for five communities on the Oregon coast: Gearhart (Clatsop County), Rockaway Beach (Tillamook County), Lincoln City and Newport (Lincoln County), and Port Orford (Curry County). Gearhart and Rockaway Beach are located on the northern Oregon coast, Lincoln City and Newport are on the central Oregon coast, and Port Orford is on the southern Oregon coast (**Figure 1-1**). These communities were selected on the basis of discussions with DLCD and the respective community planners and emergency officials, who needed tsunami evacuation modeling and Hazus results in order to guide community-based tsunami planning efforts. The five communities are ideal choices for inclusion in this pilot Hazus study due to their 1) diverse population demographics, 2) historical and contemporary development patterns, 3) distinct socioeconomic characteristics, 4) proximity to the CSZ rupture zone, which affects tsunami wave arrival times, and 5) unique bathymetric, topographic, and geologic characteristics that influence both tsunami runup and evacuation potential and building damage. The tsunami wave arrival time is especially important for assessing a community's ability to quickly evacuate its population, which directly affects the potential for fatalities. For example, wave arrival at Port Orford is ~17 minutes compared with 33 minutes at Gearhart. This means there is much less time for people on the south coast to respond to the earthquake shaking compared with those in the north. Combined, each of these characteristics will factor into community preparation, response and, ultimately, recovery following a CSZ earthquake and tsunami. This Results section presents the Hazus results in a generalized form; more detailed community-specific characteristics are examined and discussed in Appendix A.

Table 3-1, **Table 3-2,** and **Figure 3-1** present summary demographic information for the five communities examined. **Table 3-1** and **Figure 3-1** define the permanent population within each of the communities and includes a conservative estimate of the temporary population that may also be present; the temporary population is derived from a summer 2 AM weekend scenario that maximizes visitor occupancy. Four facts stand out from such a comparison:

1. The fraction of the total community population within the XXL1 tsunami zone varies widely between the communities, with virtually 100% of the town's population located within the XXL1 zone at Gearhart, Rockaway Beach, and Port Orford, but less than 25% inside XXL1 at Newport and Lincoln City. This reflects contrasting patterns in coastal geomorphology and inundation extents between the communities as well as the distribution of permanent residents within the communities;
2. As expected, the numbers of permanent and temporary residents within each tsunami zone increase as the magnitude of the earthquake and tsunami scenarios increases (i.e., from M1 to XXL1, **Table 3-1**);
3. The communities of Rockaway Beach, Lincoln City, and Newport can experience very large (~620–700% increase in the XXL1 tsunami zone) influxes of visitors, well exceeding their resident populations (**Table 3-1**). We identified a somewhat smaller influx of visitors for Port Orford (~230% increase); and,
4. The total permanent resident population (all communities) present on the Oregon coast <u>within a tsunami zone</u> ranges from ~22,380 (M1) to ~56,500 (XXL1); these numbers exclude the temporary (visitor) population. Resident populations defined in this study for the L1 tsunami zone (32,630, **Table 3-1**), are comparable to numbers reported by Wood and others (2015), which gives us confidence in our overall approach.

Table 3-1. Permanent and temporary resident demographics per tsunami inundation zone.

	Permanent Residents Tsunami Inundation Zone			Temporary Residents[1] Tsunami Inundation Zone			Percent (%) Increase[2] Tsunami Inundation Zone		
Community	**M1**	**L1**	**XXL1**	**M1**	**L1**	**XXL1**	**M1**	**L1**	**XXL1**
Gearhart	725	1,454	1,495	1,672	5,251	5,459	331	461	465
Rockaway Beach	910	1,200	1,440	6,399	7,202	7,592	803	700	627
Lincoln City	972	1,275	2,154	4,582	6,920	11,844	571	643	650
Newport	460	624	1,161	3,287	4,423	7,171	815	809	718
Port Orford	29	290	896	74	310	1,181	355	207	232
Total of five communities	3,096	4,843	7,146	16,014	24,106	33,247			
Entire Oregon Coast	22,379	32,630	56,506	—	—	—			
Wood and others (2015)[3]		*33,244*							

Notes: Tsunami inundation zones (M1 = Medium; L1 = Large; XXL1 = Extra Extra Large) defined from Priest and others (2013e). "—" = no data.

[1] Temporary population estimate assumes a summer 2 AM weekend scenario.

[2] The calculated percent increase in community populations due to the addition of visitors.

[3] Resident population derived from data provided by Wood and others (2015).

Table 3-2 and **Figure 3-1** evaluate the resident population by differentiating the population by age group (<65 and ≥65 years of age). These results have an important bearing on the speed at which people may be able to travel to reach safety; recall that evacuation speed for those ≥65 is reduced by a 0.8 walking speed reduction factor (see **Section 2.6.2.4**). Thus, communities with larger numbers of people ≥65 years of age ought to evaluate where these people are situated with a focus toward developing community evacuation response plans specific to their needs (e.g., prioritizing mitigation such as constructing a vertical evacuation structure in one part of town over another because more elderly live in that area). As can be seen from **Table 3-2,** the coast-wide population ≥65 makes up ~25% of the total population in the M1 tsunami zone and increases slightly to ~27% for the XXL1 tsunami zone. However, as is evident from the five communities examined here, the actual number of people age ≥65 can vary significantly from one community to another (**Figure 3-1**). For example, **Table 3-2** indicates that Newport and Port Orford have a generally larger number of people ≥65 in the various tsunami inundation zones.

Table 3-2. Permanent resident age demographics per tsunami inundation zone.

	Tsunami Inundation Zone								
	M1			L1			XXL1		
Community	< 65[1]	≥ 65[1]	Older Age Ratio[2]	< 65[1]	≥ 65[1]	Older Age Ratio[2]	< 65[1]	≥ 65[1]	Older Age Ratio[2]
Gearhart	553	172	24%	1,048	406	28%	1,064	431	29%
Rockaway Beach	605	304	33%	779	420	35%	938	502	35%
Lincoln City	686	286	29%	892	383	30%	1,510	644	30%
Newport	235	225	49%	337	287	46%	679	482	42%
Port Orford	15	14	48%	164	126	43%	562	333	37%
Oregon Coast	16,774	5,605	25%	24,133	8,496	26%	41,509	14,997	27%

Note: Tsunami inundation zones (M1 = Medium; L1 = Large; XXL1 = Extra Extra Large) defined from Priest and others (2013e).

[1]defines the age in years.

[2]denotes number of people ≥65 divided by the total community population.

Figure 3-1. (*left*) Permanent resident (solid blue area) and temporary (visitor, gray area) populations by community for the XXL1 tsunami inundation zone. The total population (inside and outside the tsunami zone) in each community is defined by the black square; (*right*) population demographics for each community.

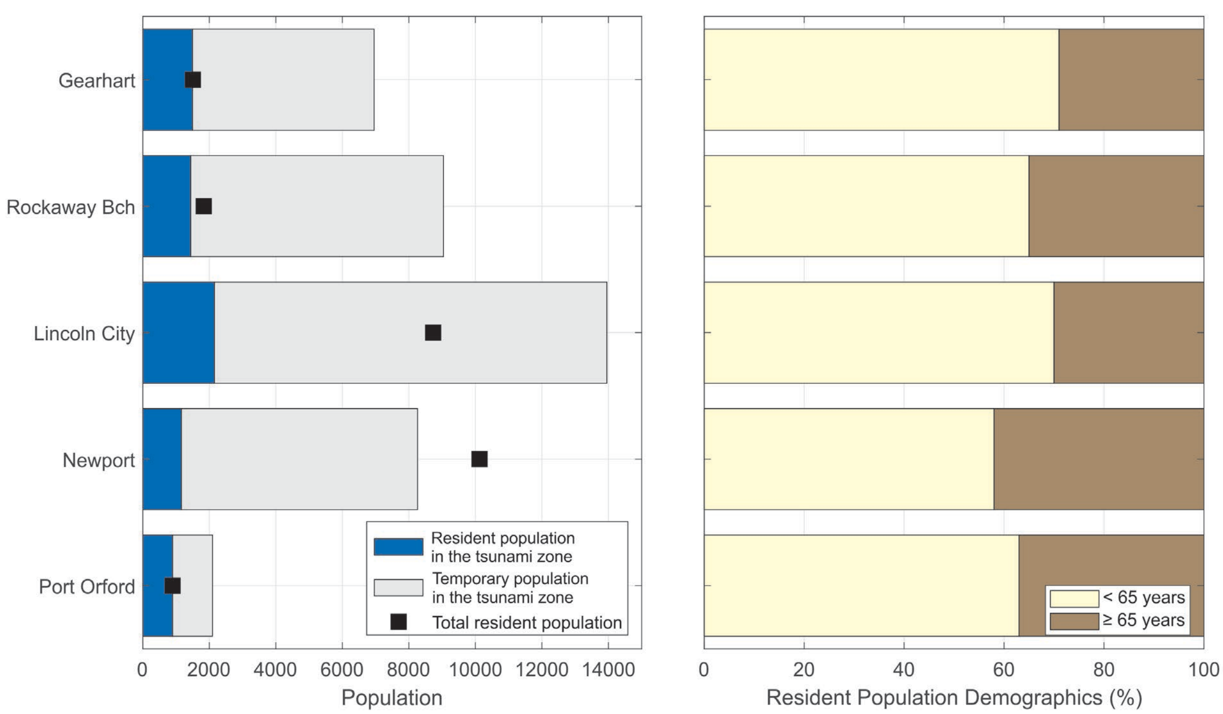


Table 3-3 defines the number of residents (permanent and temporary) per building occupancy type per community. As with the data presented in **Table 3-1**, the building occupancy type is summarized graphically in **Figure 3-2**. Apparent from both the table and figure are the differences among the communities. These differences reflect such characteristics as the dominance of single-family dwellings in Gearhart compared with fewer such homes in the tsunami zone in Newport. Such differences are probably largely controlled by topography — Newport has more high ground than Gearhart. Conversely, both Newport and Lincoln City have more people in multi-family residential buildings. With respect to temporary residents, hotel/motel availability in Newport and Lincoln City also stands out relative to other communities. Conversely, although communities such as Rockaway Beach have a large number of motel/hotel rooms, the majority of people staying in this community are likely to occupy single-family residential rental units (e.g., VRBOs), of which there are many more available.

Basic statistics on single-family residential buildings, the dominant housing type present on the Oregon coast, is further explored in **Table 3-4**. These data are especially important for use in pre- and post-disaster tsunami planning. Results from **Table 3-4** reveal two interesting patterns for residential usage on the coast:

1. The percentage of single-family homes that are permanently occupied in the tsunami zone range from a low of 27% in Rockaway Beach, compared with a high of 64% at Port Orford; and,
2. The results highlight the dramatic increase in the number of temporary and permanent residents staying in single-family residential homes during a summer weekend compared with a winter mid-week (final two columns, **Table 3-4**). This effectively demonstrates the prevalence of a low population in winter compared with a summer population, when population numbers on the Oregon coast are maximized. Of note is the substantial increase in the number of people in single-family homes at Lincoln City (0.78 [winter] to 5.1 [summer]) and Rockaway Beach (0.5 [winter] to 4.3 [summer]), emphasizing the fact that both these communities are major recreational population destinations.

With these data in mind, the question that follows is what happens to these types of buildings (and others) as a result of the earthquake ground motion and the subsequent tsunami. These data are presented in **Table 3-5**, which provides insights into the likely damage to buildings in the tsunami zone. As can be seen from the table, damage from the earthquake shaking (in the tsunami zone) accounts for about one quarter of the building damage. However, the tsunami results in destruction levels that start at ~68% (Lincoln City) and reach 98% in Gearhart for an XXL1 event; combined losses from the earthquake and tsunami range from 78% destruction in Lincoln City to complete destruction in Gearhart. These data reflect the large hydraulic forces associated with the tsunami and the prevalence of light-frame construction material (i.e., wood frame) on the Oregon coast. **Table 3-5** indicates that the total replacement cost for these buildings (excluding building content and other assets) would likely exceed $2.5 billion for the five communities alone. The weight of debris generated is estimated at ~776,000 tons (**Table 3-5**, equivalent to ~ 78,000 dump trucks). This estimate is almost certainly on the low end, as it does not include debris associated with content from buildings (personal items, business equipment etc.), road rip-ups, vehicles, and vegetation.

Our Hazus analyses indicate that injuries from the earthquake greatly outnumber fatalities (**Table 3-6**). This is in stark contrast with conditions associated with a tsunami, where fatalities greatly exceed injuries; injuries associated with a local XXL1 tsunami are calculated at ~1% to 9% of the population, while tsunami deaths account for 90% to 99% of the population. The number of tsunami injuries and fatalities varies widely by community (**Table 3-6**, **Figure 3-3**). This is due to many factors, but most important is the relative distance to high ground. Fatalities for the maximum considered XXL1 tsunami scenario were found to range from a low of ~750 people in Newport to a high of ~6,600 in Gearhart, while the combined total number of fatalities in all five communities is estimated at ~13,000 people. The large number of fatalities in Gearhart alone is entirely due to the significant travel distances required in order to reach high ground in the eastern foothills. It is for this reason that the community of Gearhart designated several areas of "optional" high ground nearer to downtown Gearhart that are deemed safe under the L1 tsunami scenario and could be used by locals instead of trying to evacuate to the east. As a reminder, the L1 scenario encompasses 95% of the expected inundation modeled by DOGAMI tsunami inundation scenarios. For this reason, we include fatality estimates for the L1 tsunami inundation scenario for Gearhart in the notes of **Table 3-6**. As seen in the table notes, the L1 results indicate that fatalities in Gearhart would drop by 70% to 1,980 if the tsunami were closer to an L1 tsunami event.

Given that these casualty estimates are for just the five communities examined here, total deaths caused by an XXL CSZ tsunami for the 38 communities on the Oregon coast could well exceed OSSPAC's original estimate of ~5,000 people (OSSPAC, 2013). For context, tsunami casualties provided by OSSPAC (2013) are based on an M1 (medium) tsunami earthquake scenario, which covers ~79% of the DOGAMI tsunami inundation scenarios.

Figure 3-3 presents a graphical summary of the estimated fatalities and displaced population for an XXL1 tsunami event for the five communities. Fatalities and displaced population estimates are presented for the permanent resident population (black) and the temporary visitor population assuming 10%, 50%, and 100% visitor occupancy levels. Because the permanent resident population is easiest to define in our population model, we argue that this likely reflects a low-end estimate of fatality numbers associated with the XXL1 scenario. This is shown in **Figure 3-3** by the left edge of the gray shaded region. Conversely, the resident plus visitor population (assuming 100% occupancy), is characterized by the right edge of the gray shaded region. Accordingly, the area in between reflects the uncertainty associated with the visitor population that could be present in the tsunami zone within each of the communities. Accordingly, one could speculate on the visitor occupancy by developing scenarios that could vary from 10% (e.g., winter, dark blue shading) or 50% (an average, cyan shading) to better define the potential number of fatalities and displaced people. Refining such estimates, guided by local input, would help clarify a range of possible scenarios leading to more informed estimates. The larger fatalities determined for Gearhart and Rockaway Beach (**Figure 3-3**, *left*) are indicative of the fact that in both these communities, high ground, and hence safety from the tsunami, is some distance away. Conversely, the much lower casualty numbers in Lincoln City and Newport are due to the fact that high ground is close by, enabling more people to escape. Regardless of differences in local geography, it is evident from **Figure 3-3** that the number of fatalities associated with an XXL1 size event has the potential to be large when scaled up for the rest of the Oregon coast.

For the displaced population (**Figure 3-3**, *right*), we can make similar assumptions about the local population groups. Apparent from the figure is the extremely large number of displaced visitors that each community could potentially have to deal with. This is most apparent for Lincoln City, Newport, and Rockaway Beach, each of which might potentially have to deal with several thousand people, many of whom would be nonresidents. These numbers are directly a function of the fact that these communities are major tourist destinations with large numbers of motel/hotels and vacation homes located in the tsunami zone. However, as noted previously, because high ground is close by, fatalities are generally low. Conversely, the low number of displaced people in Gearhart and Port Orford is indicative of the fact that so many people in these two communities could be killed by an XXL1 tsunami. As noted above, fatality estimates for the L1 tsunami inundation scenario at Gearhart is 70% less, while at Port Orford it is 75% less, highlighting the large differences between the effects of an XXL1 size event versus an L1 tsunami.

Table 3-3. Number of residents per building occupancy type per community in the XXL1 tsunami zone.

	Permanent Residents — Housing Type							Temporary Residents — Housing Type						
Community	Single-Family Residential	Manuf. Housing	Multi-family Residential	Hotel/ Motel	Mobile[1]	Other[2]	Total	Single-Family Residential	Manuf. Housing	Multi-family Residential	Hotel/ Motel	Mobile[1]	Other[2]	Total
Gearhart	1,335	18	82	10	0	50	1,495	4,624	10	653	124	48	0	5,459
Rockaway Beach	858	404	109	34	0	35	1,440	6,040	428	690	393	42	0	7,592
Lincoln City	1,375	215	418	54	19	74	2,154	7,719	94	858	2,732	441	0	11,844
Newport	443	85	343	32	101	158	1,160	1,845	38	1,080	1,921	2,097	250	7,231
Port Orford	560	151	73	7	91	13	895	862	38	82	69	20	110	1,181

Notes: [1]*Mobile* includes tents, boats, and recreational vehicles. [2]*Other* includes mixed use buildings where primary building usage is other than residential. Building counts are limited to those in the community's urban growth boundary. Temporary population estimate assumes a summer 2 AM weekend scenario.

Table 3-4. Number of single-family residential buildings and occupancy in the XXL1 tsunami zone by community.

Community	Total Number of Single-Family Residential Homes	Number of Permanently Occupied Single-Family Residential Homes	Number of Permanent Residents	Number of Temporary Residents	Percent of Single-Family Residential Homes Permanently Occupied	Number of Residents per Permanently Occupied Home	Number of People per Single-Family Residential Building: Mid-Winter, Mid-Week	Number of People per Single-Family Residential Building: Mid-Summer, Weekend
Gearhart	1,312	573	1,335	4,624	44%	2.33	1.02	4.54
Rockaway Beach	1,599	424	858	6,040	27%	2.02	0.54	4.31
Lincoln City	1,773	633	1,375	7,719	36%	2.17	0.78	5.13
Newport	515	230	443	1,845	45%	1.93	0.86	4.44
Port Orford	446	286	560	862	64%	1.96	1.26	3.19

Notes: Limited to buildings in the community's urban growth boundary. Temporary population estimate assumes a summer 2 AM weekend scenario.

Table 3-5. Building damage estimates for a CSZ earthquake and XXL1 tsunami zone by community.

Community	Total Number of Buildings	Total Building Square Footage (thousand)	Total Building Replacement Cost ($ Million)	Damaged Buildings (tons)	Loss Ratio[1]		
					Earthquake	Tsunami	Combined[2]
Gearhart	1,627	3,759	$471	161,000	26%	98%	100%
Rockaway Beach	2,361	4,460	$529	190,000	28%	93%	97%
Lincoln City	2,312	5,007	$689	169,000	21%	68%	78%
Newport	1,071	4,268	$638	195,000	36%	77%	87%
Port Orford	833	1,547	$183	61,000	25%	95%	96%
Total	***8,204***	***19,091***	***$2,510***	***776,000***			

Notes:

[1]Loss ratio is defined as the buildings' repair cost divided by the buildings' replacement cost.

[2]Hazus method for combining earthquake and tsunami loss ratios into an overall loss ratio are described in Section 5.7 in FEMA (2017a).

Table 3-6. Estimated injury and fatalities associated with a CSZ (M_w = 9.0) earthquake and XXL1 tsunami, based on a 2 AM summer weekend scenario by community. Population/injury/fatality numbers are limited to occupants within the community's urban growth boundary. Earthquake injury estimates combine Level 1–3 estimates (Table 2-3), while fatality estimates are Level 4. Tsunami injury and fatality estimates assume a departure time of 10 minutes after earthquake commencement.

Community	Total Population in UGB Tsunami Zone	Earthquake		Tsunami		
		Injuries	Fatalities	Injuries	Fatalities	Injury Ratio[¥]
Gearhart[1]	6,954	88	4	90	6,620	1%
Rockaway Beach	9,032	121	3	200	3,090	6%
Lincoln City	13,998	141	5	110	1,170	9%
Newport	8,332	93	4	50	750	7%
Port Orford[2]	2,077	26	2	15	1,230	1%
Total	***40,393***	***469***	***18***	***465***	***12,860***	***4%***

Notes:

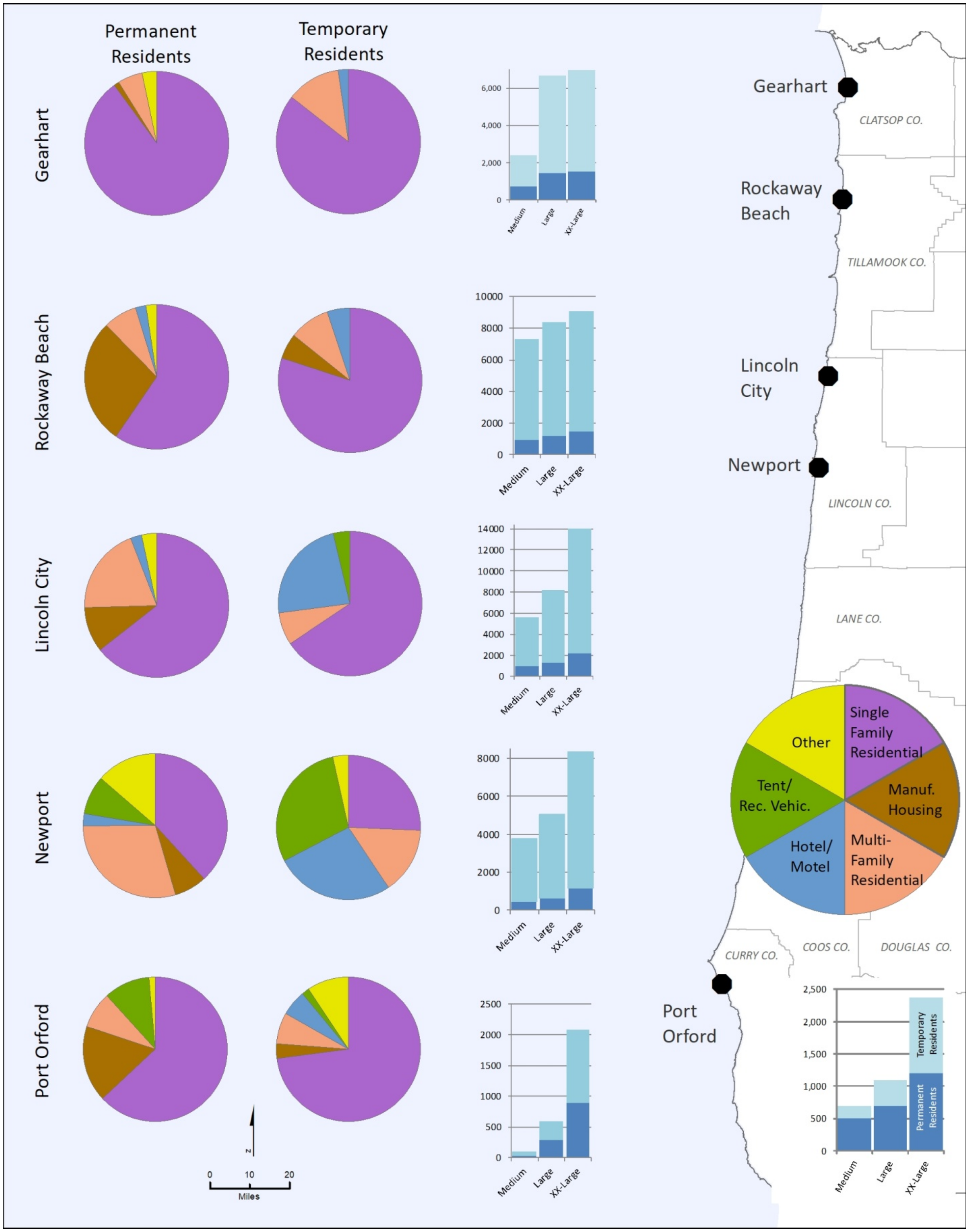
[¥] Tsunami Injury ratio is the number of tsunami injuries divided by total number of tsunami casualties (injuries plus fatalities). Tsunami injury and fatality estimates are rounded to the nearest ten.

"L1" tsunami inundation scenario casualties reflect the following estimates:

[1] Gearhart injuries = 30; fatalities = 170.

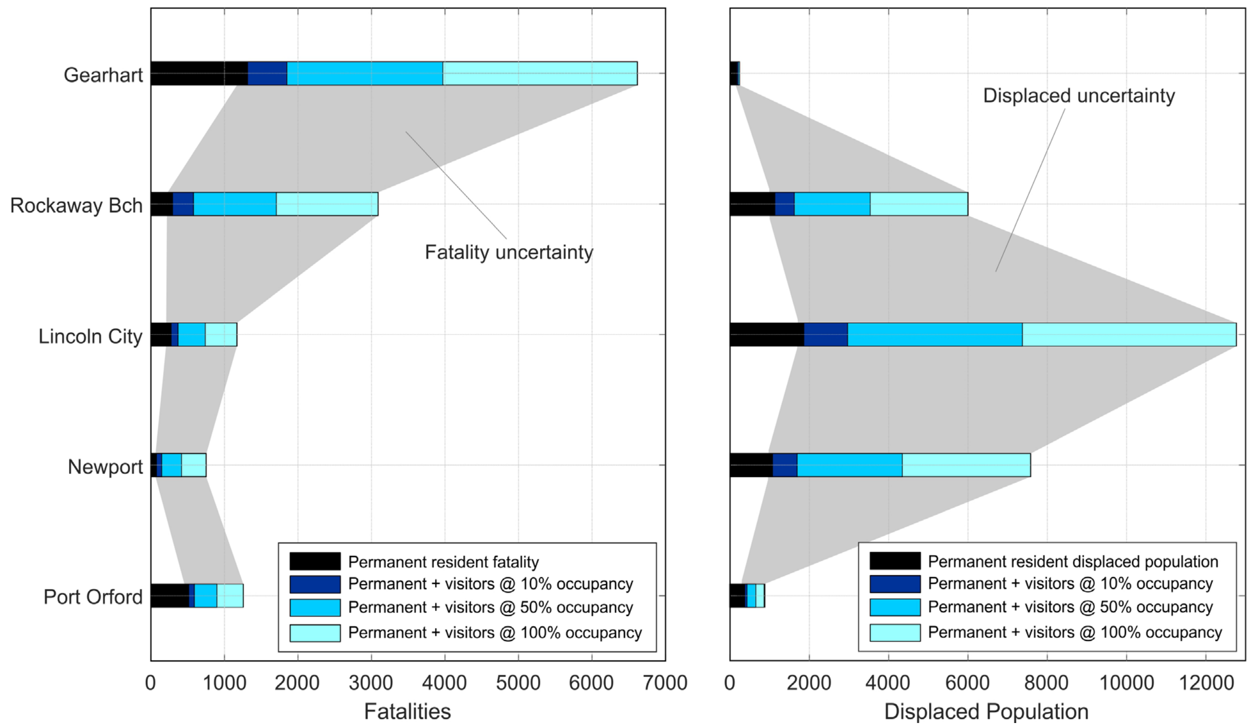
[2] Port Orford injuries = 20; fatalities = 310.

Figure 3-2. Community overview showing building occupancy type (pie charts) for permanent and temporary residents in the XXL1 tsunami zone, and estimates of permanent and temporary residents within the Medium (M), Large (L), and Extra Extra Large (XXL) tsunami zone (bar charts).



Notes: Tsunami inundation zones (M1 = Medium; L1 = Large; XXL1 = Extra Extra Large) defined from Priest and others (2013e); Bar chart y axis exhibits number of people for summer 2AM weekend scenario: permanent residents (dark blue) and temporary population (light blue).

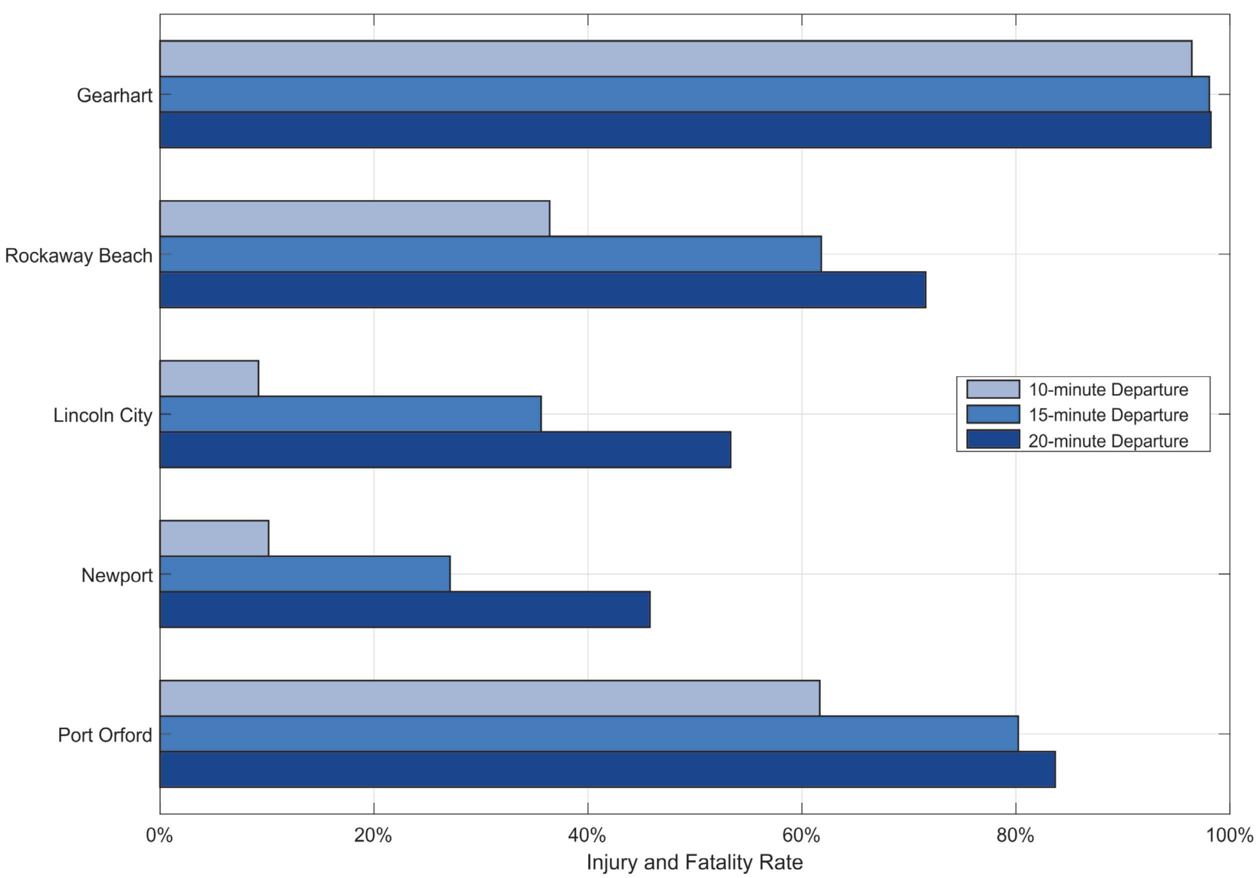
Figure 3-3. (*left*) Estimated fatality numbers by community for an XXL1 tsunami event assuming various visitor occupancy levels; (*right*) Estimates of the displaced population in each community assuming various occupancy levels.



Our analyses confirm two additional concepts that will save lives. **Figure 3-4** demonstrates that the longer people take before leaving for high ground (i.e., milling), the greater the casualty rate. Our Hazus modeling takes a somewhat conservative approach by assuming that it will take people ~10 minutes to evacuate a building and get underway (this includes the 3–5 minutes of expected earthquake shaking). The faster individuals are able to exit a building, the lower the fatality rates. Similarly, the faster people travel toward high ground, the lower the fatality estimates (**Figure 3-5**). Thus, our results support a key message to coastal communities that ***injury and fatality rates can be significantly reduced if people evacuate as soon as possible and travel on foot as fast as possible to safety***.

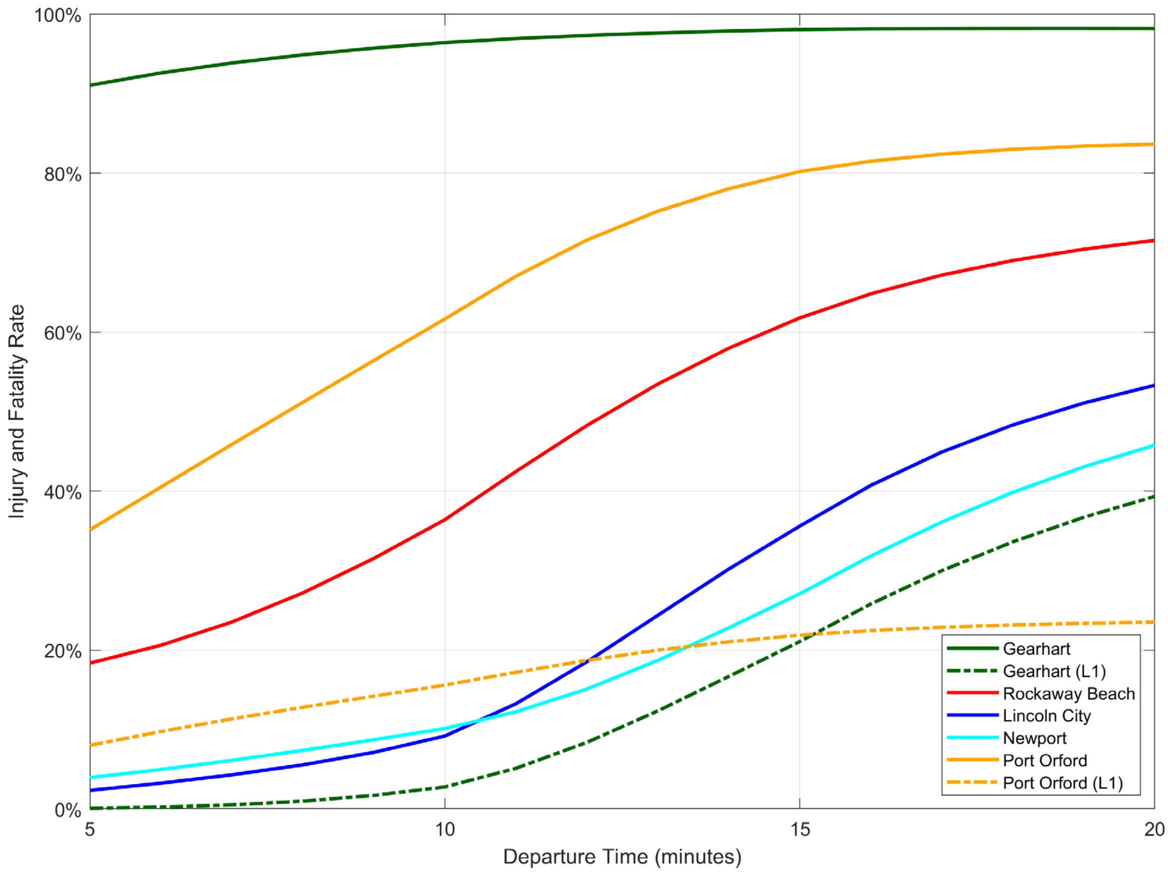
Finally, we include results for the Gearhart and Port Orford L1 scenarios in **Figure 3-5** to demonstrate the difference in the casualty rate between the L1 and XXL1 scenarios. We include these results because Gearhart includes optional areas of high ground for an L1 event in its evacuation maps, while wave arrival times for Port Orford occur very quickly after the start of earthquake shaking, leaving little time to respond. As can be seen from **Figure 3-5**, the contrast in the casualty rates between XXL1 and L1 is dramatic.

Figure 3-4. Projected tsunami injury and fatality rates by community as a function of departure time for a summer weekend 2 AM scenario, assuming an XXL1 tsunami event.



Note: The rate is the number of tsunami injuries and fatalities divided by the total population in the tsunami zone at the time of the earthquake.

Figure 3-5. Tsunami injury and fatality rate by community as a function of group departure time and walking speed (4 fps) for a summer weekend 2 AM scenario, assuming an XXL1 tsunami event. Results for an L1 tsunami event striking Gearhart and Port Orford are included (green dash and orange dash lines respectively).



Note: The rate is the number of injuries and fatalities divided by the total population in the tsunami zone at the time of the earthquake.

4.0 DISCUSSION

This is the first study in Oregon that implemented the 2017 FEMA Hazus methods for estimating building loss and casualties from a catastrophic earthquake and tsunami, caused by a rupture along the Cascadia subduction zone. The approach used the best available information on the CSZ earthquake (M_w 9.0, Madin and Burns, 2013) and resultant XXL1 tsunami (Priest and others, 2013e), together with a detailed building database, and an up-to-date population model that accounts for both permanent and temporary residents (2 AM occupancy). While previous studies evaluated statewide casualty estimates for permanent residents (OSSPAC, 2013), our study significantly expands on earlier work by evaluating in more detail five coastal community populations. The present study extends the population model to include significant new information that accounts for temporary population influxes, types of housing that permanent and temporary residents occupy and where, and the number of businesses and jobs, and wages paid in the community's tsunami zone. Such information is critically important because communities on the Oregon coast presently do not have adequate information on the likely socioeconomic effects of a CSZ earthquake and accompanying tsunami. Accordingly, it is hoped that the information presented in this report may be used to assist with community pre- and post-disaster planning, including addressing such needs as the development of tsunami evacuation wayfinding signage plans, mass-care planning, debris removal plans, and individual community tsunami evacuation facilities improvement plans, as described in the DLCD (2015) tsunami land use guide.

Building damage and debris: Our analyses reveal that the earthquake alone accounts for building losses in the XXL1 tsunami inundation zone that range from 21% to 36% (**Table 3-5**). These variations reflect differences in the type and age of building construction among the communities, as well as the number of buildings situated on liquefiable soils. Earthquake-induced damage to buildings will also occur outside of the XXL1 tsunami inundation zone. However, damage outside the tsunami zone were not quantified as part of this study; hence the numbers provided in **Table 3-5** are at the low end of likely building damage within the communities.

Damage to buildings from the tsunami is catastrophic — combined earthquake/tsunami destruction ranges from ~78% to 100% loss (**Table 3-5**), due to the prevalence of light-frame construction, primarily wood-frame building construction, which is very vulnerable to tsunami damage. Building debris generated from the destruction of these of buildings will be scattered throughout the tsunami zone. Planners should consider that buoyant debris within the tsunami zone will be redistributed and may accumulate around low points, which often include key transportation routes (Park and Cox, 2019). Our analyses indicate that the generated debris from building damage alone (excluding content and other asset types) is estimated to vary widely from ~61,000 tons in Port Orford to ~195,000 tons in Newport (**Table 3-5**). These estimates are almost certainly on the low end, because they presently do not account for all debris types in the inundation zone. Nonetheless, the weights listed provide a starting point for communities as they begin the process of developing earthquake/tsunami debris plans.

Injuries and fatalities: Our analyses indicate that the permanent resident population present on the entire Oregon coast within a tsunami zone varies from ~22,380 (M1) and ~32,630 (L1) to ~56,500 (XXL1). Adding the temporary (visitor) population will increase these numbers substantially. Our Hazus analyses presented in **Table 3-1** suggest that the temporary visitor population could potentially reflect an additional 33,000 people in the XXL1 tsunami zone for the five communities studied, compared with a permanent population of 7,100 people. While reinforcing the importance of these communities as major recreational coastal destinations, the results also highlight the tremendous burden that each community could potentially face following a CSZ earthquake and tsunami to address the needs of both the permanent and temporary populations. However, this assumes that every lodging facility is fully booked and in use at the time of the event. Regardless, the point remains that there is a high probability that a significantly large number of displaced temporary visitors will need emergency care and support following a Cascadia event, in addition to the displaced permanent residents. Further refinements to these numbers are therefore critical for communities to develop short-term mass-care plans, and for state and federal agencies to develop their long-term plans.

Our Hazus casualty estimates of the number of people killed in the XXL1 tsunami inundation zone for the five communities examined here as well as from the earthquake could reach ~13,000 people, surpassing estimates provided in the Oregon Resilience Plan, which ranged from 600 to ~5,000 fatalities for the entire coast (OSSPAC, 2013); note that the results from OSSPAC were based on an M1 event that accounts for 79% of the expected inundation scenarios. As a result of these statistics and given our focus on just five communities, it is apparent that coast-wide tsunami fatality estimates for an XXL1 tsunami could be substantial, potentially even approaching or exceeding levels observed in the 2011 Tōhoku, Japan event. To assist the public, considerable hazard related information have been developed over the past decade to enable coastal communities and visitors make informed decisions, including evacuation maps for every coastal community that are available online (e.g., http://nvs.nanoos.org/TsunamiEvac). Recent evacuation modeling has helped clarify where people need to evacuate to and how fast they need to travel to reach safety. These efforts demonstrate the simple fact that ***for every community, the injury and fatality rate can be substantially reduced if people practice their evacuation routes, evacuate as soon as possible, and travel as fast as possible (e.g., a fast walk, jog, or run) to safety*** (**Figure 3-4** and **Figure 3-5**). Building a culture of tsunami awareness on the Oregon coast that reduces the potential injury and fatality rate can be accomplished through concerted education/outreach campaigns, developing school curricula on tsunami hazards, improving signage, and implementing frequent evacuation drills reminding people of where they need to go. In terms of the latter, Oregon Emergency Management developed a guidance document for how to organize and hold a tsunami evacuation drill (OEM, 2017), providing a valuable starting point for coastal communities intending on pursuing this option.

We quantified impacts to both temporary and permanent populations in our injury and fatality estimates for two reasons: 1) planners can apply their own judgment to their community's population at off-peak times, such as assuming that wintertime temporary population is 10%–50% of peak summertime (e.g., **Figure 3-3**); and 2) tsunami preparation and education awareness levels of permanent residents versus temporary populations are likely to differ. For example, temporary populations generally have little to no knowledge of the hazard, evacuation procedures, optimal routes to safety, and are more likely to engage in counterproductive milling behaviors that will lead to greater risk of death. In contrast, we hypothesize that permanent residents will generally be better prepared (are generally aware of the hazard and their evacuation routes) and are less likely to mill following an earthquake. Again, planners can apply their own judgment on the level of preparedness, including departure times and evacuation speeds, between the groups, to better refine the estimates of injuries and fatalities that may occur in their community (e.g., Appendix A: **Table RB-5**).

Depending on the community, ***the temporary population on average may be closer to the ocean, and thus farther away from safety, compared with the permanent resident population***. Market forces often drive such housing arrangements (Raskin and Wang, 2017). This is the case in Rockaway Beach and Newport, where hotels, motels, and rental homes are located closest to the beach. This sets up a problematic situation where a presumed less-informed group is farther away from safety and may take longer to depart, with resultant higher proportion of fatalities compared to the permanent residents (see Appendix A: **Figure NP-9** and **Figure RB-11**).

However, even with permanent residents, our assumptions of individuals' preparation and awareness may not match actual preparedness, including the assumption of a 10-minute departure time after the earthquake begins. Grumbly and others (2019) noted that permanent residents in a Washington coastal town underestimated the distance to tsunami safety and were often not aware of the optimal route to safety at different locations in their community. The City of Seaside survey data gathered by Buylova (2018) pointed to a pressing need for continued education on the tsunami threat. That study targeted primary and secondary homeowners but did not sample vacationers. Regarding the initiation of evacuation, 29.6% of survey respondents indicated that they would likely wait for confirmation of a tsunami prior to evacuation. However, about half the population indicated they were unlikely or very unlikely to wait for tsunami confirmation (24.3% and 22.8%, respectively). Many of the respondents (78 out of 207, or 38%) indicated they would attempt to evacuate by driving, which would be problematic given Seaside's constrained road evacuation network. Oregon state and county emergency management officials strongly discourage vehicular travel following an earthquake and instead emphasize travel on foot. The top three behaviors respondents said they would very likely assume after a major earthquake is evacuating to higher ground immediately following the earthquake (51%), contacting loved ones (49.5%), and checking social media and television (40.3%).

The underlying field survey data used in Buylova's (2018) study provided further insights into the education challenges. We obtained raw responses for selected survey questions (A. Buylova, written communication, November 2018). Among the 209 respondents, 17% did not correctly identify their home as being in or out of the tsunami zone. Most of those who responded incorrectly (16%) identified their house as outside the tsunami zone, although their house was actually inside the tsunami zone. Only a small portion of the residents identified themselves as secondary homeowners (5% respondents), and no significant difference was observed in perceptions or in plans between the two groups. Continued tsunami education and outreach are critically important for local residents as well as visitors in order to build the necessary culture of awareness needed to survive such a disaster; education and outreach can be achieved through awareness programs at local, state, and federal levels.

Our study was not directly comparable to the injury and fatality estimates of Wood and others (2015), primarily due to that study's usage of the L1 scenario defined by DOGAMI (Priest and others, 2013e) and a 15-minute wave arrival time assumption for all communities. Furthermore, Wood and others did not quantify the earthquake effect. Nevertheless, the overall observations and conclusions identified in our study are consistent with those of Wood and others, reinforcing the grave threat a CSZ event presents to Oregon's coastal communities and state economy.

Finally, given that the focus of this study is on just five communities and the greatest uncertainty in our modeling is quantification of the temporary population, it is essential that similar types of investigations be undertaken for other coastal communities to better define the probable consequences of a CSZ earthquake and tsunami.

Displaced population: Given the near-complete destruction of buildings within the tsunami zone (**Table 3-5**), planners should assume that all people who were in the area impacted by the tsunami and who successfully evacuated will need short-term (days to weeks) and perhaps even longer-term shelter needs (weeks to months for permanent residents who previously resided in the tsunami zone). The large influx of temporary visitors in the summertime will increase demands on mass care facilities, placing even greater strain on local, state, and federal emergency managers.

5.0 RECOMMENDATIONS

This study has been part of a broader investigation to complete new tsunami evacuation modeling in five high-risk coastal communities, Gearhart (Clatsop County), Rockaway Beach (Tillamook County), Lincoln City and Newport (Lincoln County), and Port Orford (Curry County), coupled with a pilot Hazus investigation to extrapolate estimates of casualties, damage potential, and debris weights. The overarching goal of this work is to assist communities in their overall hazard preparation by identifying some of the expected challenges that will occur when the next great earthquake occurs on the CSZ and tsunami is triggered.

Tsunami evacuation modeling results have been described in several technical reports (Gabel and Allan, 2017; Gabel and others, 2019a,b; unpublished, 2020). The purpose of this report was to evaluate the socioeconomic effects of both a great (M_w 9.0) earthquake and accompanying maximum considered XXL1 tsunami for each of the five communities, in order to document potential building losses, debris weight, fatalities and injuries, and estimated numbers of the displaced populations. Summary statistics of our main findings are discussed in Sections 3 and 4, Detailed community profiles are presented in the Appendix A. These profiles include evaluations of vulnerable population groups, essential facilities, and critical infrastructure integral to response and recovery. Each community profile contains tailored recommendations focused on education, mitigation, response, and recovery as well as recommendations common to all communities (discussed more broadly in Sections 3 and 4).

Great care has been taken as part of this study to address the needs of local communities. Discussions with local community planner helped frame the overall study approach and assumptions applied in our Hazus modeling. Nevertheless, planners, emergency responders, and community leaders should keep in mind the scope of this study and limitations of our modeling approach. Of note, we provide estimates for the existing (as-built) environment, which account for a few key mitigation options such as bridge seismic upgrades and trail hardening. While we did not evaluate building relocation scenarios or future development and population growth scenarios, the building damage and casualty estimates for the existing conditions may still be used as a guide for future development outside of the tsunami zone, or in areas closest to high ground.

Finally, it is recommended that this pilot study be expanded to include the rest of the Oregon coast. Presently, similar Hazus analyses are underway in the coastal communities of Clatsop and Tillamook counties. This latest effort is funded by the National Weather Service of NOAA via the National Tsunami Hazard Mitigation Program. This effort will more broadly quantify the effects of a great earthquake and accompanying tsunami by expanding on the efforts begun here.

Education

Our analyses have improved estimates of fatalities and identified the presence of potentially very large temporary visitor populations, variations in the spatial concentration of temporary versus permanent population groups within each community, and potential challenges facing those with physical or mental disabilities. Addressing these factors will be an important part of education and outreach at both the local and state level.

Our community-based information on the types of lodging visitors may occupy (e.g., motel, vacation rental, second home, or tent) and where these lodgings are predominantly located provide insights about the potential challenges that may face a community. Such information may help local communities better target their tsunami education/outreach activities and messaging to address the lack of hazard awareness by visitors, while also meeting the unique needs of the residential community. For example, ~85% people visiting Gearhart are likely to end up in single-family vacation or second homes that are farther from high ground. This contrasts with places like Newport and to a lesser extent Lincoln City, where a significant number of the temporary population (respectively, 27% and 23%) are much more likely to stay in hotel/motels that are for the most part located closer to high ground (e.g., **Figure NP-3** or **Figure LC-3**). These data further contrast with the challenge facing campsite occupants at South Beach State Park (SBSP) in south Newport, who must travel significant distances along numerous trails in order to find high ground outside the tsunami zone. According to Gabel and others (2019a), there are three key evacuation routes people should take depending on their location in SBSP at the time of the earthquake. Articulating these differences is key and can be accomplished through site-specific evacuation maps (such as "You are Here" tsunami signage) and evacuation arrows guiding people along trails toward safety. Recently, the Oregon Parks and Recreation Department with the assistance of DOGAMI initiated efforts to improve signage throughout the park, with improved signage installed along several trails. This effort is ongoing.

Similarly, at Rockaway Beach virtually every hotel/motel and large numbers of VRBO type rental property are located in the tsunami zone. High ground may be some distance away. Thus, tsunami education and outreach targeting each of these lodging groups becomes essential in order to mitigate against the potentially large loss of life likely to occur without such measures.

Two key approaches are presently in place to begin to address such needs. The first is the development by Oregon Emergency Management of the "Tsunami Safe" program (*Hospitality begins with Safety*). This effort focuses on increasing tsunami awareness among hospitality industry employees, including providing key tsunami and safety instructions that may be disseminated to hotel/motel guests. Trained hospitality staff can provide accurate messaging to the public before and during an event and, importantly, are able to help guide people out of the inundation zone. Evacuation guidance presupposes that hospitality staff at every establishment know exactly where their nearest point of high ground is located. To address this need, DOGAMI staff in partnership with the Northwest Association of Networked Ocean Observing System (NANOOS) developed a "print-your-own-tsunami-brochure" tool that is integrated in the NANOOS Visualization System (NVS) tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac). This tool allows any individual or business to develop their own custom evacuation brochure for any location on the Oregon coast. More recently, DOGAMI has initiated the development of higher-resolution tsunami evacuation maps[9] that can be printed with conventional printers. It is thus conceivable that hotel/motel rooms could display tsunami evacuation maps, in a manner similar to the fire escape exit maps required in every room. Increasing local awareness of these tools should thus be integrated in any future planned outreach activity.

Our analyses have repeatedly demonstrated the simple fact that the more quickly people begin their evacuation after the end of the earthquake shaking and the faster they travel, the more lives will be saved. Graphical information such as that in **Figure 3-4** and **Figure 3-5** may be refined and used as part of existing outreach campaigns to further stress the need for quick departure following an earthquake (i.e., prolonged milling results in death) and traveling as quickly as possible out of the tsunami zone. Such information when used with animations that demonstrate what happens when people delay their departure or travel too slowly and are killed, may have an impact with viewers who don't fully appreciate the urgency. The creation of professionally developed animations would demonstrate the efficacy of leaving as soon as possible, without waiting for confirmation on whether to evacuate.

The evacuation maps presented in the community profiles (e.g., **Figure GH-7**) may be further enhanced to emphasize various aspects such as showing the seasonal variations in population density or the locations of vulnerable populations by applying a heat map. We feel it will be especially effective to emphasize the locations of those who may not have adequate time to evacuate (e.g., Fraser and others, 2014, Figure 7). This group is of particular concern because, as the community profiles show, several of the communities have a significant number of people with disabilities, especially vision, cognitive, or

[9] https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro_neighborhoods.htm

ambulatory disabilities, who will need help evacuating from the tsunami zone. Knowing where people with disabilities are located relative to the tsunami zone could be further evaluated for each community and appropriate plans developed for how to help them.

Finally, building a culture of awareness is needed to survive the next CSZ tsunami. Such effort could include funds to post and maintain tsunami wayfinding signage of sufficient density along core evacuation routes and funds to establish and support tsunami coordinators in every county. Tsunami coordinators could assist with identifying locations of people with disabilities, work with the local hotel/motel industry to develop appropriate evacuation map products, and perform outreach at the grassroots level.

Mitigation

Our evacuation simulations (see community profiles in Appendix A) indicate that improving existing evacuation trails for unimpeded passage, along with increased saturation of tsunami wayfinding signage will help save lives. Of particular importance is having a sufficiently dense network of signs (either posted and/or on road/path surfaces) that direct people along core routes to areas outside the tsunami zone. Signs of this nature need to be spaced sufficiently far apart and illuminated at night so that the signage can be easily seen at all times. Consideration should also be directed at barriers that may impede rapid evacuation. For example, downed power lines could pose a significant barrier to safe evacuation if the wires remain live following the earthquake. Communities could initiate conversations with local utility districts to assess if power can be immediately shut down during a major earthquake, or alternatively over time move toward locating new power lines underground and relocating existing power lines.

We recommend and encourage local communities to practice periodic tsunami evacuation drills, ideally on at least an annual basis, to instill a culture of tsunami hazard awareness for residents and visitors. Studying an evacuation map is not the same as actually walking an evacuation route. Although we recognize that such an approach may be disruptive to the local economy and difficult to organize, holding periodic drills will save lives. Such a culture is in practice in the Japanese way of life and likely helped save many thousands of lives during the catastrophic tsunami event on March 11, 2011 (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Mitigation options to improve evacuation may also include facility improvements such as seismic retrofits of key bridges or the construction of vertical evacuation structures. Although seismically retrofitting bridges is important for evacuation in several of the communities studied here, as well as for post-disaster recovery, constructing vertical evacuation towers in targeted locations is much more likely to save lives. Communities in this report that would especially benefit from vertical evacuation structures are Gearhart, Cutler City in southern Lincoln City, Port Orford, and possibly Rockaway Beach.

In many communities, people reside in older manufactured housing. Manufactured houses installed prior to 2003 are subject to slipping off their foundations (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014), potentially blocking or compromising egress. Even if a manufactured house is relatively close to high ground, compromised egress may hinder timely evacuation. Seismic upgrades of such structures to current building standards may be cost-prohibitive. FEMA (2012, Section D) advises having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting. Such tools may provide manufactured housing occupants with a low-cost solution for rapidly exiting their structure in the critical time interval between earthquake cessation and tsunami arrival.

Response

Our analyses demonstrate that destruction of buildings in the tsunami zone will be virtually complete. Accordingly, all Oregon coastal communities will need to be prepared to shelter large numbers of people who successfully escape the tsunami. The need for shelter is likely to last many weeks until the tsunami evacuees can be relocated. This will be especially challenging for communities with potentially large numbers of temporary residents, all of whom are unlikely to be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017). As demonstrated here, depending on the time of year the number of displaced persons could range from several hundred (e.g., Port Orford, mid-winter) to thousands (e.g., up to 13,000 in Lincoln City, in a worse case summer scenario with every vacancy filled). Because of the unique characteristics of each community, these data reinforce the need to undertake similar evaluations for every Oregon coastal community.

Mass casualties will vary significantly from community to community due to exposure and access to high ground. Overall, injuries caused by the tsunami alone were found to be low, averaging about 1% to 9% of the affected community. This outcome is because the overwhelming majority of people who are unable to evacuate in time and are caught by the tsunami are killed. Combined earthquake and tsunami related injuries presented here could range from a few tens of people (e.g., Port Orford), to ~300 people (e.g., Rockaway Beach), while the total for the five communities could approach 900. Given that there are about 483 licensed beds at the 11 coastal hospitals (OSSPAC, 2013), these facilities could be easily overwhelmed, especially when estimated injuries presented here (for five communities) are scaled up for the whole coast. Furthermore, because the numbers of injured are calculated for just those in the tsunami zone, incorporating earthquake related injuries outside of the tsunami zone will almost certainly increase the overall numbers even further. Aside from increasing capacity, Wang (2018) examined approaches for coastal hospitals to better prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for fuel and water needs. In addition to these suggestions, mass care planning is necessary to prepare coastal hospitals for a potential surge in injuries following Cascadia. To that end, further work is required to better refine these casualty numbers, especially by incorporating earthquake related injuries from outside the tsunami zone. Again, these data reinforce the need to undertake similar evaluations for every Oregon coastal community.

Recovery

A CSZ earthquake and tsunami will be catastrophic to both the state and local economies. At the local level, these impacts will vary substantially. Quantifying such economic impacts is well beyond the scope of this investigation. Nevertheless, we can speculate on several likely scenarios. Overall, building destruction in the five communities examined will yield an estimated 776,000 tons of debris. This is almost certainly on the low end, as these estimates exclude the content within buildings (e.g., personal and business-related items), vehicles, and other forms of debris. The estimated building replacement cost for the five communities alone is likely to exceed $2.5 billion.

Wood-frame construction predominates in many Oregon coastal communities. The overwhelming majority of wood-frame buildings located in the tsunami zone will be destroyed by the tsunami. This means that for certain low-lying communities such as Gearhart, Rockaway Beach, and even Port Orford, there is likely to be a shortage of suitable housing in the months and perhaps years following the disaster. In the absence of housing, tsunami refugees will likely migrate away from such communities, further decimating the local economy. The housing situation will likely be compounded by the altered coastal landscape due to local subsidence effects caused by the earthquake. For example, the XXL1 earthquake deformation model indicates that the coastline could drop by an estimated 6–15 ft, with the amount of subsidence varying along the coast. Such changes will inevitably lead to accelerated rates of coastal erosion along with an increased incidence of coastal flooding in low-lying areas. These initial changes can be expected to be significant in the weeks following the event, with further change progressively decreasing over time as the coastline re-equilibrates to the new sea level regime.

Our analysis suggests the communities of Lincoln City and Newport will likely endure the effects and will probably recover over time, due to the large number of residences and many businesses located outside the tsunami inundation zone. However, both communities can expect significant disruption to their local economy, due to the probable lack of tourism over the short term and disruption to the commercial fishing industry in Newport. Recovery could be long and gradual.

Finally, our analyses indicate that many buildings in the tsunami zone are outside existing coastal or riverine FEMA flood zones. As a result, owners are not required by federally backed mortgage lenders to carry flood insurance. However, flood insurance is available to all building owners in the tsunami zone through the National Flood Insurance Program, which covers building loss due to a tsunami (FEMA, 2018c), and can aid in community recovery. More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

Vulnerable Populations

We provided population estimates from American Community Survey (ACS) data for selected population groups that may have special challenges understanding preparedness messages or evacuating (Section 2.9). The ACS estimates are for the entire community, including people outside the tsunami zone, so the total number of individuals is likely to be on the high end for each given community. Planners wanting to further understand the specific locations of vulnerable populations are encouraged to discuss the situation with their local public health preparedness coordinators. Other resources include the emPOWER database that tracks electricity-dependent Medicare populations and the Centers for Disease Control and Prevention's Behavioral Risk Factor Surveillance System (BRFSS), which tracks health-related risk behaviors, chronic health conditions, and use of preventive service by U.S. residents. Although our focus in this study was on quantifying casualties from a local tsunami, such information on vulnerable populations can also be useful when planning evacuation from distant-source tsunamis.

Our model does not account for populations living in the tsunami zone who are currently experiencing homelessness. However, homeless encampments are likely present in the tsunami zones of many Oregon coastal communities, and outreach messaging can include this population.

5.1 Areas for Further Research

Population Dynamics: Data Collection and Modeling

We consistently heard from community members on the need to better understand the quantity of visitors, on both overnight and day trips, and second-home owners. Following the recommendation of DLCD (2015), we applied the highest seasonal occupancy rates to lodging facilities. However, this addresses neither the number of visitors on day trips nor the distribution and influx of people throughout the day into and out of the tsunami zone. In some communities, many overnight visitors stay in lodging outside the tsunami zone but recreate or do business in the tsunami zone during the day. Population models based on overnight accommodations are adequate for a nighttime scenario, but do not account for the wide distribution of people throughout recreation-oriented areas such as beaches and commercial and recreational districts. Even within commercial and recreational buildings, significant variations can occur throughout the day (FEMA, 2012b, Chapter 3). The diurnal population models presented by Fraser and others (2014) focused on a working community (Napier-Hastings Urban Area, New Zealand) with a large commuting population. Such an approach could be applied here in Oregon by refining our population modeling approach. However, the Napier-Hastings Urban Area is not recreation-oriented, and their model did not include a large influx of visitors who may recreate outside. Oregon coast visitor data gathered to date have focused on economic impact, estimating overnight visitors at regional levels or total annual visits (Longwoods International, 2018; White, 2018), and are not directly usable in a tsunami casualty model. We encourage FEMA, researchers, and stakeholders to pursue population models and techniques that can help coastal communities threatened by local tsunamis better understand the potential range of daytime population scenarios.

Our South Beach State Park daytime beach population model, along with the beach and town population model discussed by Mostafizi and others (2017), can be considered a starting point for future model development and could be validated with field surveys, including drone (aerial) photography.

Our overnight temporary population model improves upon the population estimation methods of Wood and Schmidtlein (2013). We purposely applied a high per-bedroom occupancy rate, following city ordinances on vacation rentals where applicable, per community feedback. However, our people-per-bedroom assumptions for temporary occupancy in second homes and vacation rentals should be validated with non-intrusive survey data.

Public Perception of Tsunami Risk

The Oregon Parks and Recreation Department conducts visitor surveys of day use and overnight visitors of Oregon state parks, resurveying on a roughly 6-year cycle (e.g., Bergerson and Rushing, 2017; Bergerson and Mouw, 2011). We encourage OPRD in future visitor surveys to include questions on user perceptions of natural hazards, such as what they may encounter while visiting the park and what measures the visitor plans to take to prevent injury and loss of life. Survey questions could include flooding and wildfire as well as tsunamis and earthquake hazards.

Evacuation Behavior

We recommend continued research into areas that address the acknowledged shortcomings of the Hazus tsunami casualty model (discussed in Section 2.10.5), including community misperceptions on tsunami safety zones and routes to safety (Grumbly and others, 2019), fatalism (Johnson and others, 2013), and milling behavior (Buylova, 2018).

We are not aware of any studies that quantify risk perception and associated behavioral differences between temporary and permanent residents in Pacific Northwest coastal communities. Research into this topic is needed to help quantify the risk. Our report provides injury and fatality estimates for the two population groups for different departure times and allows planners to supply their own judgment in terms of the two groups' tsunami awareness levels. Given the large numbers of temporary residents who visit the Oregon coast, it is essential that work be undertaken to better understand the potential knowledge and behavioral gap between the two population groups.

Capacity Planning

Our study assumes that all tsunami safety locations can adequately accommodate all evacuees for 24 hours. We did not estimate the numbers of individuals that may gather at individual evacuation point, nor did we evaluate any potential for pedestrian or multi-model transportation congestion. Our population models in combination with our detailed evacuation networks can be used as a basis to quantify such needs. Further evaluation is needed to assist local communities in defining the expected population that could coalesce at identified evacuation destinations, or key assembly area sites. These data are essential for planning mass care response immediately following such an event. Coastal emergency managers in some communities have begun to identify "community points of distribution," or CPODs, to help with post-disaster mass care. Results presented here may be used to further refine community shelter needs as part of post-disaster mass care planning.

Debris

Our debris tonnage estimates are limited to buildings and do not estimate construction debris washed out to sea. We encourage FEMA to continue pursuing methods for such estimation, along with standardized methods for estimating damaged building content and inventory tonnage, vegetation, and other debris sources.

Future earthquake and tsunami impact studies can include estimates on transportation-specific debris, including automobiles, recreational vehicles, boats, and trucks, using the non-building debris weight estimates of FEMA (2013, Table 7.6).

Tsunami cleanup may be impeded by the presence of hazardous materials. Our study did not identify locations or types of hazardous materials. A GIS analysis such as the approach used by Wood and Good (2004) and Appleby and Bauer (2018) could be conducted for all Oregon coastal communities.

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8.0 APPENDIX A: COMMUNITY PROFILES

The community profiles are intended to provide more detailed analyses of community-specific impacts from a CSZ earthquake and tsunami that can inform preparation, recovery, and mitigation planning. Following the guidance of DLCD (2015), we include data on vulnerable population groups that may need special accommodation for evacuation. The following is a summary of methods and data limitations; more thorough descriptions of the methods are provided in the main report text in Section 2.1.

Area analyzed: Based on community feedback we summarized data when possible within the community's designated urban growth boundary (UGB) (DLCD, 2017) rather than within city limits. Planners considered the UGB as a more inclusive and useful aggregation unit. However, some data are available only at the city limits level, specifically the most current population estimates and U.S. Census Bureau American Community Survey data. We include maps of each community that highlight the UGB, city limits, building placements, and the tsunami zone, which, unless otherwise stated, refers to the XXL1 tsunami zone as defined by Priest and others (2013e).

Building loss and injury and fatality estimates: Population, building loss, debris, injury and fatality, and displaced population estimates resulting from a M_w 9.0 Cascadia Subduction Zone earthquake and XXL1 (or in some cases L1) tsunami are limited to the people and structures within the tsunami zone. Planners should keep in mind that extensive damage and numerous injuries will occur outside the tsunami zone. Further, our injury and fatality estimates are limited to a 2 AM nighttime scenario (excluding daytime visitors).

To standardize tsunami injury and fatality estimation across all communities in this study, we assume the population, as a group, evacuates at 4 feet per second (2.7 miles per hour), which is regarded as a moderate walk by Wood and Schmidtlein (2012). For each community, we provide graphical representations of the tsunami injury and fatality estimates that demonstrate the efficacy of leaving for high ground quickly, while also traveling as fast as possible. Injury and fatality estimates for the community's permanent and temporary populations are reported separately. Planners can apply their own judgment as to the tsunami awareness levels between the two population groups and how that may translate into their departure times.

For reporting purposes, we rounded the tsunami injury and casualty estimates to the nearest ten. Given the uncertainties in the Hazus tsunami casualty model (discussed in detail in Section 2.6.2), we felt that more than this suggested a precision in the model that is not warranted. For example, the model's estimates of 173 and 1,284 fatalities would be represented in our summary tables as 170 and 1,300 fatalities, respectively.

Named facilities: For this report we use the *essential facility* definition provided in 2017 Oregon Revised Statute 455.447. We define *special facilities* as facilities that are likely to contain population segments which may present additional tsunami evacuation challenges. Examples include assisted living facilities, or facilities where groups of children are placed in the care of non-family-member adults. The list was constructed from various data sources and discussions with community members but should not be considered comprehensive. Further, the inclusion of such a facility on the list should not be interpreted as any type of statement on the facility's tsunami preparedness. The *key infrastructure* list includes facilities necessary for community recovery but not covered in the essential facilities list, such as water treatment plants and electrical substations.

Employment: Employers identify their type of business using the nested 6-digit North American Industrial Classification System (NAICS) code. We report the highest employment sectors by number of jobs, using the North American Industrial Classification System 2-digit codes (NAICS descriptions available at https://www.census.gov/cgi-bin/sssd/naics/naicsrch). We limit reporting on employment summaries, per the employer privacy restrictions specified in the Quarterly Census of Employment and Wages data use agreement (OED, 2018a,b).

Social characteristics: American Community Survey (ACS) 2013–2017 5-year estimates were based on data collected between January 1, 2013 and December 31, 2017. We note that ACS estimates are for the city jurisdiction and not the UGB and that ACS data are not available by tsunami zone. Planners wanting to further understand the specific locations of vulnerable populations are encouraged to discuss the situation with their local public health preparedness coordinators. Other resources include the emPOWER database from Health and Human Services (https://empowermap.hhs.gov) that tracks electricity-dependent Medicare populations and the Centers for Disease Control and Prevention's Behavioral Risk Factor Surveillance System (BRFSS, https://www.cdc.gov/brfss), which tracks U.S. residents regarding their health-related risk behaviors, chronic health conditions, and use of preventive service. Although our focus in this study was on quantifying casualties from a near-source tsunami, such information on vulnerable populations can be useful when planning evacuations for distant-source tsunamis.

The ACS Survey Disability Characteristics table (Table S1810) provides estimates for numbers of individuals with the following disability categories (taken from https://www.census.gov/topics/health/disability/guidance/data-collection-acs.html). An individual may have more than one disability.

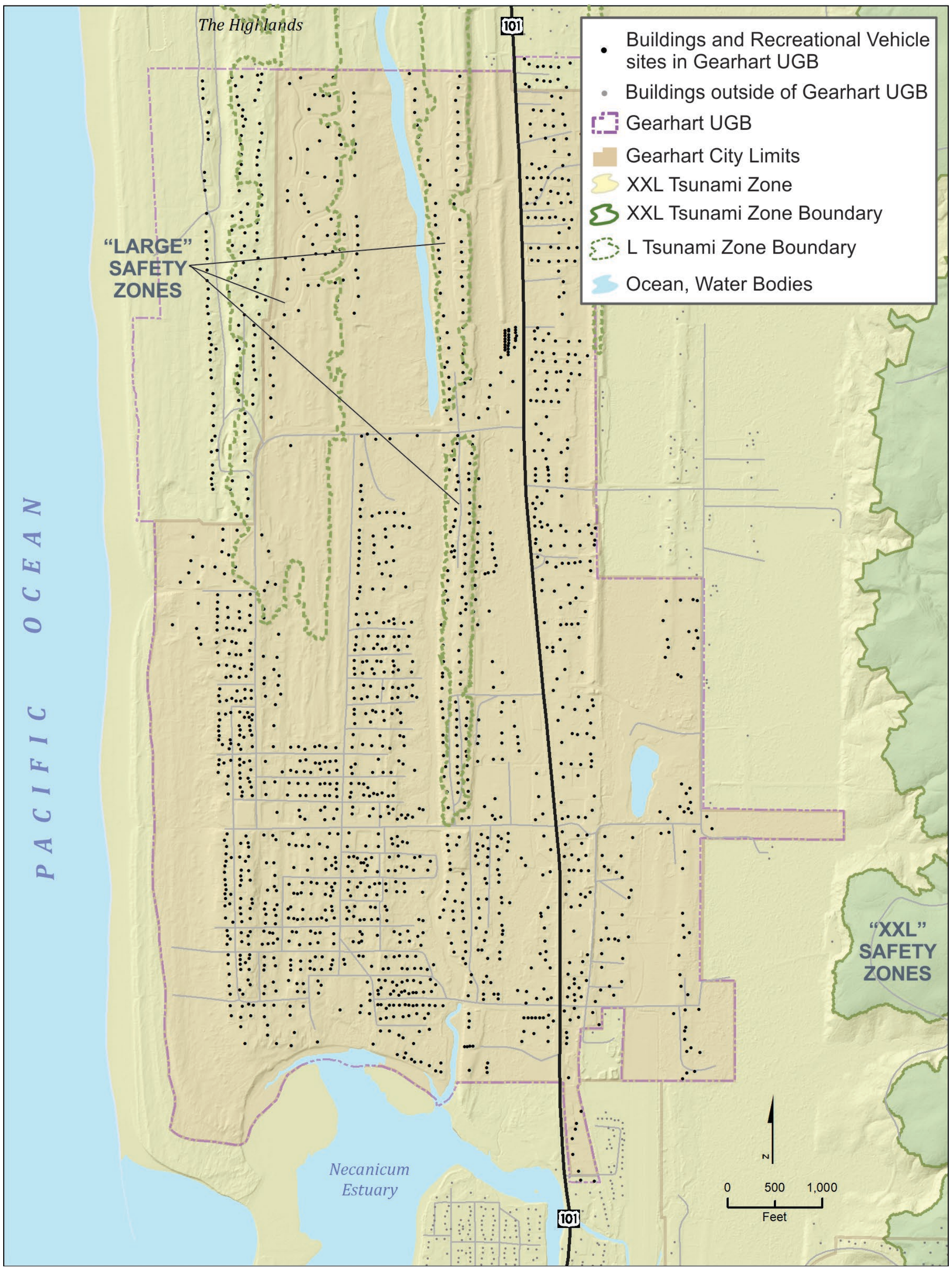
- Hearing difficulty: deaf or having serious difficulty hearing;
- Vision difficulty: blind or having serious difficulty seeing, even when wearing glasses;
- Cognitive difficulty: Because of a physical, mental, or emotional problem, having difficulty remembering, concentrating, or making decisions;
- Ambulatory difficulty: Having serious difficulty walking or climbing stairs;
- Self-care difficulty: Having difficulty bathing or dressing; and,
- Independent living difficulty: Because of a physical, mental, or emotional problem, having difficulty doing errands alone such as visiting a doctor's office or shopping.

Discussion and recommendations: Each community profile includes summary information organized into Evacuation, Response, and Recovery topics.

8.1 Gearhart

The Gearhart Urban Growth Boundary (UGB) includes “The Highlands,” a neighborhood in the northwest that is outside Gearhart city limits (**Figure GH-1**).

Figure GH-1. Gearhart UGB, city limits, and XXL tsunami zone. Buildings and recreational vehicle sites inside the UGB are shown as black points; all other buildings shown as grey points. “XXL” tsunami inundation zone safety zone is shown with green outline. Areas of high ground associated with the Large scenario are defined by the green dashed line.



8.1.1 Building and Population Characteristics

Our analyses indicate that the entire Gearhart UGB is inundated by the XXL1 tsunami, while the L1 leaves a few discrete areas of high ground within the UGB (**Figure GH-1**). As of July 1, 2018, the city had 1,505 permanent residents (PSU PRC, 2019. An additional 5,400 temporary residents may visit the community on a summer weekend; the latter estimate assumes that every residential facility is at maximum capacity. Hence, the local population has the potential to increase by ~4.6 times under the most conservative circumstances.

Within the Gearhart UGB, 29% (i.e., less than one third) of the permanent residents living in the XXL1 tsunami zone are classified as ≥65 years of age (**Table 3-2**). This is marginally higher than the XXL1 average of 27% calculated for the entire Oregon coast. Temporarily occupied households (referred to as "seasonal" in the U.S. Census database) make up 57% of the residential households in the XXL1 tsunami zone (**Table GH-1**). The results presented in **Table GH-1** and **Figure GH-2** also highlight the considerable increase in affected population for the L1 event relative to the M1 event (the transition from L1 to XXL1 is minor compared with the different between M1 and L1). These effects are entirely a function of the relatively broad, low-lying area that characterizes Gearhart.

Table GH-1. Gearhart UGB tsunami zone building statistics and demographics for three tsunami zones.

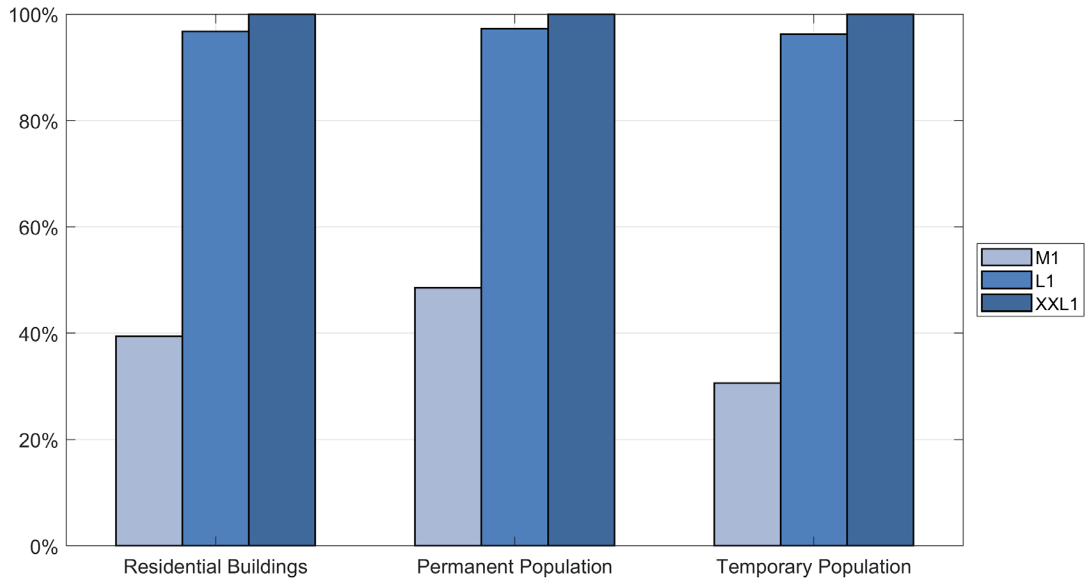
Tsunami Zone	Number of Buildings	Number of Residential Buildings	Building Replacement Cost ($ Million)	Total Number of Households (2010 Census)	Total Number of Seasonal Households (2010 Census)
M1[1]	739	536	208	530	144
L1[1]	1,577	1,316	453	1,574	905
XXL1[1]	1,627	1,360	471	1,574	905

	Permanent Resident Population Estimate			Temporary Resident Population Estimate, Summertime Weekend			
Tsunami Zone	Under 65 Years Old	65 Years and Older	Total	Under 65 Years Old	65 Years and Older	Total	Population Total, Summertime Weekend
M1[1]	553	172	725	1,313	359	1,672	2,397
L1[1]	1,048	406	1,454	4,190	1,061	5,251	6,705
XXL1[1]	1,064	431	1,495	4,356	1,103	5,459	6,954

Notes: The U.S. Census refers to temporarily occupied households such as vacation and second homes as "seasonal households." Temporary population estimates are based on a summer weekend scenario.

[1]M1, L1 and XXL1 (Priest and others, 2013e)

Figure GH-2. Gearhart UGB tsunami zone building statistics and demographics for three tsunami zones expressed as percentages relative to the XXL1 zone. Temporary population estimates assume a summer weekend scenario.



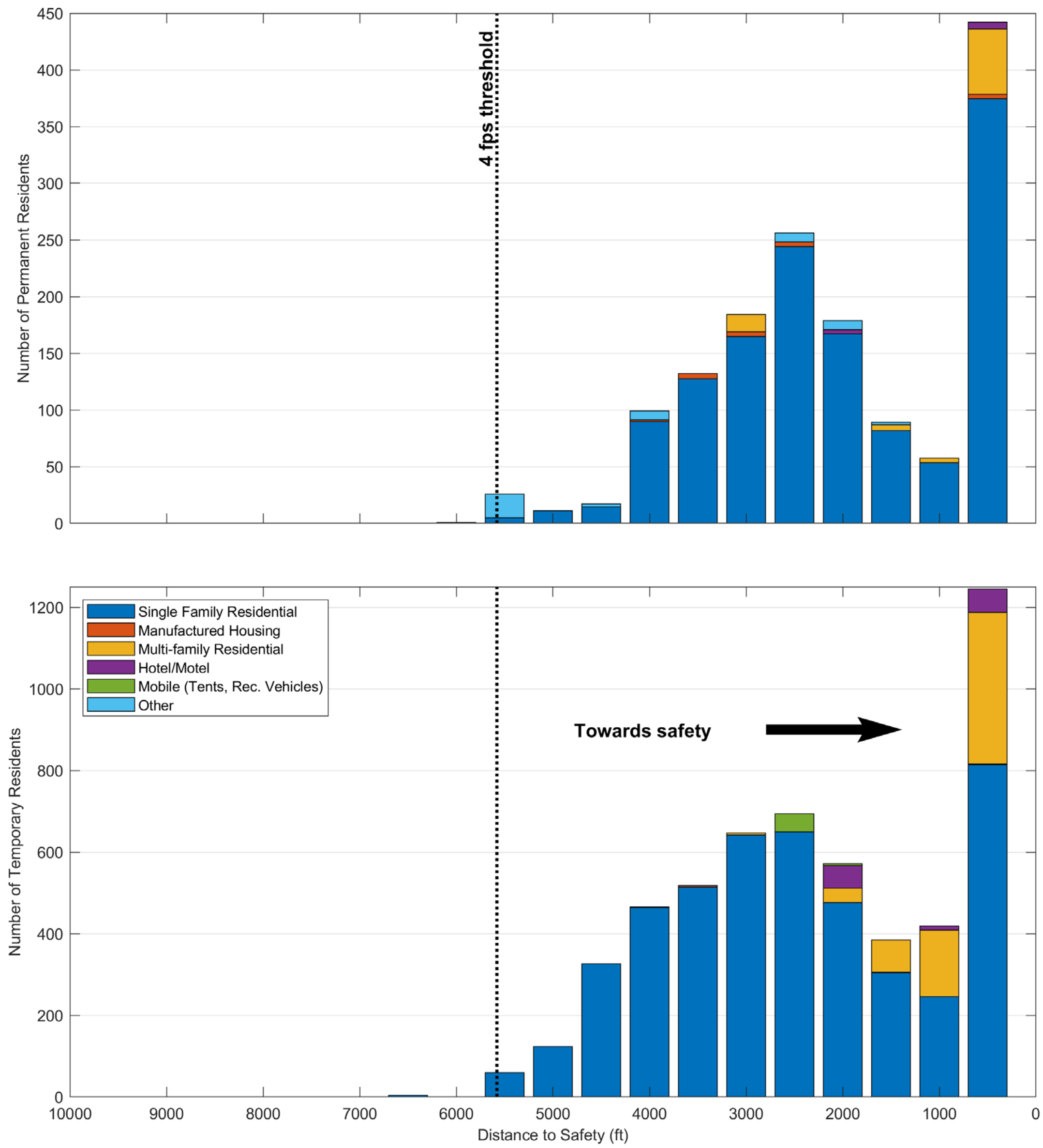
As is evident from **Table GH-2**, the majority of permanent residents within the Gearhart XXL1 tsunami zone (89%) occupy single-family residential homes. Similarly, temporary residents predominantly occupy single-family vacation and second homes (85%, e.g., Vacation Rentals by Owner, VRBO) and, to a lesser extent, multi-family residential (~12%). These results highlight some of the potential challenges facing tsunami educators and community leaders preparing a local community for the earthquake/tsunami. For example, one major challenge with such a dispersed temporary population is ensuring that every vacation home contains appropriate information about the earthquake/tsunami hazard (e.g., warning signs to look out for, response procedures), as well as site-specific information (e.g., tsunami evacuation maps) about where to go if an earthquake occurs.

Table GH-2. Estimates of permanent and temporary population by building type in Gearhart UGB XXL1 tsunami zone. Temporary population estimates assume a summer weekend scenario.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single-family Residential	1,335	89%	4,624	85%
Manufactured Housing	18	1%	10	0%
Multi-family Residential	82	5%	653	12%
Hotel/Motel	10	1%	124	2%
Recreational Vehicles	0	0%	48	1%
Other (incl. Mixed-use)	50	3%	0	0%
Total	1,495	100%	5,459	100%

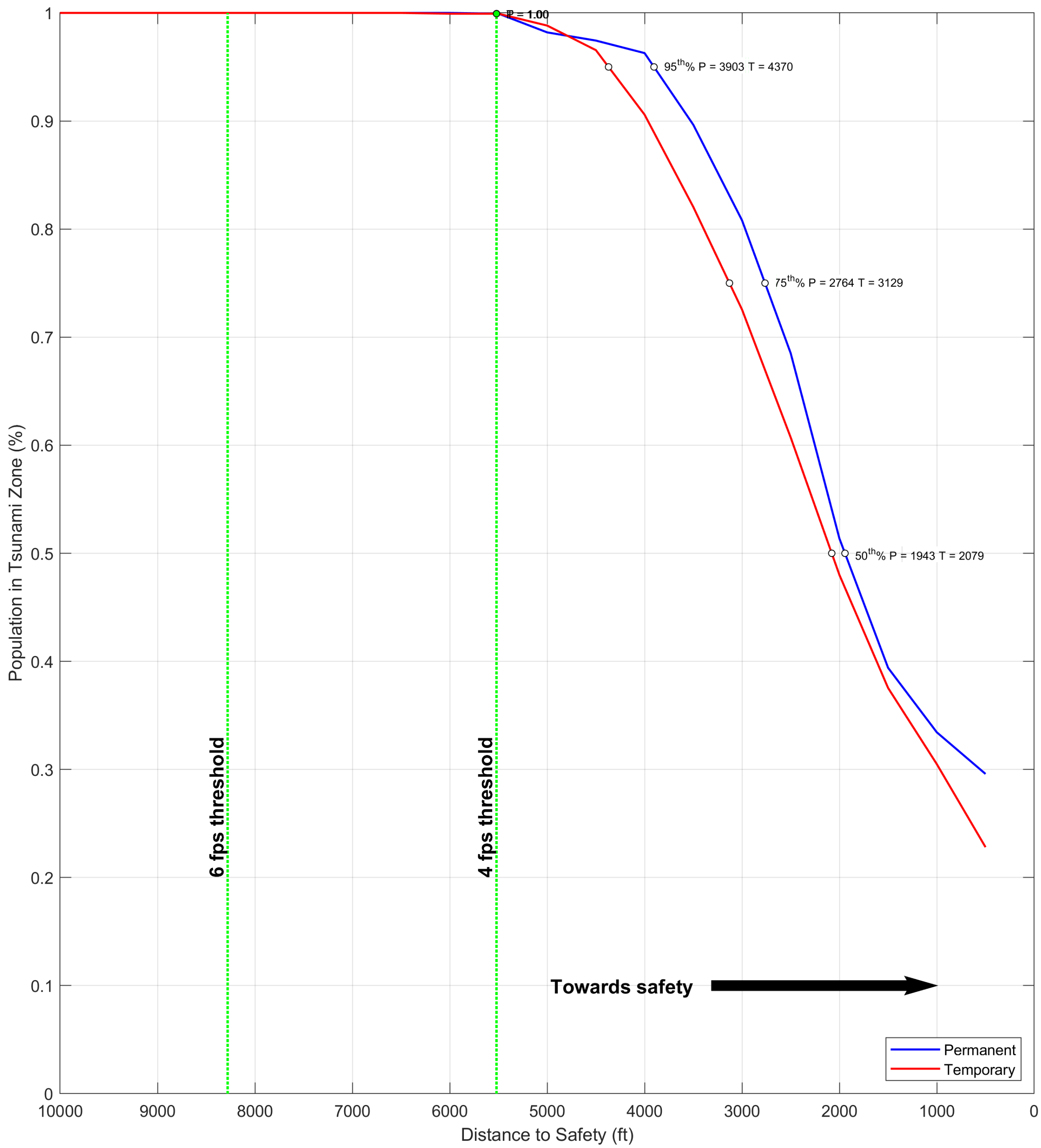
The City of Gearhart has determined that planning community evacuation from an XXL1 tsunami is not feasible due to the significantly greater distances required to travel to reach high ground along the eastern foothills. For this reason, the city has communicated to its residents that in the event of a major earthquake, people should evacuate where appropriate to the L1 tsunami “islands” located in the north and northwest (**Figure GH-1**). Accordingly, we provide distance to safety statistics using the L1 tsunami scenario in **Figure GH-3** for both the permanent (GH-3, *top*) and temporary (GH-3, *bottom*) populations, and as a cumulative distribution plot in **Figure GH-4**. Using this scenario, a 33-minute wave arrival time allows a person 23 minutes to walk to safety. Assuming a travel speed of 4 feet per second (fps), a person can thus cover 5,520 ft of ground. This threshold is shown in **Figure GH-3** as the vertical dashed line. Using a departure time of 10 minutes and walking speed assumption of 4 fps, people whose distances to safety exceed 5,520 feet (i.e., distances to the left of the threshold) would not reach safety in time to beat the tsunami. However, note that the 4 fps rate is equivalent to walking; people traveling at speeds greater than a “walk” are much more likely to survive the tsunami.

Figure GH-3. Distribution of permanent (top) and temporary (bottom) populations relative to tsunami safety within the Gearhart UGB L1 tsunami zone. Distance to safety for the permanent population estimate is based on a 2 AM scenario, while distance to safety for the temporary population estimate is based on a summer weekend. "Other" category includes mixed-use commercial buildings. See the text for significance of the 4 fps threshold.



In Gearhart, permanent residents are located slightly closer to high ground (and hence have shorter distances to travel) compared with temporary residents, who are generally closer to the beach (**Figure GH-4**). Given the threshold of 5,520 ft noted previously, our analyses suggest that ~virtually the entire community located in the L1 tsunami zone would be able to reach high ground in time traveling at speeds ≥4 fps. Thus, for those few people located at distances to safety that are ≥5,520 ft, it is imperative that they leave sooner and travel at speeds faster than 4 fps (e.g., travel at "fast walk" to "jog").

Figure GH-4. Cumulative distribution plot of permanent and temporary populations relative to tsunami safety within the Gearhart UGB L1 tsunami zone. Figure includes two evacuation reference speed thresholds: 4 fps ("walk") and 6 fps ("fast walk"). Reported values for P and T are, respectively, the permanent and temporary population.



8.1.2 Earthquake and Tsunami Building Damage and Debris Estimates

Within the XXL1 tsunami zone, building repair costs caused by the tsunami greatly exceed that from the earthquake (**Table GH-3**). This is primarily due to the prevalence in the community of wood frame and light-frame steel construction, which is unable to withstand the large hydraulic forces of a tsunami. As can be seen from **Table GH-3**, the weight of debris generated by the destruction of the buildings in the tsunami zone is estimated to be ~161,000 tons; note this is a minimum estimate because the calculation excludes content in the buildings, as well as vehicles and other forms of debris. Combined earthquake and tsunami building repair costs are calculated to be ~$470 million, with the bulk of the cost attributed to the destruction caused by the tsunami. However, these costs will almost certainly be higher when communities factor in the added cost to repair buildings and infrastructure located outside the tsunami zone that are also damaged by the earthquake.

Table GH-3. Building repair costs and debris weight calculated for the Gearhart UGB due to a CSZ earthquake and XXL1 tsunami.

Number of Buildings	Building Square Footage (thousand)	Building Value ($ Million)	Natural Hazard	Building Repair Cost ($ Million)	Loss Ratio	Debris from Damaged Buildings (tons)
1,627	3,759	$471	Earthquake	$125	27%	—
			Tsunami	$462	98%	—
			Combined	$470	100%	161,000

8.1.3 Injury and Fatality Estimates from Earthquake and Tsunami

Injury and fatality estimates for those occupying buildings during the *earthquake* are low (~1.0% and 1.4% for permanent and temporary residents, respectively; **Table GH-4**). This is because the majority of residential buildings are wood frame, which is considered to be the most seismically resilient building construction type (FEMA, 2015a). Depending on the extent of a person's injury or how they respond to the event and injury (i.e., a bookshelf collapses on them during the earthquake, or are unable to open a door to leave the building, or shock), it is likely that a portion of the injured population may not be able to evacuate from the tsunami zone in a timely manner and are therefore killed by the ensuing tsunami.

Table GH-4. Injuries and fatalities resulting from a CSZ earthquake sustained by resident group type in the Gearhart urban growth boundary, summer weekend 2 AM scenario.

Hazus Injury Severity Level	Permanent Residents	Temporary Residents	Total
Level 1: Minor Injuries	11	58	69
Level 2: Injuries Requiring Hospitalization	3	13	16
Level 3: Life-Threatening Injuries	1	2	3
Level 4: Deaths	1	3	4
Total	16	76	92

Note: See **Table 2-3** for a complete definition of the Hazus injury levels.

For Gearhart we analyzed injuries and fatalities for three tsunami evacuation scenarios (**Table GH-5**). Per input from the community, we modeled the following:

- an XXL1 scenario that assumes all evacuation routes are intact and usable, including evacuation routes to the east;
- an L1 scenario that assumes that selected evacuation routes to the east are not passable, forcing residents to evacuate toward the L1 islands in the north and northwest portions of the town; and,
- an L1 scenario that assumes all evacuation routes have been upgraded to provide unimpeded passage, including routes headed to high points east of town.

As expected, the fatality rates associated with the XXL1 scenario are extremely large, reaching 88% for the permanent population and 97% for the temporary population (**Table GH-5**). Injuries make up a very small portion of this scenario (~1%). Thus, for a worst-case XXL1 scenario, about 5% of the combined population is calculated to survive. Again, it is very important to stress that these numbers are extremely conservative in that they assume every person evacuates at 4 fps ("walk") speed. As a result, evacuees traveling at speeds greater than a walk (i.e., fast walk to jog to run) will greatly increase their chance of surviving an XXL1 event, reducing the overall casualty numbers.

Table GH-5. Injury and fatality estimates for several CSZ tsunami scenarios in the Gearhart UGB. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, 10-minute milling time prior to departure, and wave arrival time at the tsunami runup line of 33 minutes. Injury and fatality estimates are rounded to nearest 10.

Tsunami Scenario	Population Segment	Number of People	Fatalities	Injuries	Injury and Fatality Ratio	
					Fatalities	Injuries
Extra Extra Large (XXL1); all evacuation routes viable	Permanent	1,495	1,320	20	88%	1%
	Temporary	5,459	5,300	70	97%	1%
	Total	6,954	6,620	90	95%	1%
Large (L1); eastern evacuation routes discouraged	Permanent	1,495	140	10	9%	1%
	Temporary	5,459	220	30	4%	1%
	Total	6,954	360	40	5%	1%
Large (L1); all evacuation routes viable	Permanent	1,495	30	10	2%	1%
	Temporary	5,459	140	20	3%	0%
	Total	6,954	170	30	2%	0%

Note: Population and tsunami casualty estimates here are limited to people residing in the respective tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is the percentage of people in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Survivability improves considerably if the CSZ event is an L1 (or lower magnitude event), with fatalities reduced to ~2-5% of the combined permanent and temporary population (**Table GH-5**); injuries under this scenario remain very low at <1%. These results are entirely due to the proximity of homes and business to several areas (islands) of high ground near the coast in the northwest and adjacent to Highway 101 shown in **Figure GH-1**; the reduced fatalities also reflect the fact that there are fewer people overall in the L1 tsunami zone compared with the XXL1 scenario. Nevertheless, the Hazus tsunami modeling reinforces the fact that few people who are caught by the tsunami survive the event. For the L1 scenario, the inclusion of all possible evacuation routes (i.e., including evacuation routes east of town) resulted in even further reductions in overall fatalities, with the number of fatalities falling by an additional 190 people, when compared with evacuating directly to the islands of high ground.

The estimated tsunami casualties provided in **Table GH-5** assume a mean departure time of 10 minutes and a group median evacuation walking speed of 4 fps except for individuals ≥65 years in age, who evacuate at 3.2 fps. To better illustrate the evacuation situations and opportunities throughout the Gearhart UGB, we calculated the likelihood of survival based on distance to safety, walking speed, and tsunami wave arrival time for several scenarios (**Figure GH-5** to **Figure GH-10**). Survivability was determined using the survival likelihood distance breakpoints identified in the formula associated with **Table 2-4** for a tsunami wave arrival of 33 minutes. Using this approach, **Figure GH-5** and **Figure GH-6** demonstrate that an XXL1 tsunami is not survivable for most people in Gearhart, even assuming an increased evacuation speed assumption of 6 fps (akin to a fast walk) and viable evacuation routes to the east; survivability can be improved by increasing one's evacuation speed to a jog or run. Conversely, the L1 model results summarized in **Figure GH-7** to **Figure GH-10** show higher survivability, particularly when people increase their travel speed, and all viable evacuation routes are allowed.

Figure GH-5. Gearhart evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.

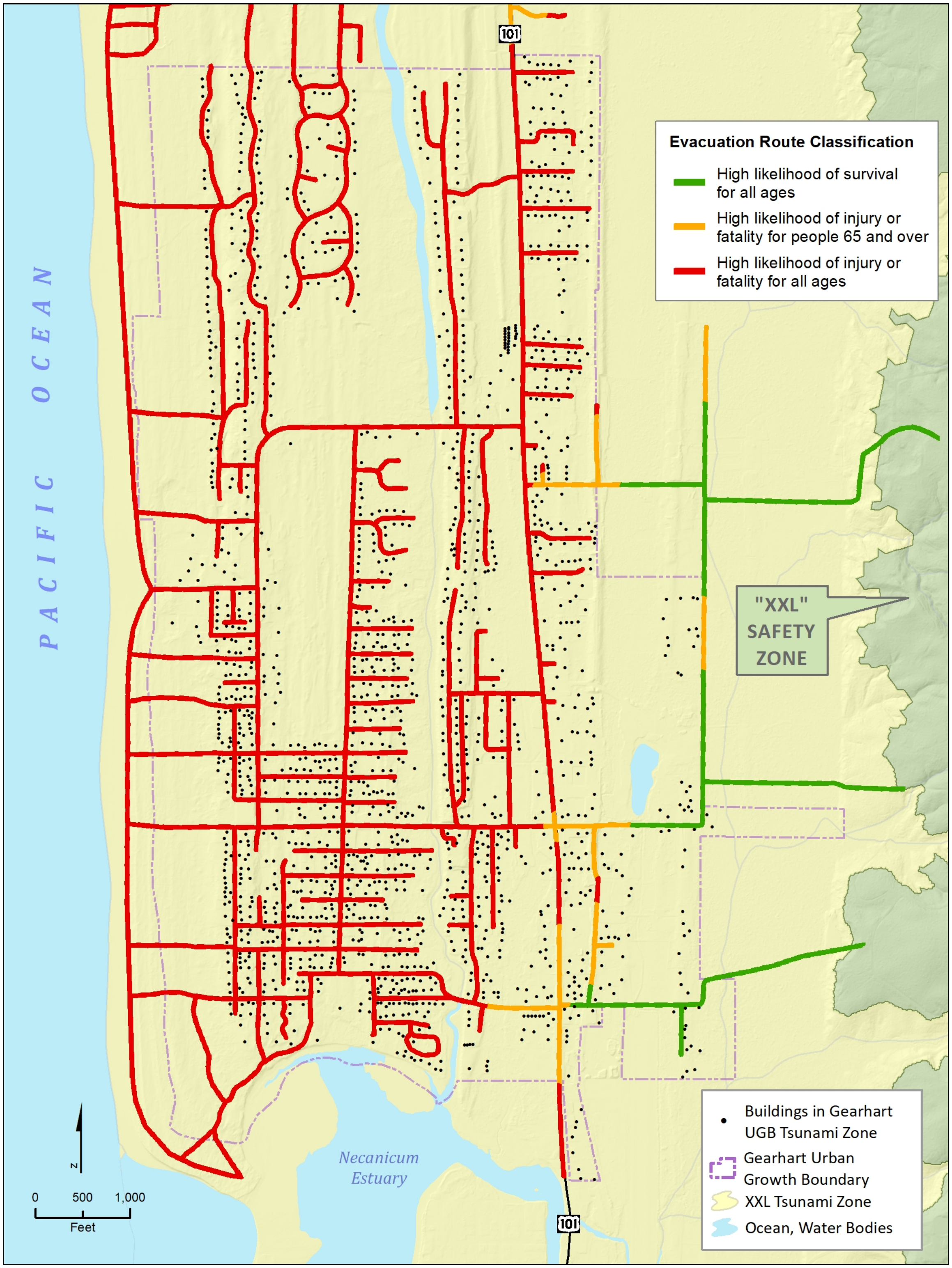


Figure GH-6. Gearhart evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.

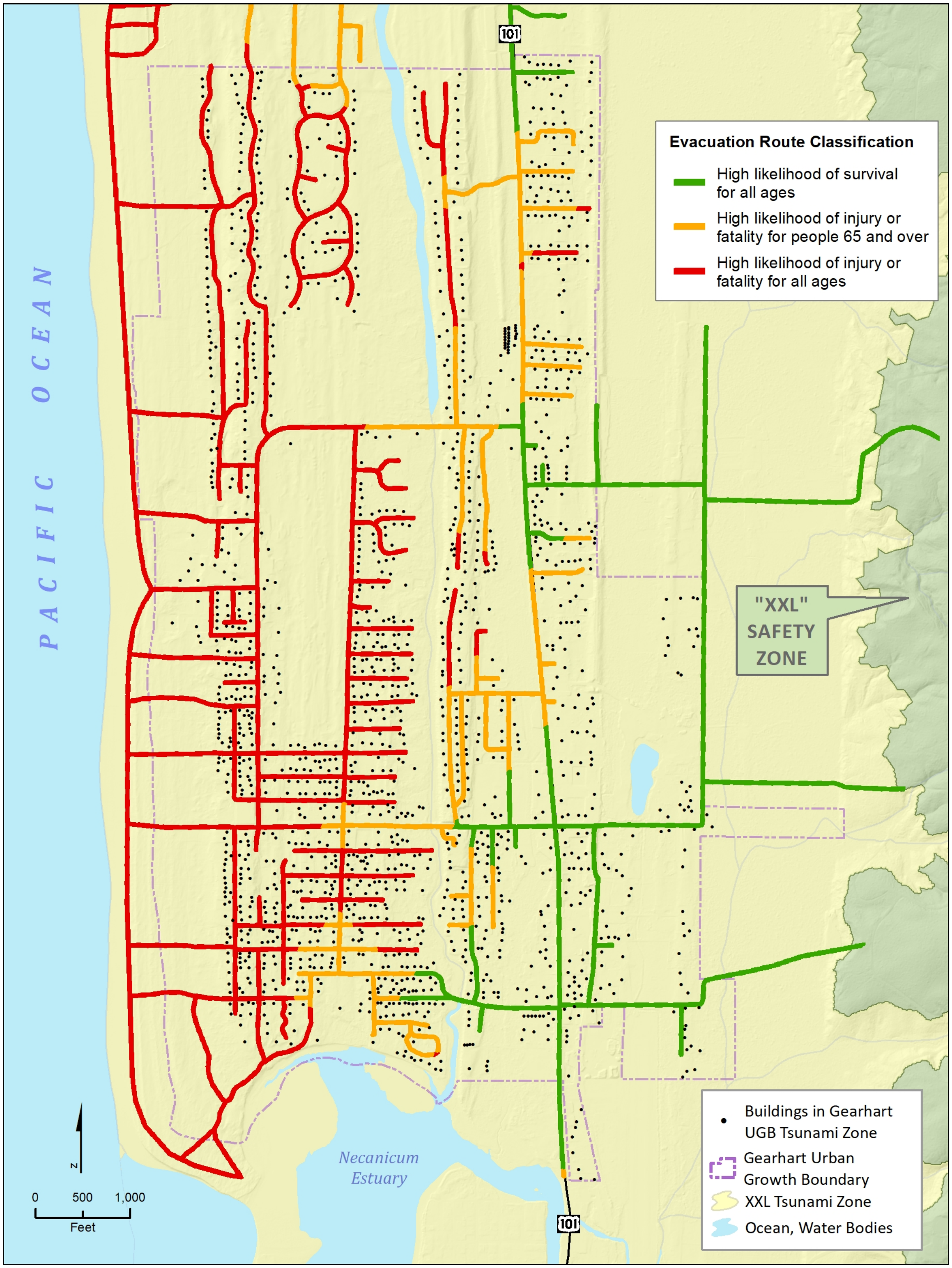


Figure GH-7. Gearhart evacuation routes and distance to tsunami safety for the L1 tsunami scenario, symbolized into survivability classes. In this scenario, eastward evacuation has been blocked, with break points at the intersection of Highway 101 and G St, Pacific Way, 5th St, and Gearhart Ave. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.

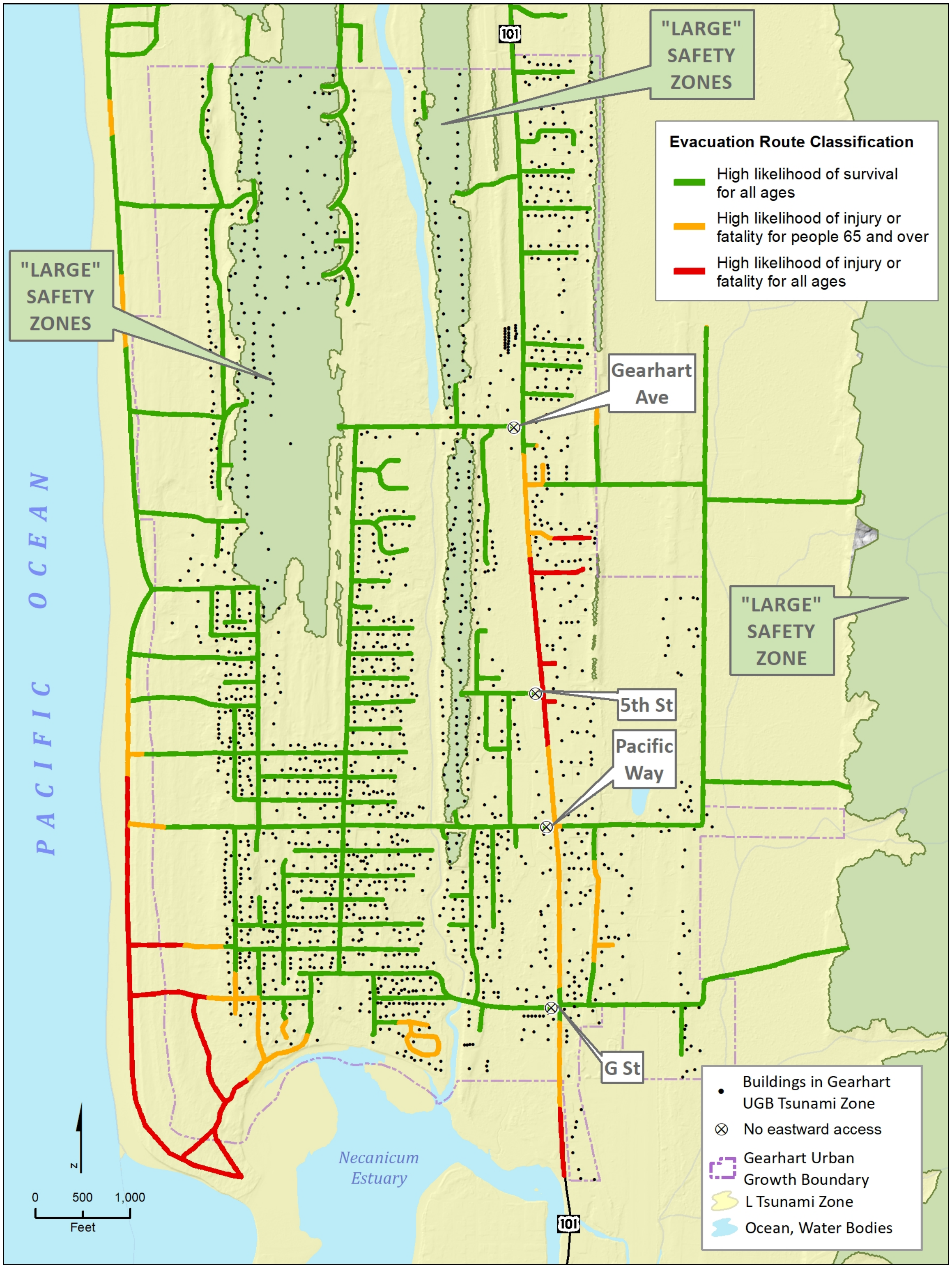


Figure GH-8. Gearhart evacuation routes and distance to tsunami safety for the L1 tsunami scenario, symbolized into survivability classes. In this scenario, eastward evacuation has been blocked, with break points at the intersection of Highway 101 and G St, Pacific Way, 5th St, and Gearhart Ave. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.

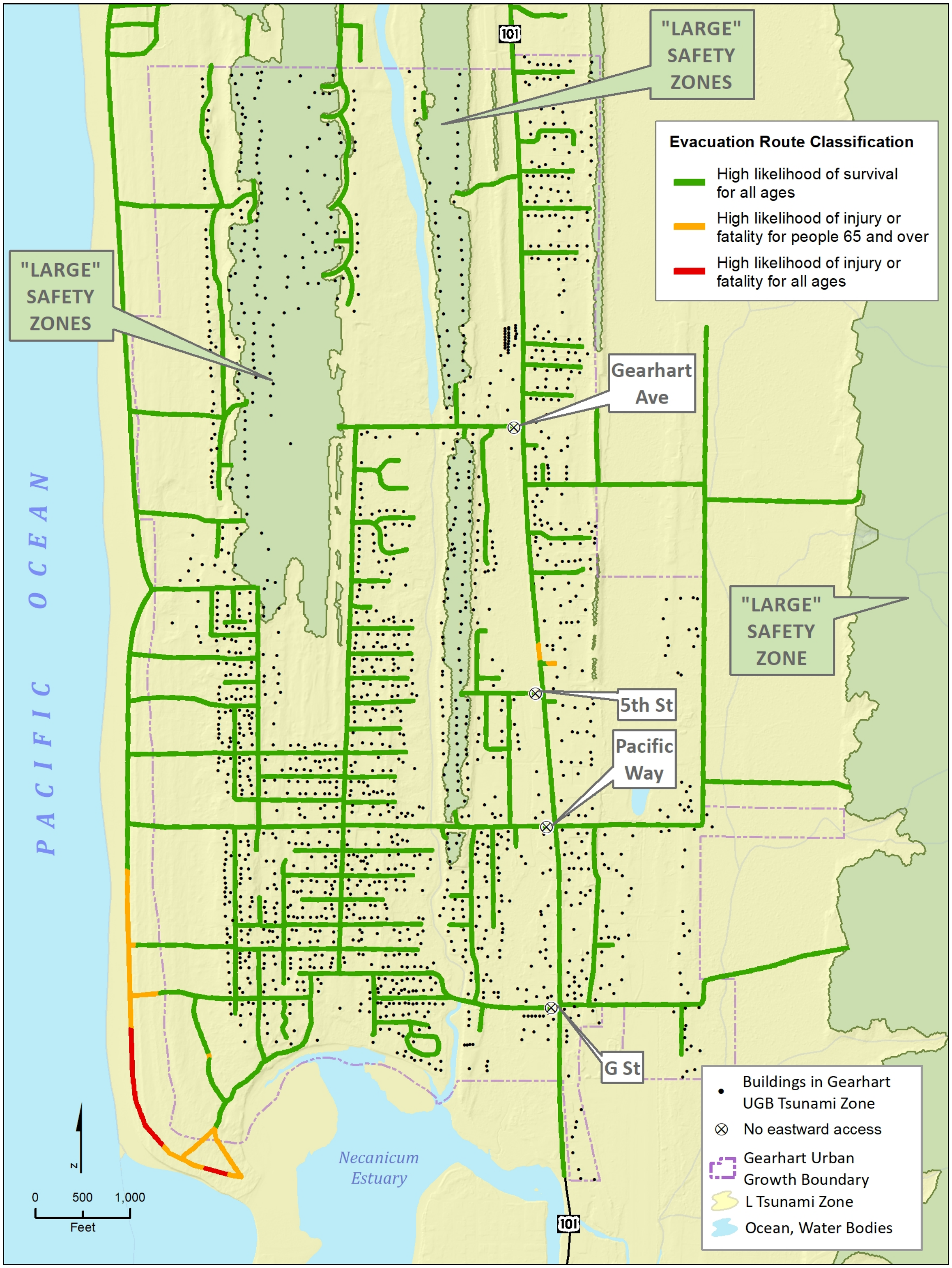


Figure GH-9. Gearhart evacuation routes and distance to tsunami safety for the L1 tsunami scenario, all evacuation routes viable, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.

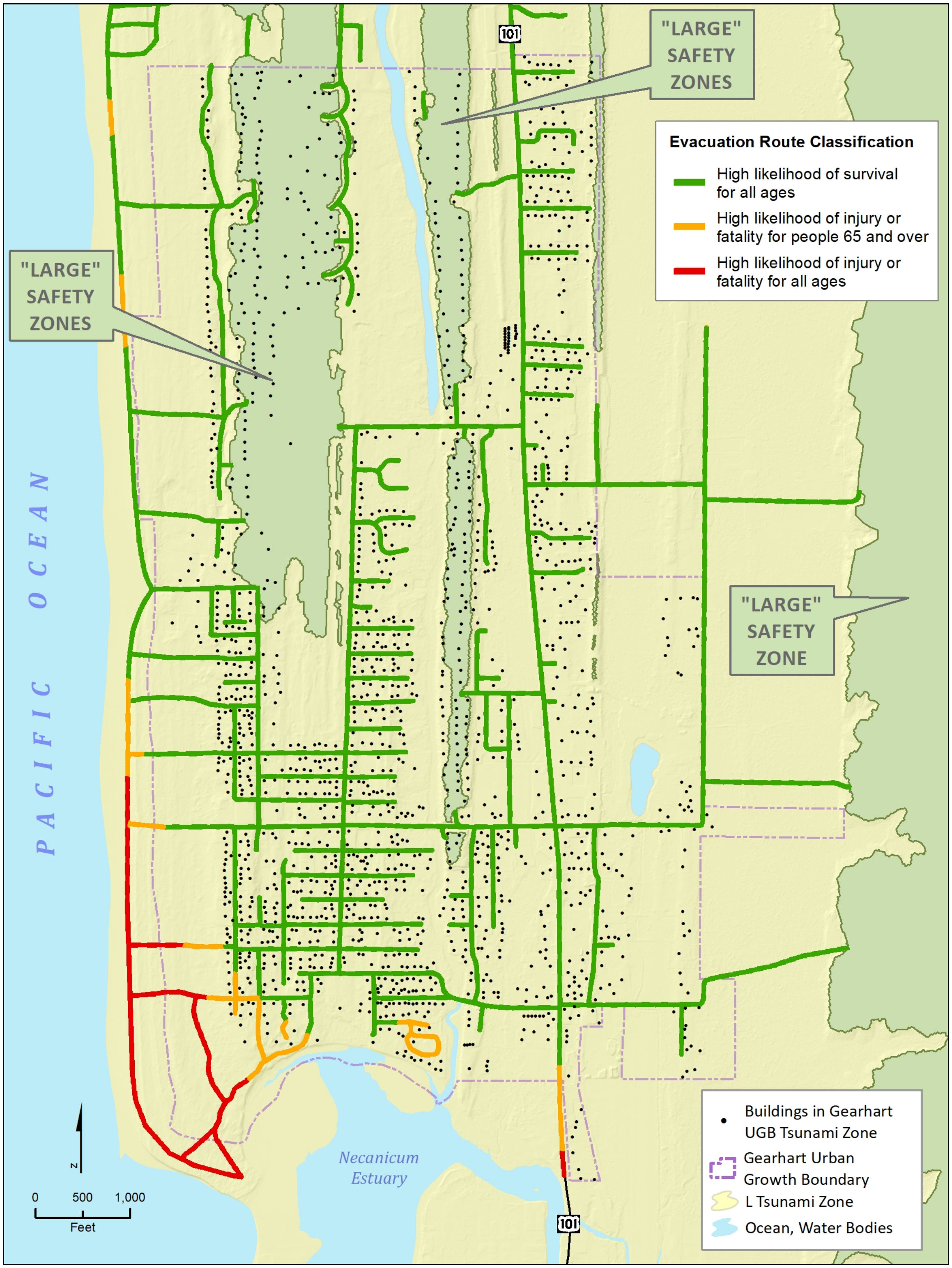
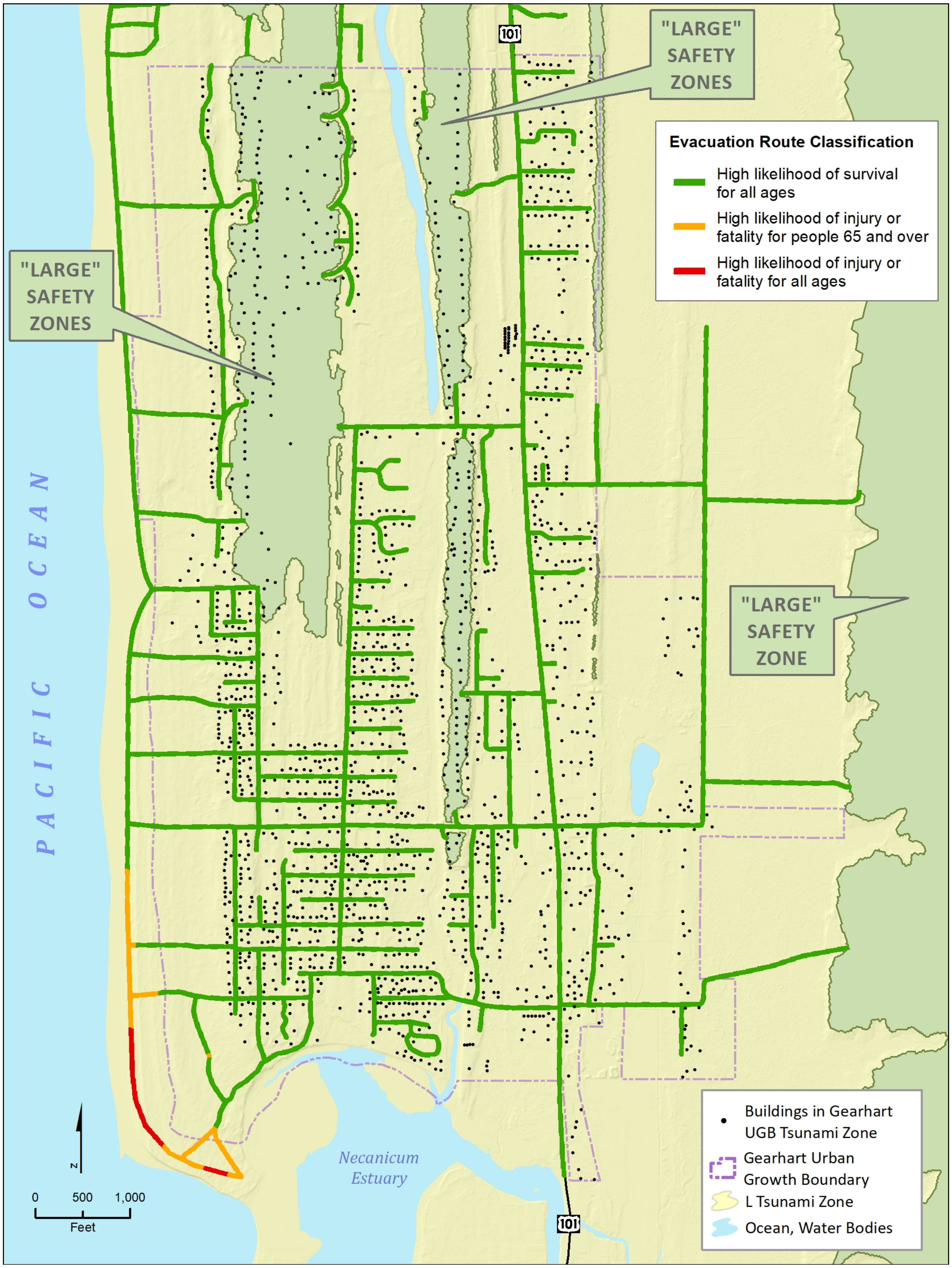


Figure GH-10. Gearhart evacuation routes and distance to tsunami safety for the L1 tsunami scenario, all evacuation routes viable, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake commences, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 33 minutes.



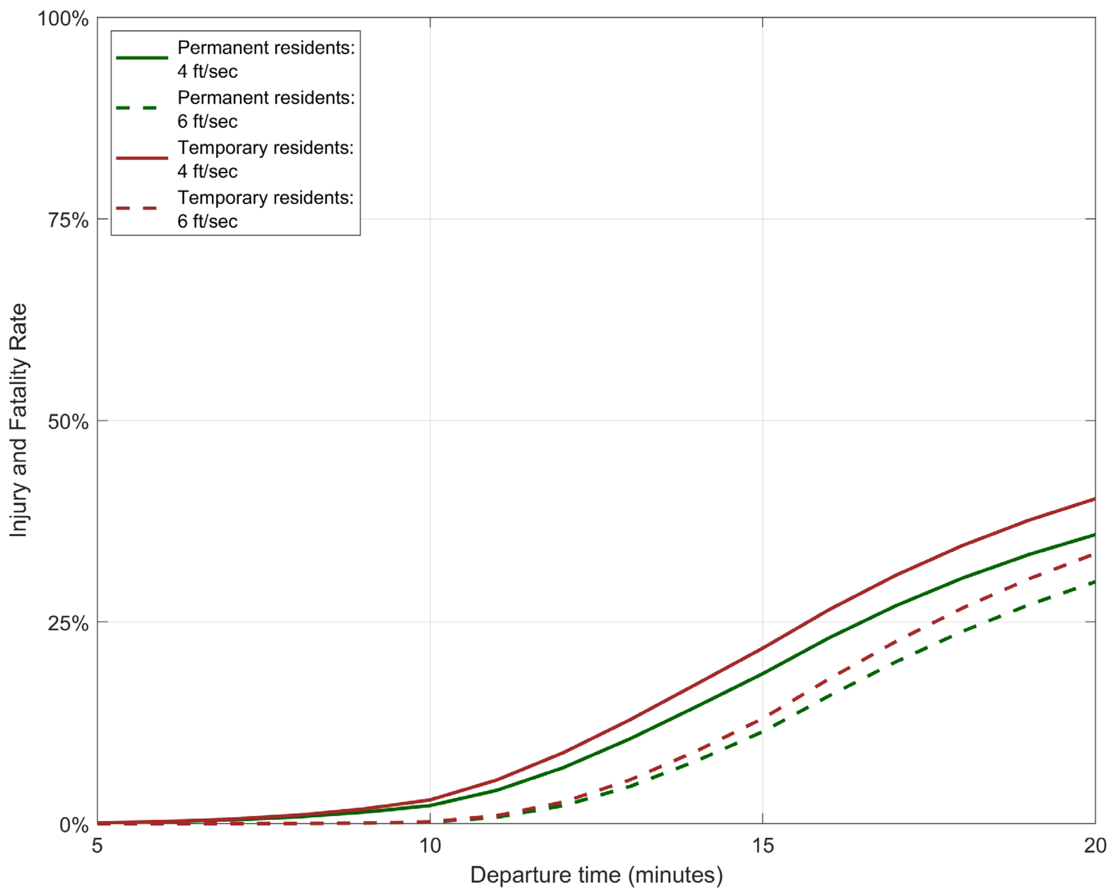
Injuries and fatalities from a tsunami can be significantly lowered if individuals evacuate as soon as possible and travel at faster evacuation speeds (e.g., "slow jog" to "run"). We obtained injury and fatality percentages from the Hazus tsunami casualty model for a variety of tsunami scenarios, varying group departure time and group walking speeds (**Table GH-6**). As expected, injuries and fatalities increase as the departure time increases (i.e., longer milling behavior). We summarize this information in **Figure GH-11** for the L1 scenario, which visually emphasizes the point that casualty numbers increase as people delay their evacuation, and decrease as the speed of travel increases. Also evident from **Figure GH-11** is the slight increase in fatality rates for the Gearhart temporary population due to being located farther on average from high ground and thus safety, when compared with the permanent population.

Table GH-6. Combined injury and fatalities for several tsunami scenarios in the Gearhart UGB. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, various milling times, and wave arrival time at the tsunami runup line of 33 minutes. Injury and fatality estimates are rounded to nearest 10.

			Average Departure (Milling) Time					
			Injuries and Fatalities			Injury and Fatality Ratio		
Tsunami Scenario	Population Segment	Number of People	10 Minutes	15 Minutes	20 Minutes	10 Minutes	15 Minutes	20 Minutes
XX-Large (XXL1); all evacuation routes viable	Permanent	1,495	1,340	1,410	1,420	87%	94%	94%
	Temporary	5,459	5,360	5,410	5,410	99%	99%	99%
	Total	6,954	6,710	6,820	6,830	96%	98%	98%
Large (L1); eastern evacuation routes discouraged	Permanent	1,495	150	410	620	10%	27%	41%
	Temporary	5,459	250	1,300	2,260	5%	24%	41%
	Total	6,954	400	1,710	2,880	6%	25%	41%
Large (L1); all evacuation routes viable	Permanent	1,495	30	280	540	2%	19%	36%
	Temporary	5,459	160	1,190	2,200	3%	22%	40%
	Total	6,954	190	1,470	2,740	3%	21%	39%

Note: Population and tsunami casualty estimates are limited to people residing in the respective tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Figure GH-11. Gearhart injury and fatality rates estimated for the L1 tsunami as a function of departure time and two different evacuation speeds. Results assume all evacuation routes are available. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the tsunami zone at the time of the earthquake.



8.1.4 Displaced Population

Permanent and temporary residents who successfully evacuate out of the tsunami zone will require short- to medium-term shelter, given that their residences are presumed destroyed or rendered uninhabitable by the tsunami (**Table GH-3**). Temporary residents will likely not be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017) and that their personal vehicles will likely be destroyed or damaged by the tsunami.

For mass care planning purposes, displaced population estimates can be obtained by subtracting the total injuries and fatalities provided in **Table GH-5** from the total number of people (permanent and temporary) estimated to be in either tsunami zone. Thus, during a summer weekend the displaced population in Gearhart could be as low as a few hundred people in an XXL1 event — only ~4–10% of the population are expected to survive the tsunami. Conversely, casualty numbers for an L1 scenario average ~4%, which means the displaced population could range from a low of ~1,460 people in winter (i.e., no temporary population) to a high of ~6,600 people in summer (permanent plus temporary). For a mid-winter scenario, planners could use the permanent resident displaced population plus a scaled-down summer weekend temporary population estimate to arrive at a potential displaced winter population estimate that is more realistic.

We note again that our analysis is primarily limited to the buildings and people in the Gearhart L1 tsunami zone. Accordingly, some portion of the permanent and temporary residents located outside of the L1 tsunami zone will likely also need food and shelter if their residential structures were damaged from the earthquake. In addition, extensive development in the L1 tsunami zone currently exists north of Gearhart, including the unincorporated Surf Pines neighborhood, and displaced people in those locations will also need temporary food and shelter.

A lesser magnitude tsunami event (e.g., a medium [M1] scenario) will produce fewer tsunami injuries and fatalities. We note that of the total population in Gearhart, 725 permanent and 1,672 temporary people occupy buildings in the Medium tsunami zone (**Table GH-1**).

8.1.5 Essential Facilities, Special Facilities, and Key Infrastructure

Our analyses indicated the following *essential facilities* in the Gearhart UGB area:

- Gearhart Police Department
- Gearhart City Hall
- Gearhart Volunteer Fire Department
- Gearhart Elementary School

We identified the following *special facilities* in the Gearhart UGB tsunami zone:

- Gearhart Kids Academy (day care and preschool)

We identified the following *key infrastructure facilities* in the Gearhart UGB tsunami zone:

- Gearhart Water Storage Facility, Pacific Way and N Marion Avenue

8.1.6 Employment

Most employers in the Gearhart UGB are located within the L1 tsunami zone (**Table GH-7**). The two highest employment sectors are Accommodation and Food Services (NAICS code 72) and Construction (NAICS code 23), accounting for 34% and 20% of jobs, respectively.

Table GH-7. Number of businesses, jobs, and annual wages paid for the Gearhart urban growth boundary determined for the L1 tsunami zone.

	L1 Tsunami Zone	Gearhart Urban Growth Boundary
Number of businesses	81	85
Number of jobs	*	522
Annual Wages Paid ($ million)	*	$17

*Excluded for employer privacy reasons.

8.1.7 Social Characteristics

We reiterate that the American Community Survey (ACS) social characteristic data span the entire community (and county) and are not at a resolution that would allow us to better define these statistics by tsunami zone. The interested reader can review the introduction to Appendix A for additional resources on the ACS in order to better understand vulnerable permanent populations living within the tsunami zone.

As noted previously, our analyses indicate that ~29% of the permanent residents in the XXL1 tsunami zone are ≥65 years of age (**Table 3-2**) and is about the same as the Oregon XXL1 tsunami zone average of 27%. We can delve deeper into the social aspect of a local population by evaluating other characteristics such as the number of people who speak Spanish (or other languages) as well as those who may have disabilities. Both datasets are important because they have a direct bearing on basic outreach (e.g., providing material that has been translated) and in terms of identifying those who may need evacuation assistance. Taking this approach, the proportion of Spanish-speaking (and other languages) households in the Gearhart UGB is presented in **Table GH-8** for both the city and with respect to the county average. Overall, we find that Spanish-speaking households in the Gearhart UGB make up a relatively small portion of the local population, ranging from ~1% to 5%.

Table GH-8. Household spoken language statistics. Data taken from American Community Survey 2013-2017 5-year estimates.

	City of Gearhart		Clatsop County
	Number of Households	Percent of Households with Margin of Error	Percent of Households with Margin of Error
Households speaking Spanish	34	5.3% ± 3.8%	4.8% ± 0.9%
Households with limited English fluency; Spanish spoken	*	*	1.1% ± 0.5%
Households with limited English fluency; all languages	*	*	1.7% ± 0.5%

* Insufficient data

Table GH-9 presents information on the percentages of people with disabilities in the City of Gearhart. Overall, these results indicate the proportion of the local population with disabilities is about the same as the county wide average, estimated to be ~19%. Of particular concern is the relatively large number of individuals with either vision, cognitive, or ambulatory disabilities, who will almost certainly need help evacuating from the tsunami zone. Not all of these individuals may reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

Table GH-9. Number of individuals with disabilities (by type) for Gearhart and for Clatsop County. Data taken from American Community Survey 2013–2017 5-year estimates. An individual with a disability may have more than one difficulty.

	City of Gearhart		Clatsop County
	Number of Individuals	Percent of Population with Margin of Error	Percent of Population with Margin of Error
Individuals with a disability	294	18.9% ± 4.9%	19.1% ± 1.4%
Difficulty Category			
Hearing	108	7.0% ± 2.7%	6.5% ± 0.8%
Vision	31	2.0% ± 1.3%	3.4% ± 0.6%
Cognitive	138	9.2% ± 4.7%	7.6% ± 1.0%
Ambulatory	88	5.9% ± 2.6%	10.0% ± 1.1%
Self-care	28	1.9% ± 1.1%	3.4% ± 0.6%
Independent Living	84	7.2% ± 3.0%	7.3% ± 1.0%

8.1.8 Discussion and Recommendations

Evacuation Challenges

Gearhart is situated at the south end of the Clatsop Plains, an area containing elongated wetlands that present evacuation barriers and low-elevation sand dunes that offer no vertical refuge from tsunamis that exceed the L1 scenario. Conversely, in an L1 tsunami scenario, several evacuation "islands" exist in the north and northwestern portions of Gearhart (**Figure GH-1**). As a result of these challenges, local emergency managers have identified these areas of optional high ground as the best sites for local evacuation. However, evacuating to these "islands" will require many residents to walk toward the ocean, which may be counterintuitive for some individuals (Mostafizi and others, 2017). Evacuation toward the east is feasible as well, though our analyses suggest this is best for those people who reside immediately adjacent to Highway 101 and to its east.

Education

We estimate that 85% of temporary visitors to Gearhart spend the night in single-family vacation or second homes. Tsunami safety messaging for visitors should therefore include focused outreach to second homeowners and vacation home renters. Besides improving basic hazard awareness, such activities could also include education on the fact that local evacuation maps can now be generated for any location on the Oregon coast via the NVS tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac) and smartphone application (http://www.nanoos.org/mobile/tsunami_evac_app.php), enabling users to post appropriate information in their homes. While knowledge of where high ground is located is critical, equally important is the practice of walking one's evacuation route to ensure familiarity with the route and any potential obstacles.

Our model results demonstrate that loss of life can be minimized for *all* residents, permanent and temporary, if individuals evacuate as soon as possible after the earthquake stops and travel on foot as fast as possible (**Figure GH-11**). Educational material can be developed to further emphasize this point.

Mitigation

Our evacuation simulations suggest that improving existing evacuation trails for unimpeded passage, along with increased saturation of tsunami wayfinding signage will help reduce casualties. Of particular importance is having a sufficiently dense network of signs (either posted and/or thermoplastic on road/path surfaces) that directs people along core routes to areas outside of the tsunami zone. Signs of this nature need to be spaced appropriately far apart so that they can be easily viewed (and read) at any time of the day. Furthermore, efforts should be directed at improving signage for people living adjacent to Highway 101. Current evacuation plans discourage eastward travel; however, our analysis suggests that ~190 lives could be saved (**Table GH-5**) by directing them towards the eastern highlands (compare **Figure GH-7** with **Figure GH-9**).

We recommend and encourage local communities to practice periodic (annual) tsunami evacuation drills. To instill a culture of awareness of the tsunami hazard facing the Oregon coast, residents (and visitors) must periodically practice their evacuation routes. Studying an evacuation map is not the same as actually walking an evacuation route. While we recognize that such an approach may be disruptive to the local economy, holding periodic drills will save many lives. Such a culture is entrenched in Japanese way of life and helped save many thousands of lives during the most recent catastrophic tsunami event that occurred on the Sendai coast on March 11, 2011. This culture is highlighted in several recent studies (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Our analyses of an XXL1 tsunami have revealed that the tsunami could results in many casualties in the Gearhart area, with as many as 6,600 fatalities. If the event is assumed to be a Large tsunami event, the number of lives lost is significantly reduced to ~2–5%, which equates to ~170 lives lost. Accordingly, the construction of tsunami vertical evacuation structures (TVES) in the Gearhart area remains an important engineering approach that should be evaluated if one is basing evacuation on an XXL1 event. Such a structure(s), placed in key areas, would almost certainly save many lives in the community. To that end, further studies to evaluate such options may be warranted.

Response

Depending on the time of year a CSZ earthquake and tsunami strike, Gearhart will have an acute short- to medium-term sheltering need after a tsunami. Should an L1 tsunami occur during peak tourist season, about 5,200 temporary residents and ~1,300 permanent residents may need shelter (assuming most of the residents safely evacuate). Even a lesser magnitude tsunami will result in significant destruction of residential property, with an M1 tsunami potentially displacing up to 2,400 people at mid-summer (**Table GH-1**). For the maximum-considered XXL1 tsunami, the numbers of displaced are low largely because of the extremely high numbers of fatalities modeled by Hazus.

The US 101 bridge crossing the Neawanna Creek at the north end of Seaside is not used by residents of Gearhart in our pedestrian evacuation model. However, its role in aiding key response and recovery services after an earthquake and tsunami may be significant — a topic our study did not address.

Wang (2018) examined a number of considerations for coastal hospitals to take in order to prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for needed fuel and water. According to the Oregon Resilience Plan documents (OSSPAC, 2013), there are about 483 licensed beds at the 11 coastal hospitals. Combined earthquake and tsunami related injuries in Gearhart is estimated to be ~180 (**Table GH-4** and **Table GH-5**); total injuries for the five communities could approach 900, exceeding existing hospital capacity on the coast. Hence, coastal hospitals will need to prepare for a surge in injuries (as well as large numbers of fatalities) that could well exceed existing capacity.

Recovery

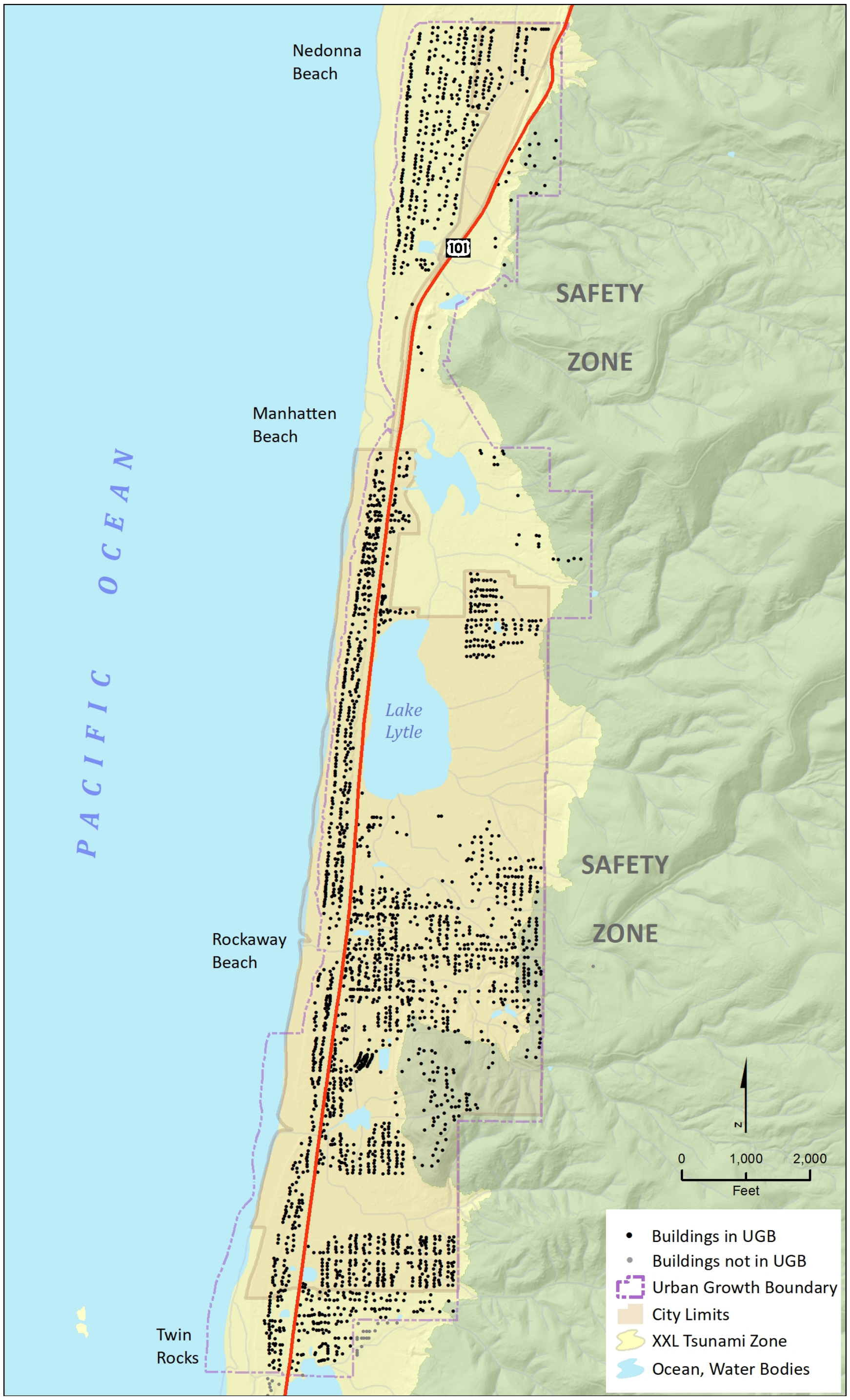
Events greater than the L1 scenario will be catastrophic for the local economy. Similarly, an L1 tsunami will also have a significant impact on local employment. Tourism-driven services, which make up 34% of the jobs in the Gearhart tsunami zone, will probably be severely affected for many months following the event.

As indicated in our results, about half of the permanent residents in Gearhart reside in buildings located in the M1 tsunami zone, while nearly all of the permanent residents in Gearhart are located in the L1 tsunami zone (**Table GH-1**). Most of the buildings in Gearhart are not in a designated FEMA flood zone (FEMA, 2019a). Building owners are not required by federally backed mortgage lenders to carry flood insurance for buildings outside of a designated flood zone. However, flood insurance is available to all building owners through the National Flood Insurance Program, which covers building loss due to a tsunami (FEMA, 2018c). More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

8.2 Rockaway Beach

The Rockaway Beach urban growth boundary (UGB) includes the neighborhoods of Nedonna Beach and Twin Rocks that are currently outside of the Rockaway Beach city limits (**Figure RB-1**).

Figure RB-1. Rockaway Beach urban growth boundary, city limits, and XXL1 tsunami zone. Buildings inside the tsunami zone and urban growth boundary are shown as black points; all other buildings shown as grey points.



8.2.1 Building and Population Characteristics

Our analyses indicate that virtually the entire community of Rockaway Beach is directly impacted by the XXL1 tsunami (**Figure RB-1**), while a few discrete areas located in the eastern hills are outside of the tsunami zone. As of July 1, 2018, the City of Rockaway Beach had 1,832 permanent residents (PSU PRC, 2019), of which ~79% live in the XXL1 tsunami zone (**Table RB-1**). Up to an additional 7,600 temporary residents may visit the community on a summer weekend and would be located within the XXl1 tsunami zone; this estimate assumes that every lodging facility is at maximum capacity. Thus, the local population within the XXL1 tsunami zone could potentially increase by ~6 times in the summer. Clearly, numbers of this magnitude would place an enormous burden on the local community in the hours to days following a major earthquake and accompanying tsunami. Our analyses also reveal that ~35% of the permanent residents in the XXL1 tsunami zone are ≥65 years of age (**Table RB-1**), which is higher when compared with the XXL1 average of 27% calculated for the entire Oregon coast. Temporarily occupied households (referred to as "seasonal" in the U.S. Census database) make up 60% of the residential households. More than 60% of the permanent population and more than 80% of the temporary population are located in the M1 tsunami zone, highest of the five communities analyzed in this study (**Figure RB-2**).

Table RB-1. Rockaway Beach urban growth boundary tsunami zone building statistics and demographics for three tsunami zones.

Tsunami Zone	Number of Buildings	Number of Residential Buildings	Building Replacement Cost ($ Million)	Total Number of Households (2010 Census)	Total Number of Seasonal Households (2010 Census)
M1[1]	1,777	1,541	394	1,712	1,106
L1[1]	2,149	1,873	484	1,978	1,227
XXL1[1]	2,361	2,069	529	2,175	1,312

Tsunami Zone	Permanent Resident Population Estimate			Temporary Resident Population Estimate, Summertime Weekend			Population Total, Summertime Weekend
	Under 65 Years Old	65 Years and Older	Total	Under 65 Years Old	65 Years and Older	Total	
M1[1]	605	304	909	5,100	1,300	6,400	7,309
L1[1]	779	420	1,199	5,741	1,461	7,202	8,401
XXL1[1]	938	502	1,440	6,053	1,539	7,592	9,032

Notes: The U.S. Census refers to temporarily occupied households such as vacation and second homes as "seasonal households." Temporary population estimates are based on a summer weekend scenario.

[1]M1, L1, and XXL1 (Priest and others, 2013e)

Figure RB-2. Rockaway Beach urban growth boundary tsunami zone building statistics and demographics for three tsunami zones expressed as percentages relative to the XXL1 zone. Temporary population estimates assume a summer weekend scenario.

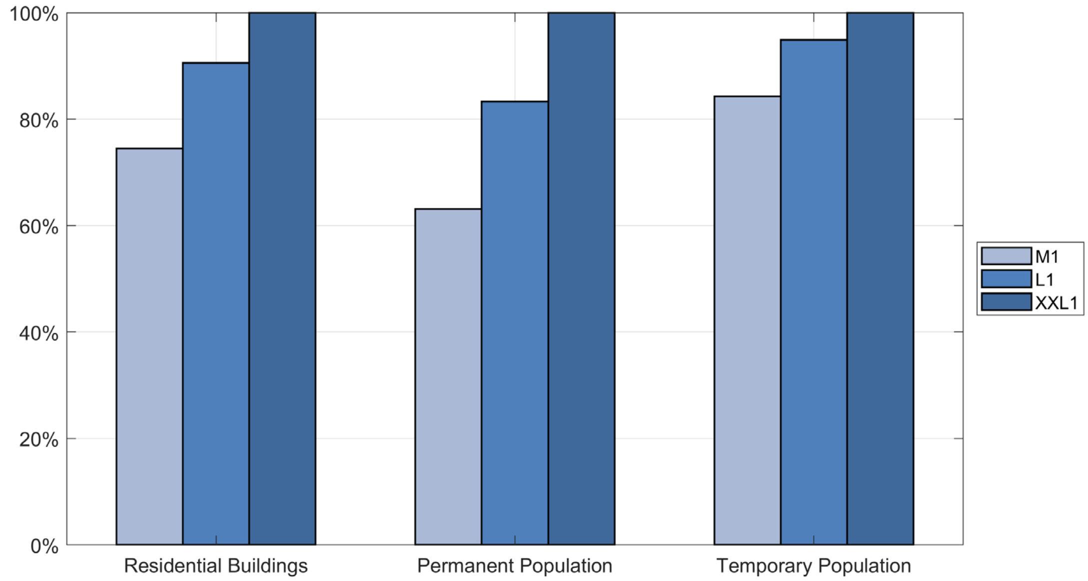


Table RB-3 indicates that the majority of the permanent residents within the Rockaway Beach tsunami zone (XXL1) occupy either single-family residential homes (60%), or manufactured housing (28%); the latter reflects the highest ratio of all the communities in this study. The remaining permanent population is distributed across a wide variety of housing classifications that include multi-family residential (8%), and hotel/motel (2%). Similarly, we find that 80% of the temporary visitor population is located in single-family vacation and second homes, manufactured housing, and multi-residential housing (9%, **Table RB-3**). About 5% of the temporary population stay in motel/hotels. These results show the importance of Rockaway Beach as a major recreational destination, while also highlighting potential challenges that tsunami educators and community leaders will need to address. For example, one major challenge with such a dispersed temporary population is ensuring that every vacation home contains appropriate information about the earthquake/tsunami hazard (e.g., warning signs to look out for, response procedures), as well as site-specific information (e.g., tsunami evacuation maps) about where to go if an earthquake occurs.

Table RB-2. Estimates of permanent and temporary population by building type in the Rockaway Beach urban growth boundary XXL1 tsunami zone. Temporary population estimates assume a summer weekend scenario.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single-Family Residential	858	60%	6,040	80%
Manufactured Housing	404	28%	428	6%
Multi-Family Residential	109	8%	690	9%
Hotel/Motel	34	2%	393	5%
Mobile (Tents and RVs)	0	0%	42	1%
Other (incl. Mixed-Use)	35	2%	0	0%
Total	1,440	100%	7,593	100%

To evaluate time and distance to high ground and thus safety, we assume it takes ~10 minutes for people to mobilize (i.e., milling behavior) prior to evacuating, while the tsunami wave fully inundates Rockaway Beach at 27 minutes. Accordingly, people have no more than 17 minutes to reach safety before the wave reaches them. If we assume that people travel at a "walk" speed (i.e., ~4 fps), we can estimate the distance of ground that can be covered (~4,080 ft) within the 17-minute time frame (Equation 2 and **Table 2-4**); people whose distances to safety exceed 4,080 ft would thus not reach safety in time assuming they maintain an evacuation speed of ≤4 fps. We provide distance to safety statistics using the XXL1 tsunami scenario (which assumes that non-seismically retrofitted bridges fail) in **Figure RB-3** for both the permanent and temporary population, and as a cumulative distribution plot in **Figure RB-4**. Using this approach, we find that for Rockaway Beach, the median distance to safety for the permanent population is ~2,460 ft, compared with ~3,330 ft for temporary residents (**Figure RB-4**). This indicates that the temporary population as a group is located farther away from safety. Furthermore, we find that the majority of hotel and motels in Rockaway Beach within the tsunami zone are spread out, with distances to safety that range from ~3,000 ft to as much as 10,000 ft to safety (**Figure RB-3**). Given the threshold of 4,080 ft and assumptions noted previously, our analyses suggest that <12% of the permanent population in the tsunami zone might not reach safety in time before the tsunami inundates the community (**Figure RB-4**). Conversely, we estimate that ~30% of the temporary visitor population would be unlikely to reach high ground, when traveling at 4 fps. Thus, for people located at distances to safety that are ≥4,080 ft, it is imperative that they leave sooner and travel at speeds faster than 4 fps (e.g., "fast walk" to "jog"). This is reinforced in **Figure RB-4**, which demonstrates that by increasing the group evacuation speed to 6 fps, ~99% (85%) of the permanent (temporary) population could potentially reach safety for an XXL1 tsunami event.

Table RB-3. Estimates of permanent and temporary population by building type in the Rockaway Beach urban growth boundary XXL1 tsunami zone. Temporary population estimates assume a summer weekend scenario.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single-family Residential	858	60%	6,040	80%
Manufactured Housing	404	28%	428	6%
Multi-family Residential	109	8%	690	9%
Hotel/Motel	34	2%	393	5%
Mobile (Tents and RVs)	0	0%	42	1%
Other (incl. Mixed-use)	35	2%	0	0%
Total	1,440	100%	7,593	100%

8.2.2 Earthquake and Tsunami Building Damage and Debris Estimates

Within the XXL1 tsunami zone, building repair costs caused by an XXL1 tsunami greatly exceed the repair cost estimated from the earthquake ground motion and earthquake-induced ground deformation (**Table RB-4**). This is primarily due to the prevalence of wood frame, light-frame steel, and manufactured housing types in the community that are unable to withstand the large hydraulic forces of a tsunami. As can be seen from **Table RB-4**, the weight of debris generated by the destruction of the buildings in the tsunami zone is estimated to be ~190,000 tons; note this estimate reflects a minimum estimate as the calculation excludes content in the buildings, vehicles, and other forms of debris. Combined earthquake and tsunami building repair costs are calculated to be ~$514 million, with the bulk of the cost attributed to the destruction caused by the tsunami. However, these costs will almost certainly be higher when communities factor in the added cost to repair buildings and infrastructure located outside of the tsunami zone that are also damaged by the earthquake ground motion.

Table RB-4. Building repair costs and debris weight calculated for the Rockaway Beach urban growth boundary dues to a CSZ earthquake and XXL1 tsunami.

Number of Buildings	Building Square Footage (thousand)	Building Value ($ Million)	Natural Hazard	Building Repair Cost ($ Million)	Loss Ratio	Debris from Damaged Buildings (tons)
2,361	4,460	$529	Earthquake	$149	28%	—
			Tsunami	$493	93%	—
			Combined	$514	97%	190,000

Figure RB-3. Distribution of permanent (top) and temporary (bottom) populations relative to tsunami safety within the Rockaway Beach urban growth boundary XXL1 tsunami zone (Gabel and Allan, 2017). Distance to safety is based on a 2 AM scenario, while the temporary population estimates assumes a summer weekend. "Other" category includes mixed-use commercial buildings. See the text for significance of the 4 fps threshold.

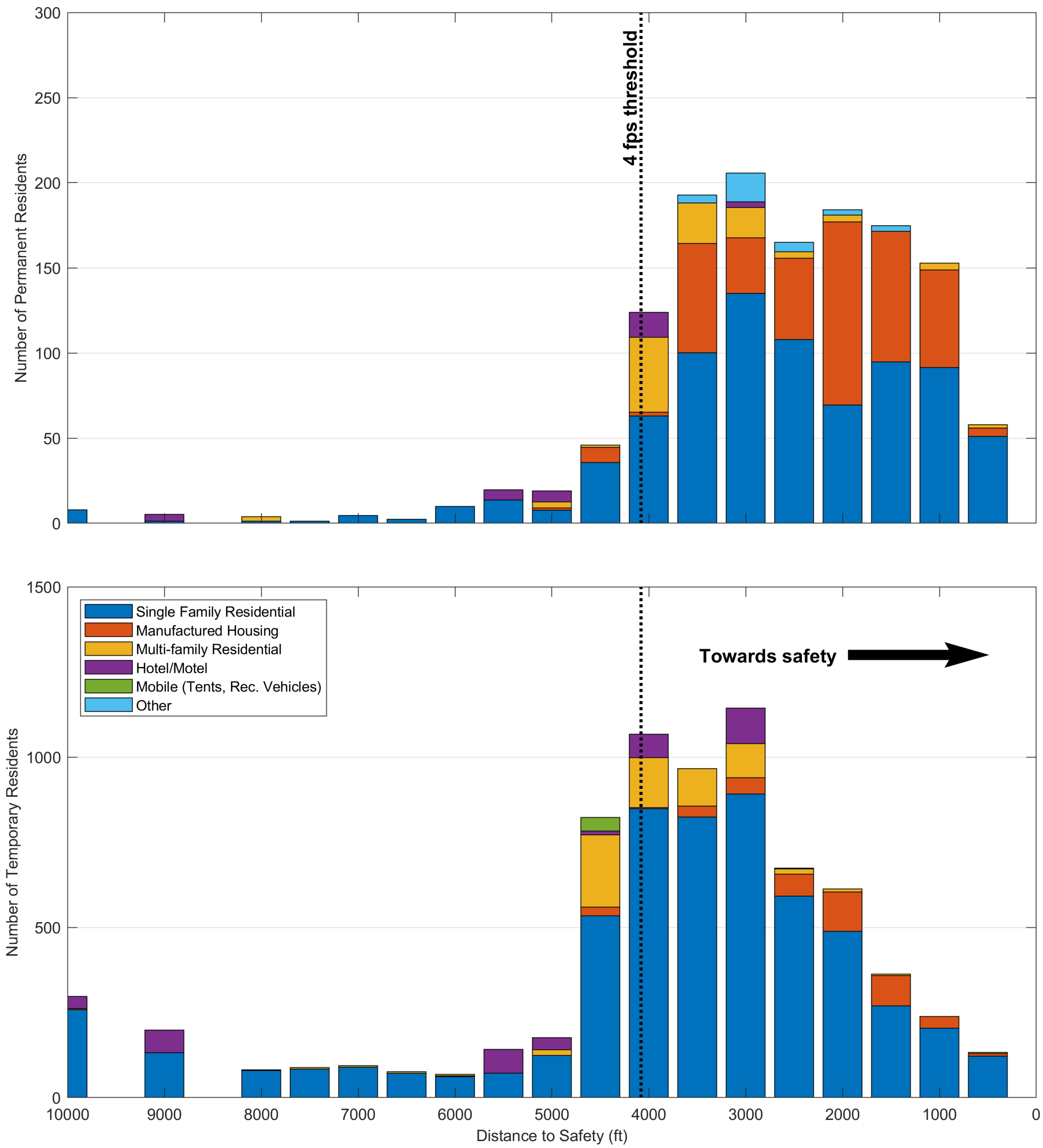
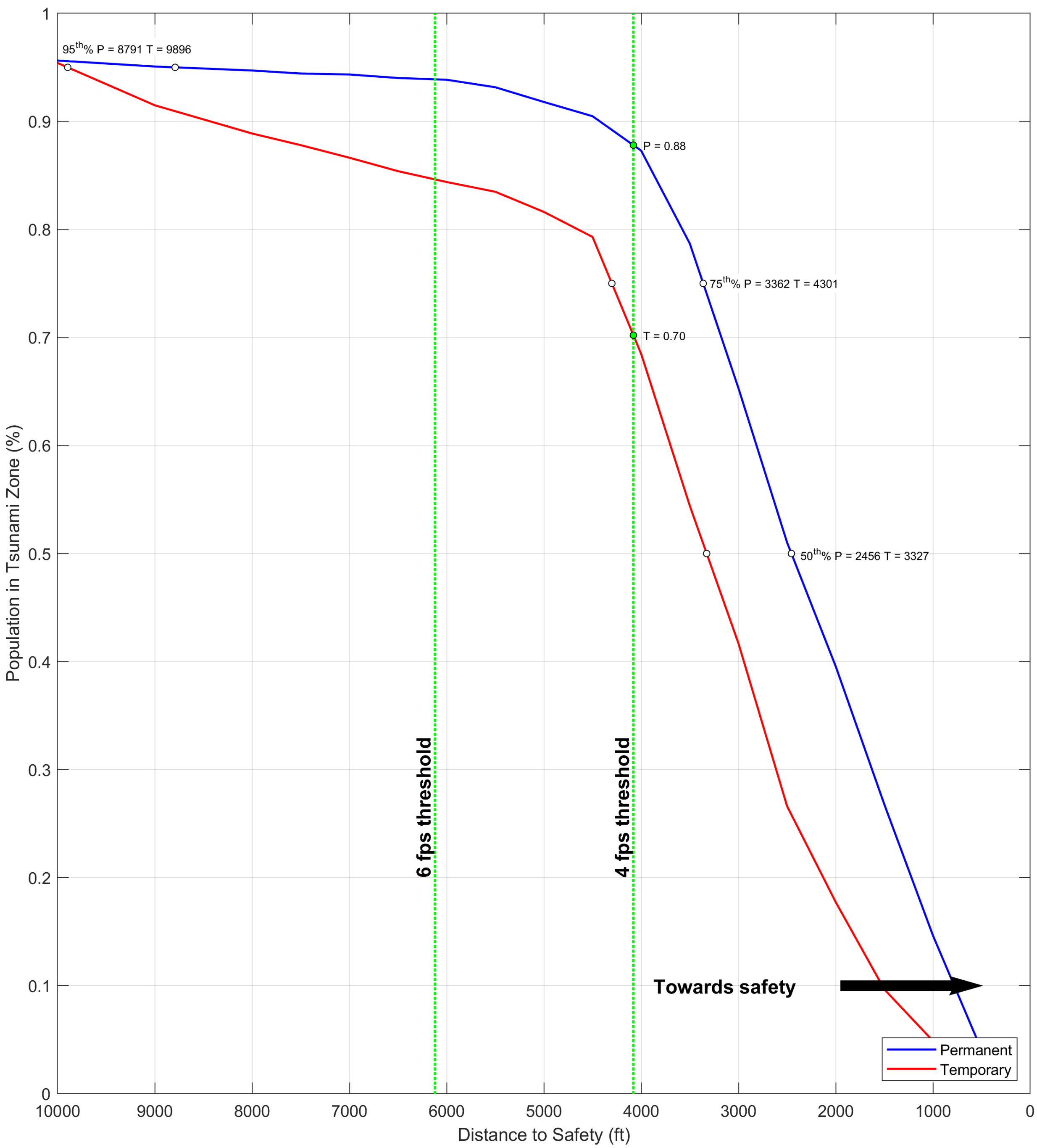


Figure RB-4. Cumulative distribution plot of permanent and temporary populations relative to tsunami safety within the Rockaway Beach urban growth boundary XXL1 tsunami zone. Figure includes two evacuation reference speed thresholds: 4 fps ("walk") and 6 fps ("fast walk"). Reported values for P and T are, respectively, the permanent and temporary population.



8.2.3 Injury and Fatality Estimates from Earthquake and Tsunami

Building occupant injury and fatality estimates due to earthquake ground motion are low (~2.3% and 1.2% for permanent and temporary residents, respectively; **Table RB-5**), given the overall population in the XXL1 tsunami zone. This is because the majority of residents occupy wood-frame buildings. This building type is considered to be the most seismically resilient building construction type (FEMA, 2015a). Depending on the extent of a person's injury or how the person responds to the event and injury (i.e., shock), it is likely that some of the injured population may not be able to evacuate from the tsunami zone in a timely manner and may therefore be killed by the ensuing tsunami as they attempt to evacuate out of the tsunami zone.

Table RB-5. Injuries and fatalities resulting from a CSZ earthquake sustained by resident group types in the Rockaway Beach urban growth boundary, summer weekend 2 AM scenario.

Hazus Injury Severity Level	Permanent Residents	Temporary Residents	Total
Level 1: Minor Injuries	25	73	98
Level 2: Injuries Requiring Hospitalization	6	15	21
Level 3: Life-Threatening Injuries	1	1	2
Level 4: Deaths	1	2	3
Total	33	91	124

Note: See **Table 2-3** for a complete definition of the Hazus injury levels.

In defining the number of casualties caused by the tsunami at Rockaway Beach, we analyzed three tsunami XXL1 evacuation scenarios described by Gabel and Allan (2017). These are:

- An XXL1 scenario that assumes that "non-retrofitted bridges fail" due to the earthquake ground motion. In this scenario, the Hazus tsunami casualty model assumes evacuees have prior knowledge that the specified bridges are likely damaged and thus will seek the most optimal route for evacuation;
- An XXL1 scenario that assumes all evacuation routes are intact and usable (i.e., bridges are seismically retrofitted); and,
- An XXL1 scenario that includes a hypothetical vertical evacuation scenario. Again, the Hazus tsunami casualty model assumes that people nearby are aware of, and are willing to use, the vertical evacuation structure.

As indicated in **Table RB-6**, fatalities caused by the XXL1 scenario at Rockaway Beach range from ~21% for the permanent population and 37% for the temporary population, while injuries make up a very small portion (~1–2%) of this scenario. The bulk of the fatalities can be attributed to visitors located in high-occupancy condominiums, motels, and vacation and second homes located between North 3rd Avenue and the Highway 101 bridge. With our second scenario (seismically retrofitting the Highway 101 and 12th St bridges), we find a slight reduction in the number of fatalities (reduced by ~300 less than the first scenario). However, overall numbers of fatalities remain high, with ~2,800 people killed in this scenario. With the construction of a hypothetical vertical evacuation at Highway 101 and NW 11th St, overall fatalities in Rockaway Beach are reduced by about 50% (i.e., ~1,400 fewer fatalities) relative to the first scenario. These data suggest that constructing some form of vertical evacuation structure could save a significant number of lives, when placed in the most appropriate location. Again, it is important to stress that these numbers assume that every person evacuates at 4 fps ("walk") speed. As a result, evacuees traveling at speeds greater than a walk (i.e., fast walk to jog to run) will greatly increase their chance of surviving an XXL1 event, reducing the overall casualty numbers. Nevertheless, the Rockaway Beach community should be mindful of the fact that as the group departure time increases (i.e., longer milling, **Table RB-7**) and/or people are unable to evacuate quickly enough along evacuation routes, the number of fatalities could begin to increase significantly. For example, a 15 (20) minute departure time (**Table RB-7**) indicates that 62% (72%) of the population in the tsunami zone could be killed.

Table RB-6. Injury and fatality estimates for several CSZ tsunami scenarios in the Rockaway Beach area. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, a 10-minute milling time prior to departure, and wave arrival time at the tsunami runup line of 27 minutes. Injury and fatality estimates are rounded to nearest 10.

Tsunami Scenario	Population Segment	Number of People	Fatalities	Injuries	Injury and Fatality Ratio: Fatalities	Injury and Fatality Ratio: Injuries
XXL1 tsunami, present day: non-retrofitted bridges fail (Highway 101 and NE 12th St)	Permanent	1,440	300	20	21%	1%
	Temporary	7,593	2,790	180	37%	2%
	Total	9,033	3,090	200	34%	2%
XXL1 tsunami with hypothetical seismic retrofit of Highway 101 and NE 12th St bridges	Permanent	1,440	280	30	19%	2%
	Temporary	7,593	2,510	210	33%	3%
	Total	9,033	2,790	240	31%	3%
XXL1 tsunami with hypothetical vertical evacuation at N Miller St and NW 11th Ave. Highway 101 and NE 12th St bridges out	Permanent	1,440	190	30	13%	2%
	Temporary	7,593	1,470	180	19%	2%
	Total	9,033	1,660	210	18%	2%

Note: Population and tsunami casualty estimates are limited to people residing in the respective tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

The tsunami injury and casualty estimates provided in **Table RB-6** and **Table RB-7** are based on a group average (median) evacuation walking speed of 4 fps, with individuals ≥65 years evacuating at 3.2 fps. The estimated fatalities are generally much larger than what was determined by Gabel and Allan (2017), who suggested that an XXL1 tsunami is survivable in most locations, *provided people evacuate at specified minimum speeds*, often faster than 4 fps. To better illustrate the evacuation situations and opportunities, we symbolize the distance to safety for the three scenarios using two different walking speeds (4 and 6 fps, adjusted to 3.2 and 4.8 fps for people ≥65), using the survival likelihood distance breakpoints identified by the formula accompanying **Table 2-4** for a tsunami wave arrival of 27 minutes.

Assuming everyone evacuates at a speed of 4 fps (walk) under existing conditions, injuries and fatalities caused by an XXL1 tsunami can be seen to be concentrated along the barrier beach located immediately west of Lake Lytle, farther north near Manhattan Beach, and in the far north at Nedonna Beach (**Figure RB-5**); casualties are also identified along the western most strip of development near Twin Rocks in the south. At 6 fps (**Figure RB-6**) the injuries and fatalities are almost entirely centralized to the barrier beach west of Lake Lytle.

As noted earlier, retrofitting the Highway 101 and 12th St bridges reduces the overall number of casualties. However, the improvements in evacuation potential are relatively minor. Most of these improvements are found in the Manhattan Beach area (compare **Figure RB-7** with **Figure RB-5**) and to a lesser extent North Miller St and NW 13th Ave. Increasing the overall evacuation speeds to 6 fps reduces the potential for casualties further, although a hot spot remains at North Miller and North 8th St (**Figure RB-8**). Construction of a hypothetical vertical evacuation structure at North Miller St and NW 11th Ave reduces the overall number of casualties by about 50% relative to the scenario without such a structure. However, even the addition of such a structure does not completely eliminate the potential for fatalities in the Lake Lytle area (**Figure RB-9**). This is only achieved when local evacuation speeds are increased to 6 fps (fast walk), and as can be seen in **Figure RB-10** the combination eliminates casualties altogether. As with the community of Port Orford, these results strongly suggest that construction of a vertical evacuation structure could save many lives.

Injuries and fatalities from a tsunami can be significantly lowered if individuals evacuate as soon as possible and travel at faster evacuations speeds (e.g., slow jog to run). We obtained injury and fatality percentages from the Hazus tsunami casualty model, varying group departure time and group walking speeds (**Table RB-7**). As expected, injuries and fatalities increase as the departure time increases (i.e., longer milling behavior), **Figure RB-11**, and decreases as speed of travel increases. Further, we estimated separate injury and fatality rates for the temporary and the permanent populations, as we previously established a distinct difference between the two groups in their distance to tsunami (**Figure RB-4**). As expected, given the increased distance to safety, temporary residents will experience higher injury and fatality rates compared to permanent residents for a given departure time and walking speed. However, even at a walking speed of 6 fps and a 10-minute departure, our model suggests that a significant portion of the temporary population (19%, **Table RB-6**) is unlikely to reach high ground in time.

Table RB-7. Injury and fatality estimates for three XXL1 tsunami scenarios in the Rockaway Beach urban growth boundary assuming different departure times. Model results assume an average walking speed of 4 fps, summer weekend 2 AM scenario, and wave arrival time at the tsunami runup line of 27 minutes. Injury and fatality estimates are rounded to nearest 10.

			Average Departure Time					
			Injuries and Fatalities			Injury and Fatality Ratio		
Tsunami Evacuation Scenario	Population Segment	Number of People	10 Minutes	15 Minutes	20 Minutes	10 Minutes	15 Minutes	20 Minutes
XXL1 Tsunami, Present Day: Non-retrofitted bridges fail (Highway 101 and NE 12th St)	Permanent	1,440	330	720	910	23%	50%	63%
	Temporary	7,593	3,000	4,900	5,600	40%	65%	74%
	Total	9,033	3,330	5,620	6,510	37%	62%	72%
XXL1 Tsunami with Hypothetical Seismic Retrofit of Highway 101 and NE 12th St Bridges	Permanent	1,440	310	710	900	22%	49%	63%
	Temporary	7,593	2,700	4,800	5,400	36%	63%	71%
	Total	9,033	3,010	5,510	6,300	33%	61%	70%
XXL1 Tsunami with Hypothetical Vertical Evacuation at N Miller St and NW 11th Ave. Highway 101 and NE 12th St Bridges Out	Permanent	1,440	220	650	860	15%	45%	60%
	Temporary	7,593	1,600	4,000	4,900	21%	53%	65%
	Total	9,033	1,820	4,650	5,760	20%	51%	64%

Population and tsunami casualty estimates are limited to people residing in the XXL1 tsunami zone within the designated urban growth boundary (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time. Casualties from tsunami are dominated by fatalities, with the injury ratios all less than 10% (**Table 3-6**).

Figure RB-5. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami "bridges-out" scenario (Gabel and Allan, 2017), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

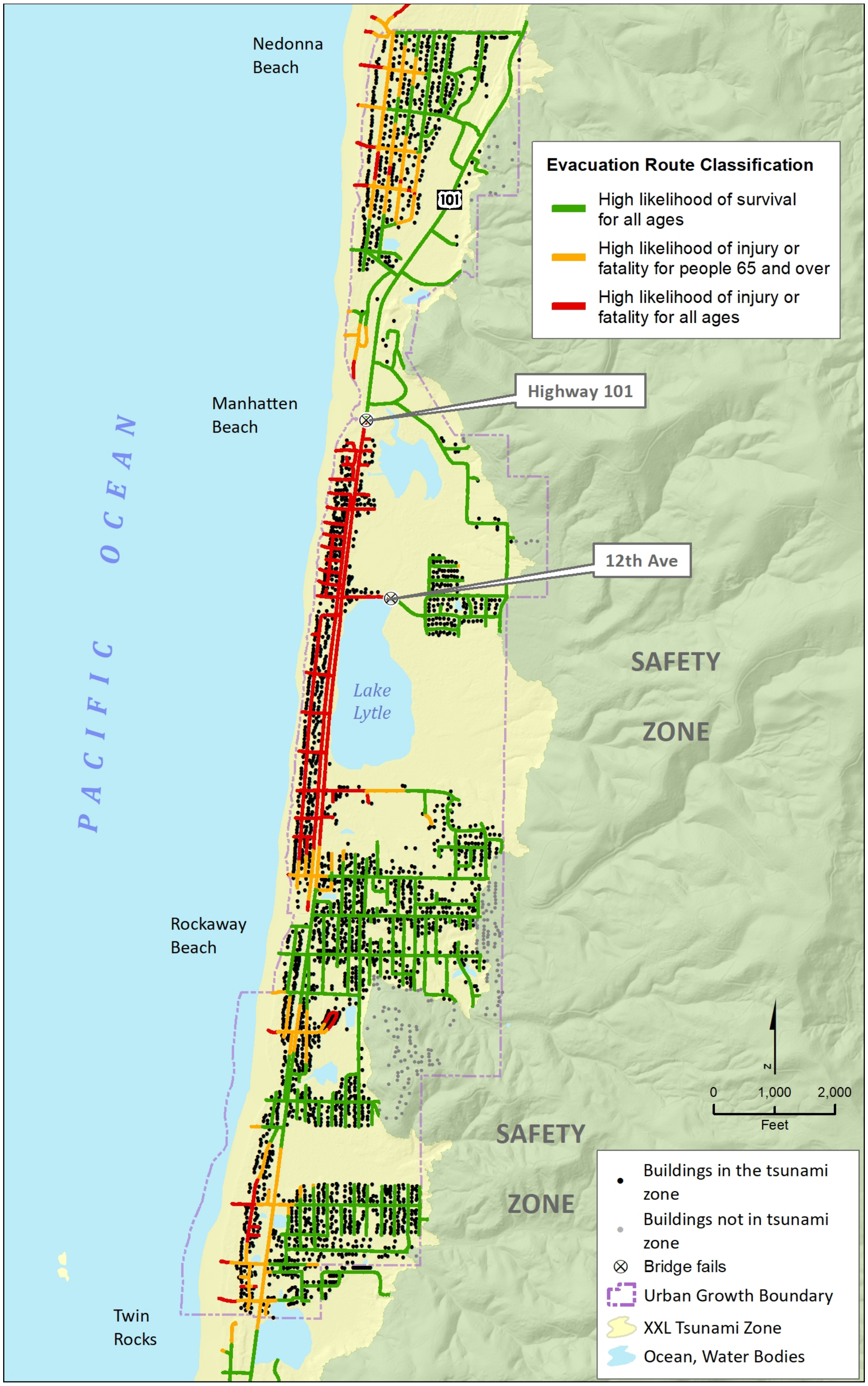


Figure RB-6. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami "bridges-out" scenario (Gabel and Allan, 2017), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

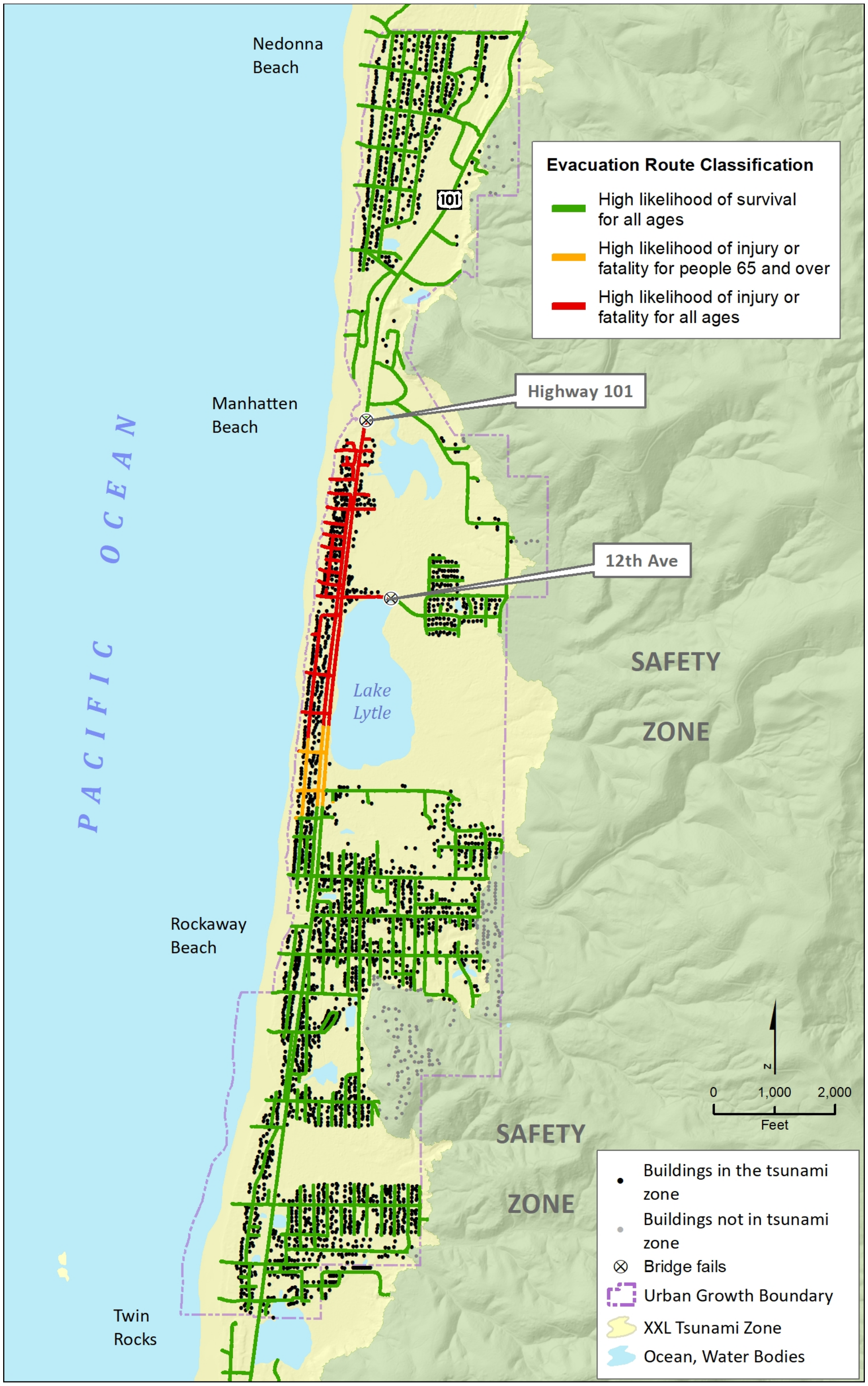


Figure RB-7. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami "retrofitted bridges" scenario (Gabel and Allan, 2017), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

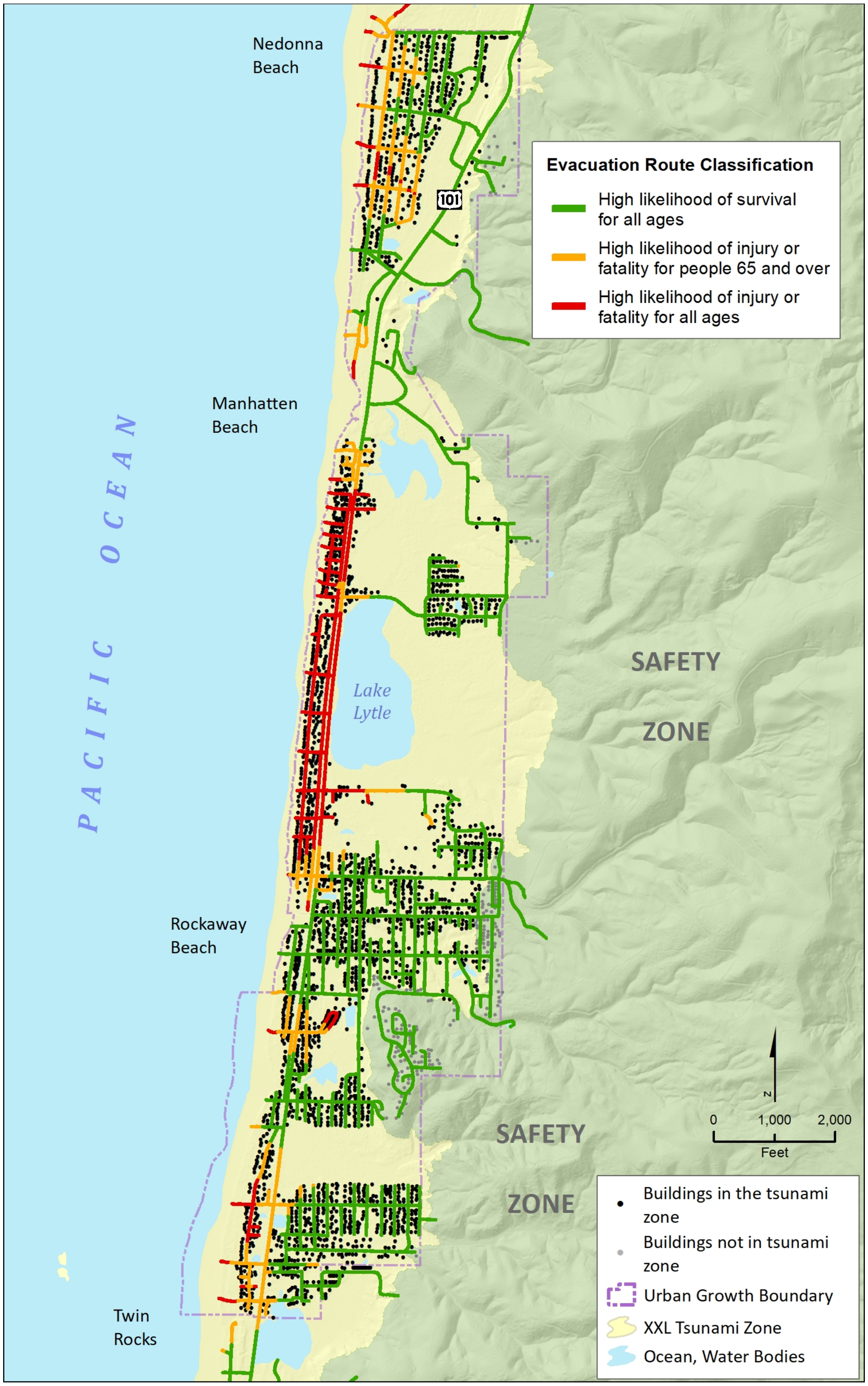


Figure RB-8. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami "retrofitted bridges" scenario (Gabel and Allan, 2017), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

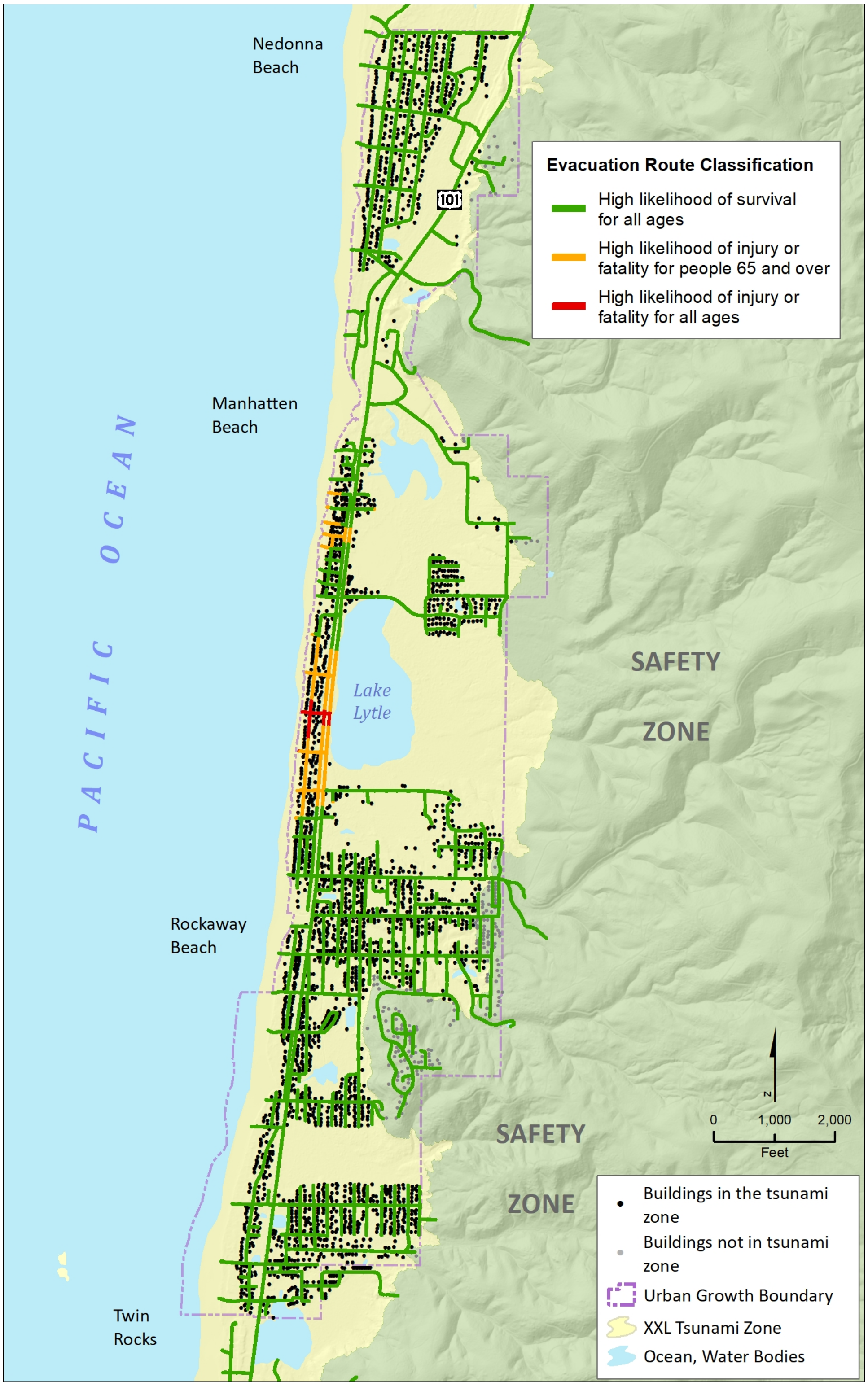


Figure RB-9. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami with a hypothetical vertical evacuation structure (represented as a star) at N Miller St and NW 11th Ave (Gabel and Allan, 2017), and a "bridges out" scenario symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

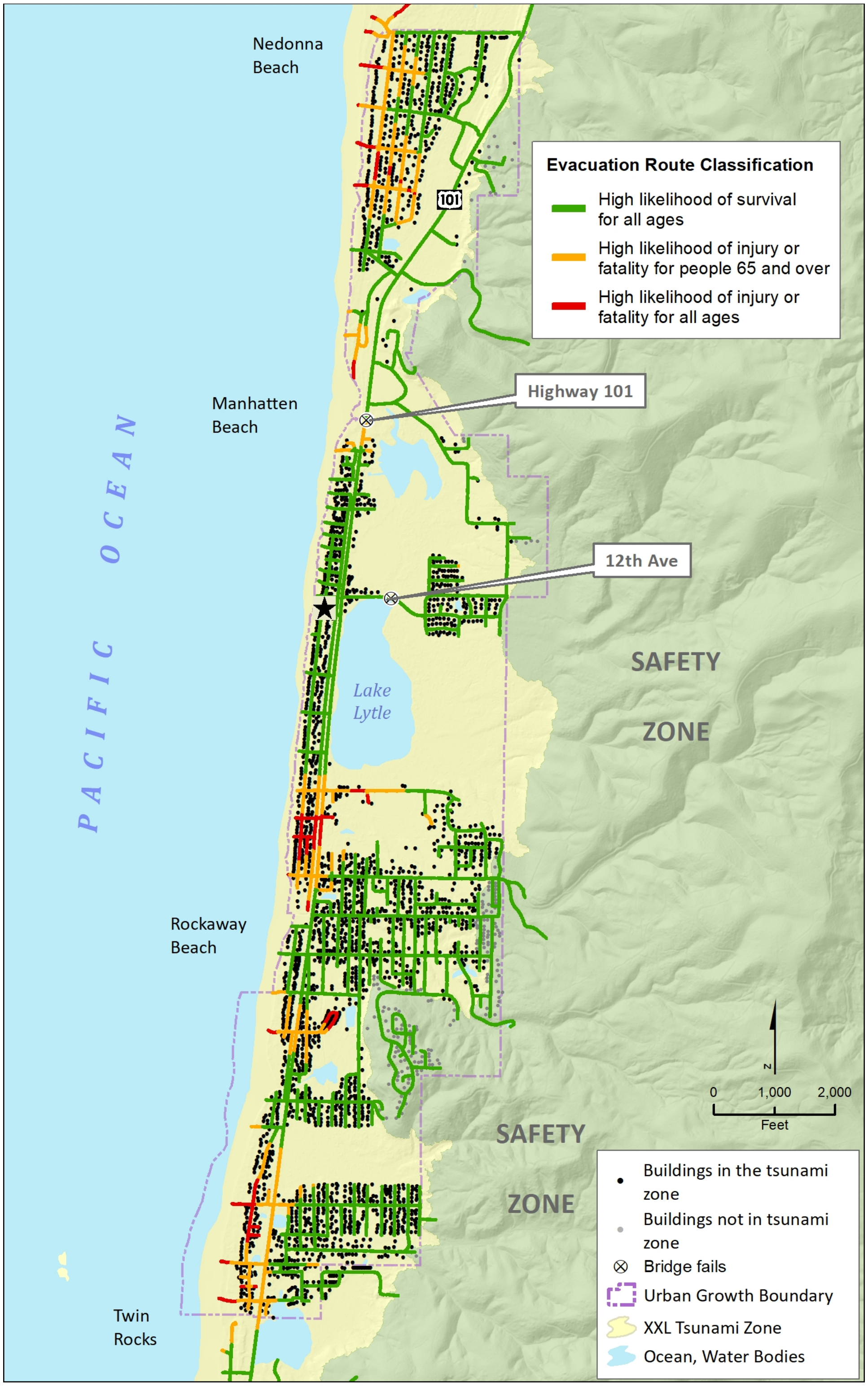


Figure RB-10. Rockaway Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami with a hypothetical vertical evacuation structure (represented as a star) at N Miller St and NW 11th Ave (Gabel and Allan, 2017), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 27 minutes.

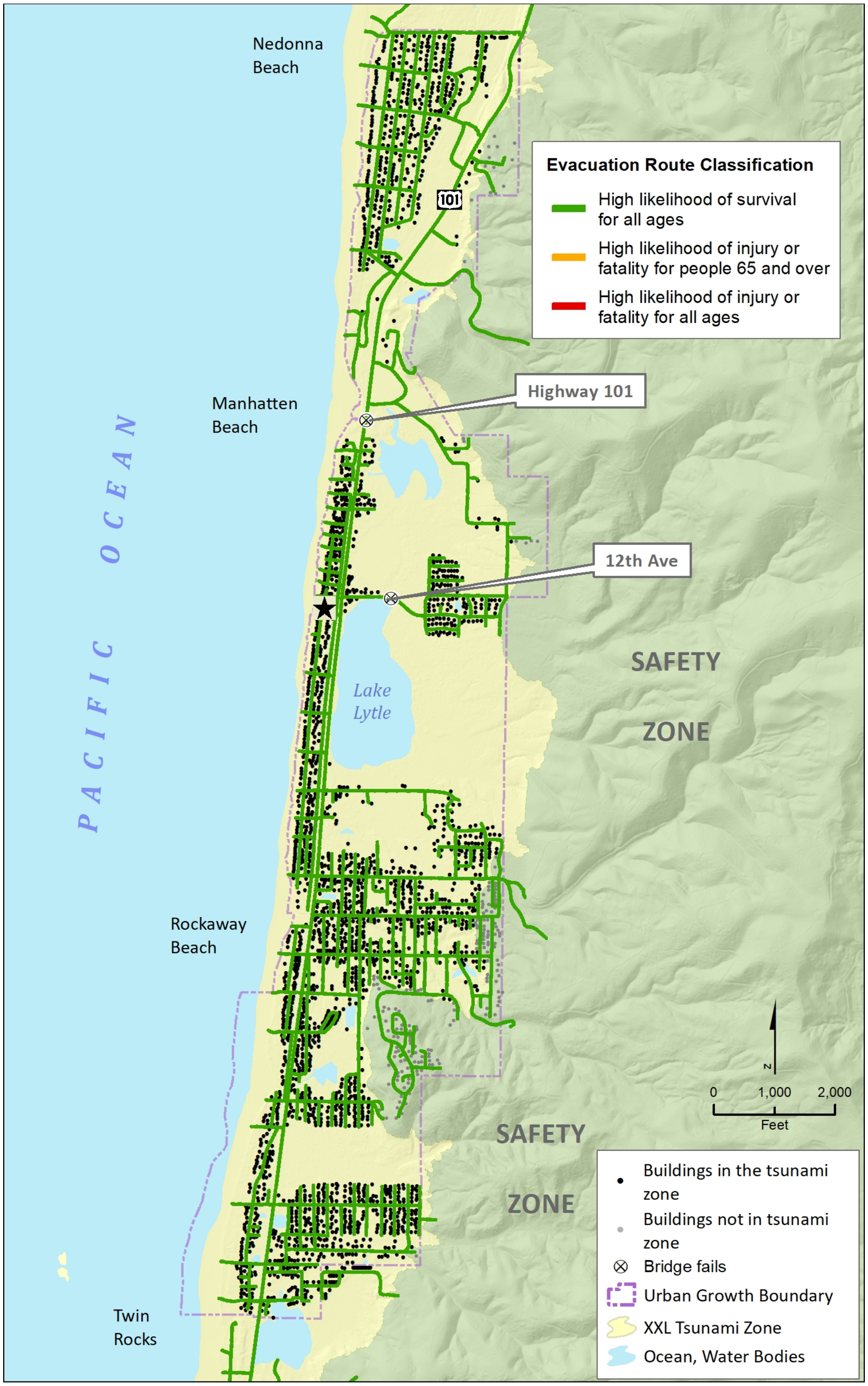
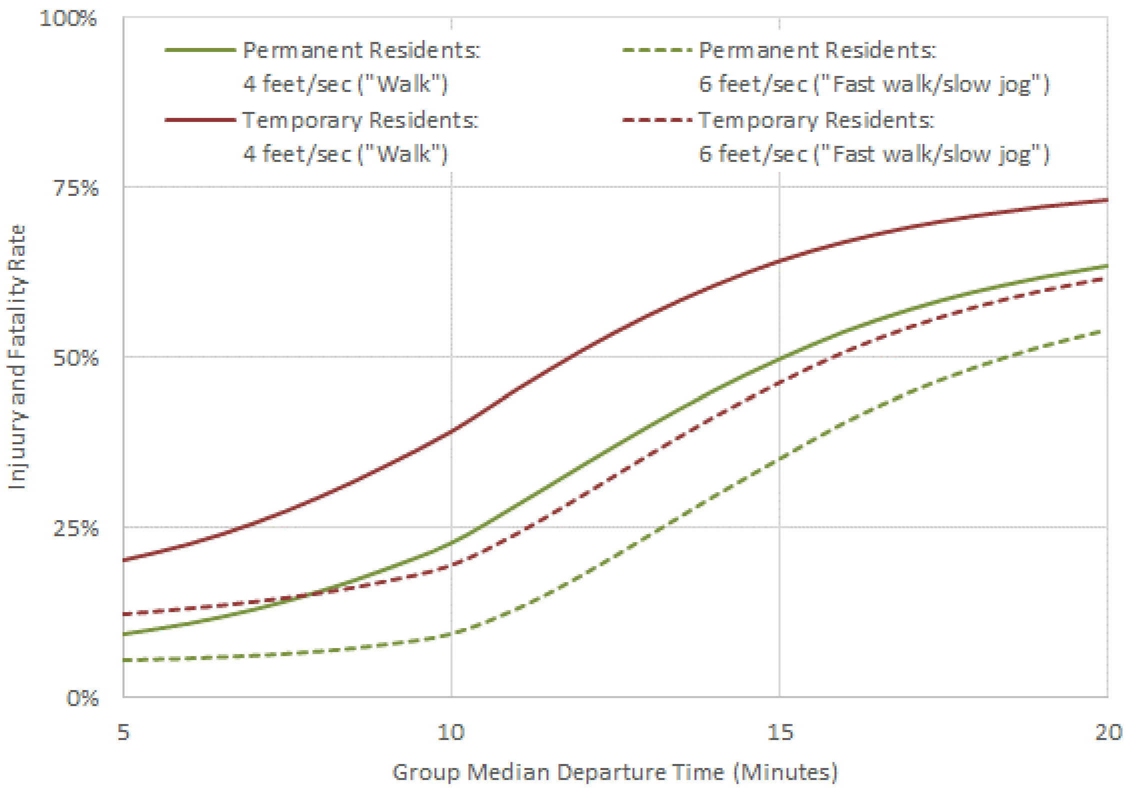
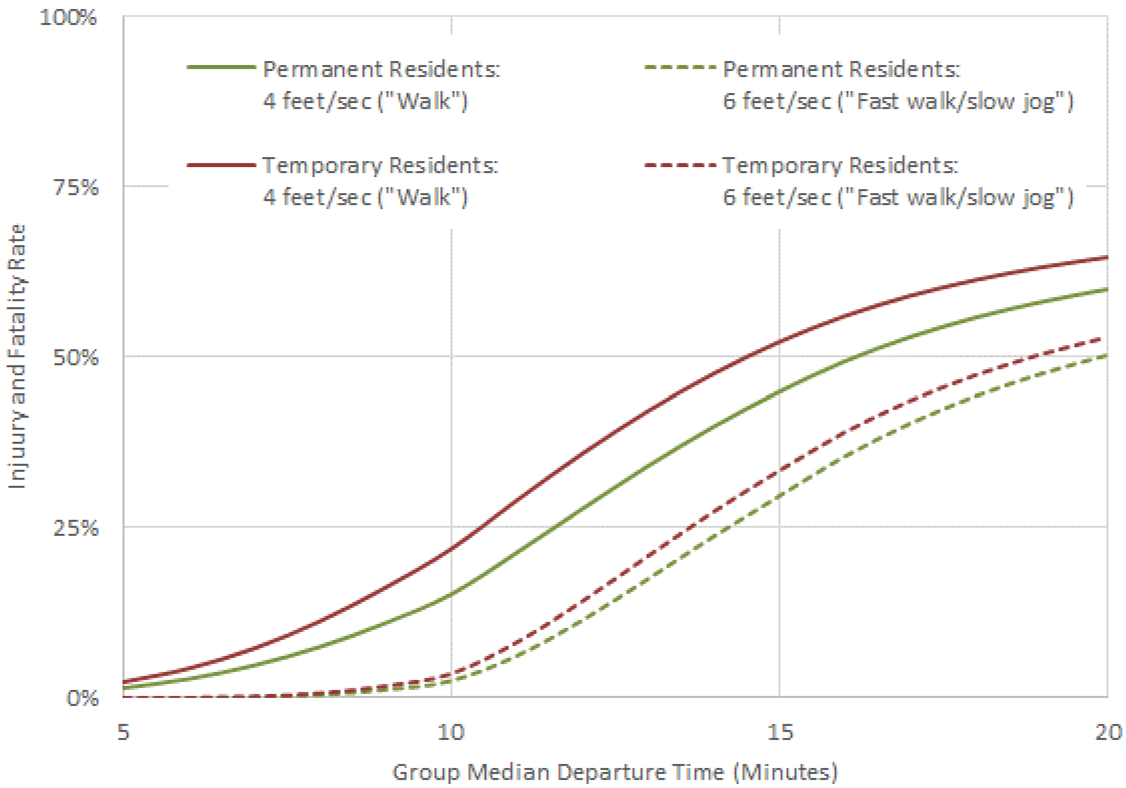


Figure RB-11. Rockaway Beach injury and fatality rates estimated for an XXL1 tsunami "bridges-out" scenario as a function of departure time and two different evacuation speeds. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the tsunami zone.



When repeated for the hypothetical vertical evacuation scenario (located at N Miller St and NW 11th Ave), our analyses indicate that the fatality rates are near zero (dashed lines in **Figure RB-12**) at ~10 minute departure (6 fps evacuation speeds) for *both* permanent and temporary population, consistent with the results of **Figure RB-9** and **Figure RB-10**. Note, however, that the Hazus tsunami casualty model incorporates a statistical dispersion factor (C_{STD}) that accounts for a range of departure times and walking speeds (**Figure 2-2**); the 10-minute departure and 6 fps walking speed are assumed to be group averages. Thus, the Hazus tsunami casualty model suggests that a small portion of the population will not evacuate successfully, even with a vertical evacuation structure. This will likely be the actual situation, given that some portion of the population may not be able to sustain a 6-fps walking speed. If the statistical dispersion factor (C_{STD}) is set to near zero, the injury and fatality count at 10-minute departure, 6 fps indeed becomes zero.

Figure RB-12. Rockaway Beach injury and fatality rates estimated for an XXL1 tsunami with a hypothetical vertical evacuation structure as a function of departure time and two different evacuation speeds. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the tsunami zone.



8.2.4 Displaced Population

Permanent and temporary residents who successfully evacuate out of the tsunami zone will very likely require short- to medium-term shelter, given that their residences are presumed destroyed or rendered uninhabitable (**Table RB-4**). Temporary residents will likely not be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017) and that their personal vehicles will likely be destroyed or damaged by the tsunami.

For mass care planning purposes, displaced population estimates can be obtained by subtracting the total injuries and fatalities in **Table RB-6** from the total number of people (permanent and temporary) estimated to be in the XXL1 tsunami zone. From those data we estimate that the displaced population in Rockaway Beach from an XXL1 event could be as low as ~1,100 people and increase to almost 6,000 people. The former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every vacation home, rental facility, and RV facility at maximum capacity.

We note again that our analysis is limited to the buildings and people in the Rockaway Beach XXL1 tsunami zone. Some portion of the permanent and temporary residents outside of the tsunami zone can be assumed to need food and shelter, as their residential structures, including motels and hotels, may have been heavily damaged from the earthquake ground motion. In addition, extensive development in the tsunami zone currently exists south of Rockaway Beach UGB (Barview), and displaced people in those locations will need shelter.

A lesser magnitude tsunami event, such as a M1 scenario, will produce fewer tsunami injuries and fatalities, but will have likely destroyed or render uninhabitable nearly all the residential buildings in the M1 tsunami zone. Note that of the total population in the Rockaway Beach tsunami zone, 63% and 84% of the permanent and temporary residents (respectively) occupy buildings in the M1 tsunami zone (**Table RB-1**). While more people are expected to survive this particular tsunami event, a significant portion of the population will need short-term shelter.

8.2.5 Essential Facilities, Special Facilities, and Key Infrastructure

Our analyses indicate the following *essential facilities* in the Rockaway Beach UGB tsunami zone:

- Rockaway Beach City Hall and Public Works
- Rockaway Beach Fire Dept.
- Rockaway Beach Police Dept.
- Neah-Kah-Nie Middle School
- Neah-Kah-Nie High School

Our analyses revealed no *special facilities* in the Rockaway Beach UGB tsunami zone. However, we did identify this *key infrastructure facility*:

- Rockaway Beach Water Treatment Plant, S 3rd Ave and S Easy St

8.2.6 Employment

Nearly all businesses and jobs in the Rockaway Beach UGB are located within the tsunami zone (**Table RB-8**). The two highest employment sectors are Accommodation and Food Services (NAICS code 72) and Educational Services (NAICS code 61) and with 42% and 32% of the jobs, respectively.

Table RB-8. Number of businesses, jobs, and annual wages paid in the Rockaway Beach XXL1 tsunami zone.

	XXL1 Tsunami Zone	Rockaway Beach Urban Growth Boundary
Number of businesses	43	44
Number of jobs	405	*
Annual wages paid ($ million)	$13.30	*

* Numbers excluded for employer privacy reasons.

8.2.7 Social Characteristics

We reiterate that the American Community Survey (ACS) social characteristic data span the entire community (and county) and are not at a resolution that would allow us to better define these statistics by tsunami zone. The interested user is encouraged to review the introduction to Appendix A for additional resources on the ACS in order to better understand vulnerable permanent populations living within the tsunami zone.

As noted previously, our analyses indicate that ~35% of the permanent residents in the Rockaway Beach XXL1 tsunami zone are ≥65 years of age (**Table 3-2**), which is higher than the Oregon XXL1 tsunami zone average of 27%. We can delve deeper into the social aspect of a local population by evaluating other characteristics such as the number of people who speak Spanish (or other languages) as well as those who may have disabilities. Both datasets are important because they have a direct bearing on basic outreach (e.g., providing material that has been translated) and in terms of identifying those who may need evacuation assistance. The proportion of Spanish-speaking (and other languages) households in

Rockaway Beach is significantly smaller when compared to the Tillamook County average of 6.2%. Insufficient sample size prevents an estimate for households with limited English fluency regardless of language (**Table RB-9**).

Table RB-9. Household spoken language statistics in City of Rockaway Beach. Data taken from American Community Survey 2013–2017 5-year estimates.

	City of Rockaway Beach		Tillamook County
	Number of Households	Percent of Households with Margin of Error	Percent of Households with Margin of Error
Households speaking Spanish	5	0.9% ± 1.2%	6.2% ± 1.0%
Households with limited English fluency; Spanish spoken	*	*	0.5% ± 0.4%
Households with limited English fluency; all languages	*	*	0.5% ± 0.4%

* Insufficient data

Table RB-10 presents information on the percentages of people with disabilities in the Rockaway Beach area. Overall, these results indicate the proportion of the local population with disabilities (~24%) is slightly higher when compared with the county wide average, estimated to be ~20%. Of particular concern is the relatively large number of individuals with ambulatory (~12.1%), cognitive, or hearing disabilities, as well as a large (~9.6%) number of people classified as experiencing independent living difficulty, all of whom are likely to need significant help evacuating from the tsunami zone. Not all of these individuals may reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

Table RB-10. Number of individuals with disabilities (by type) for City of Rockaway Beach and Tillamook County. Data taken from American Community Survey 2013–2017 5-year estimates. An individual with a disability may have more than one difficulty.

	City of Rockaway Beach		Tillamook County
	Number of Individuals	Percent of Population with Margin of Error	Percent of Population with Margin of Error
Individuals with a disability	317	24.3% ± 6.4%	20.2% ± 1.7%
Difficulty Category			
Hearing	104	8.0% ± 3.5%	7.4% ± 0.9%
Vision	34	2.6% ± 2.0%	2.9% ± 0.7%
Cognitive	82	6.5% ± 2.8%	7.9% ± 1.2%
Ambulatory	153	12.1% ± 5.2%	11.0% ± 1.3%
Self-care	19	1.5% ± 1.7%	4.4% ± 1.0%
Independent Living	100	9.6% ± 4.8%	9.3% ± 1.5%

8.2.8 Discussion and Recommendations

Evacuation Challenges

The topography, physiographic barriers, older infrastructure, and human settlement patterns in Rockaway Beach have created challenges for timely evacuation from a tsunami. Distance to safety is longest in areas to the immediate west of Lake Lytle, along the Manhattan Beach shoreline, and in buildings close to the ocean in the Twin Rocks area. Other notable areas of concern include Nedonna Beach in the far north, and at the Rockaway Beach RV Park on S Beacon St. Overall, our analyses indicate that temporary residents (visitors) tend to be located closer to the ocean, and thus farther away from high ground. This is in stark contrast with permanent residents, who are on average about 1,000 ft closer to high ground. Other challenges facing the local community are key bridges that could fail during the earthquake, thereby blocking or limiting more efficient routes to safety. The most significant of these is the 12th St bridge over Lake Lytle. While the Highway 101 bridge is also expected to fail during the earthquake, it is likely that people may be able to still scramble across the creek in order to get to nearby high ground in the north by Neah-Kah-Nie School. Many residents occupy manufactured housing, the foundations of which may fail during an earthquake, slowing down evacuation. One out of three permanent residents in the tsunami zone is 65 or older, compared with the Oregon tsunami zone average of one out of four.

Education

Of the five communities examined in our study, Rockaway Beach is characterized with the largest difference between where permanent and temporary residents are predominantly located. This is summarized in **Figure RB-3** and **Figure RB-4**, which indicate that the temporary (visitor) population is located closer to the ocean, and thus farther away from high ground out of the tsunami zone. This is further illustrated in the calculated casualties for both population groups (**Table RB-6**). Coupled with the large ratio between temporary and permanent populations on a summer weekend (**Table RB-1**), the tsunami fatality estimates are dominated by casualties associated with temporary residents. If one assumes temporary residents may engage in milling behavior that delays their departure (e.g., confirming with others on whether to evacuate or waiting for an evacuation siren), and/or are unaware of the fastest route to safety, the number of temporary fatalities can be expected to increase. For example, on a summer weekend, milling behavior by the temporary population of even five minutes will increase the overall mass casualties from ~3,000 to 4,900 (**Table RB-6**, Present Day scenario). These data demonstrate the need to educate all visitors on the tsunami hazard. To better understand the target audiences for outreach purposes, **Figure RB-3** graphically demonstrates the relatively diverse building types temporary residents occupy: single-family residential (including manufactured housing), motels, and recreational vehicle parks. Tsunami safety messaging for visitors should thus include focused outreach to hotel/motels as well as to vacation homes and second-home owners. Besides improving basic hazard awareness, such activities could also include education that local evacuation maps can now be generated for any location on the Oregon coast via the NVS tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac) and smartphone application (http://www.nanoos.org/mobile/tsunami_evac_app.php), enabling home owners to post appropriate information in their homes for their visitors. While knowledge of where high ground is located is critical, equally important is the practice of walking one's evacuation route to ensure familiarity with the route and any potential obstacles.

Rockaway Beach has a large ratio of permanent residents living in manufactured housing (23%, **Table RB-3**). Manufactured homes installed prior to 2003 are subject to slipping off their foundations (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014), potentially compromising one's ability to leave the structure quickly. Although many of the manufactured houses are relatively close to high ground (**Figure RB-3**), the compromised egress may hinder timely evacuation by the occupants. Seismic upgrades of such structures to current building standards may be cost-prohibitive. FEMA (2012a, Section D) advises having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting. Such tools may provide manufactured housing occupants a low-cost solution for rapidly exiting in the critical time interval after the earthquake ends and before the tsunami arrives.

Our model results demonstrate that loss of life can be minimized for *all* residents, permanent and temporary, if individuals evacuate as soon as possible after earthquake cessation and travel on foot as fast as possible (**Figure RB-11**).

Mitigation

Potential mitigation solutions include several approaches. For example, seismically retrofitting key bridges identified by Gabel and Allan (2017), accompanied with appropriate education and signage, could save potentially several hundred lives (**Table RB-6**). As with all bridge recommendations in this study, we recognize that there may be other motivations and benefits for seismically retrofitting the bridges, such as their being fundamental to response and recovery phases, but such evaluations are beyond this study's scope.

Another option is a tsunami vertical evacuation structure, such as the hypothetical structure we modeled in the Lake Lytle area. As demonstrated in this report, of all the potential mitigation options evaluated here, a vertical evacuation structure could save many thousands of lives. In reality though, multiple structures would probably need to be established throughout the community, sited in areas where the structures are likely to save the most lives. As with any mitigation strategy, such an approach would need to be evaluated with community input (McCaughey and others, 2017) and accompanied by well-considered post-construction education to inform residents on the best route to safety (Mostafizi and others, 2019). Furthermore, such a structure would have to be extremely high due to the large flow depths experienced throughout the Rockaway Beach area and be able to resist extremely powerful tsunami forces.

Besides structural options, we recommend the city continue to saturate the area with appropriate tsunami wayfinding signage. Of particular importance is having a sufficiently dense network of signs (either posted and/or thermoplastic on road/path surfaces) that direct people along core routes to areas outside the tsunami zone. Signs of this nature need to be spaced appropriately far apart so that they can be easily viewed and read at any time of the day or night.

Finally, we recommend and encourage local communities to practice periodic (annual) tsunami evacuation drills. To instill a culture of awareness of the tsunami hazard facing the Oregon coast, residents (and visitors) must periodically practice their evacuation routes. Studying an evacuation map is not the same as actually walking an evacuation route. Although such an approach may be disruptive to the local economy, holding periodic drills will save many countless lives. Such a culture is entrenched in Japanese way of life and likely helped save many thousands of lives during the catastrophic tsunami event on the Sendai coast on March 11, 2011. This culture is highlighted in several recent studies (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Response

Depending on the time of year a CSZ earthquake and tsunami strike, Rockaway Beach is likely to experience acute short- to medium-term sheltering needs. Should an XXL1 tsunami occur, we estimate that the displaced population in the Rockaway Beach area could range from a low of ~1,100 people to almost 6,000 people in the peak of summer (**Table RB-6**). Even a lesser magnitude tsunami will result in significant destruction of residential property. For example, an M1 tsunami will likely destroy 75% of the residential structures in the Rockaway Beach UGB, displacing ~900 permanent residents and several thousand temporary visitors (**Table RB-1**, assuming most of the residents safely evacuation from the M1 tsunami).

Rockaway Beach (and Tillamook County) will need to prepare for potentially large numbers of casualties. Overall, injuries caused by the tsunami were found to be low, averaging about 6% of the affected community. This outcome is because the majority of people who are unable to evacuate in time and are caught by the tsunami are killed. Combined earthquake and tsunami related injuries presented for Rockaway Beach are estimated to reach ~300 people (**Table RB-5** and **Table RB-6**). However, because the numbers of injured are calculated for just those in the tsunami zone, incorporating earthquake related injuries outside of the tsunami zone will almost certainly increase the overall number, potentially approaching many hundreds of people. Further work is required to better refine these numbers, especially by incorporating earthquake related injuries from outside the tsunami zone. Total fatalities calculated for the XXL tsunami scenario are estimated to be ~3,000 people (**Table RB-6**). However, this number is likely high since it assumes 100% occupancy throughout the community.

Wang (2018) examined a number of considerations for coastal hospitals to take in order to prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for needed fuel and water needs. According to the Oregon Resilience Plan documents (OSSPAC, 2013), there are about 483 licensed beds at the 11 coastal hospitals. Combined earthquake and tsunami related injuries in Rockaway Beach are estimated to be ~300 people (**Table RB-5** and **Table RB-6**); total injuries for the five communities could approach 900, exceeding existing hospital capacity on the coast. Hence, coastal hospitals will need to prepare for a surge in injuries (as well as large numbers of fatalities) that could well exceed existing capacity.

Recovery

An XXL1 tsunami will have a significant impact on local employment and ultimately on the Rockaway Beach economy. Tourism-driven services, which account for 42% of the jobs in Rockaway Beach, are almost entirely located with the XXL1 tsunami zone and are expected to be seriously impacted. This is especially the case given the number of motel/hotels located along the Rockaway Beach foredune, along with the many vacation and second homes located farther inland. Unfortunately, the situation does not improve even with an M1 earthquake and tsunami scenario, as the bulk of tourist-related businesses are in this tsunami zone. These impacts are expected to be exacerbated due to the potential disruption to transportation networks leading into Rockaway Beach, effectively shutting down any form of local tourism for what is likely to be many months after the event. Education and educational administration jobs, the second biggest sector (32%), will also be significantly impacted, given the expected outward migration of residents from the community in the days following the event.

About 1,400 permanent residents in Rockaway Beach reside in buildings within the tsunami zone (**Table RB-1**). Given the predominance of wood frame construction in the tsunami zone, nearly all the buildings will likely be destroyed in an XXL1 tsunami; about 60% of these buildings are likely to be destroyed even in a smaller earthquake event such as the M1 scenario. Many of these buildings are not in coastal flooding zones, and thus the owners are not currently required by federally backed mortgage lenders to carry flood insurance for buildings outside of a designated flood zone. However, flood insurance is available to all building owners through the National Flood Insurance Program, which covers building loss due to a tsunami (FEMA, 2018c). More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

8.3 Lincoln City

The Lincoln City urban growth boundary (UGB) includes seven distinct communities within city limits (from south to north: Cutler City, Taft, Nelscott, Delake, Oceanlake, Wecoma, and Roads End (**Figure LC-1**) as well as neighborhoods surrounding Devils Lake that are outside city limits.

Figure LC-1. Lincoln City urban growth boundary (UGB) city limits, and XXL1 tsunami zone. Buildings inside the tsunami zone and UGB are shown as black points; all other buildings shown as grey points. Figure includes tent and recreational vehicle sites in the tsunami zone as black points.

8.3.1 Building and Population Characteristics

Our analyses indicate that only certain limited areas throughout the Lincoln City UGB are directly impacted by the XXL1 tsunami (**Figure LC-1**), while most of the area is located outside of the tsunami zone. This is because large parts of the Lincoln City area are located on marine terraces, well outside of the tsunami zone. As of July 1, 2018, the City of Lincoln City had 8,730 permanent residents (PSU PRC, 2019), of which about a quarter (2,154) live in the XXL1 tsunami zone (**Table LC-1**). An additional 11,844 temporary residents potentially visit the community on a summer weekend and would be located within the tsunami zone, assuming that every facility is at maximum capacity. Thus, the local population within the XXL1 tsunami zone could potentially increase by ~6 times under the most ideal circumstances in the summer. Clearly, numbers of this magnitude would place a very large burden on the local community in the hours and days following a major earthquake and tsunami. Our analyses also reveal that ~30% of the permanent residents are ≥65 years of age (**Table 3-2**), which is marginally higher when compared with the XXL1 average of 27% calculated for the entire Oregon coast. Temporarily occupied households (referred to as “seasonal” in the U.S. Census database) make up 50% of the residential households in the XXL1 tsunami zone (**Figure LC-2**). Finally, it is worth noting in **Table LC-1** and **Figure LC-2** that both the permanent resident and temporary populations roughly double from an M1 event to an XXL1 event.

Table LC-1. Lincoln City urban growth boundary tsunami zone building statistics and demographics for three tsunami zones.

Tsunami Zone	Number of Buildings	Number of Residential Buildings	Building Replacement Cost ($ Million)	Total Number of Households (2010 Census)	Total Number of Seasonal Households (2010 Census)
M1[1]	900	760	280	1,167	530
L1[1]	1,288	1,109	405	1,559	703
XXL1[1]	2,312	2,048	689	2,353	1,183

Tsunami Zone	Permanent Resident Population Estimate			Temporary Resident Population Estimate, Summertime Weekend			Population Total, Summertime Weekend
	Under 65 Years Old	65 Years and Older	Total	Under 65 Years Old	65 Years and Older	Total	
M1[1]	686	286	972	3,622	960	4,582	5,554
L1[1]	892	383	1,275	5,500	1,420	6,920	8,195
XXL1[1]	1,510	644	2,154	9,362	2,482	11,844	13,998

Notes: The U.S. Census refers to temporarily occupied households such as vacation and second homes as “seasonal households.” Temporary population estimates are based on a summer weekend scenario.

[1]M1, L1, and XXL1 (Priest and others, 2013e)

Figure LC-2. Lincoln City urban growth boundary tsunami zone building statistics and demographics for three tsunami zones expressed as percentages relative to the XXL1 zone. Temporary population estimates assume a summer weekend scenario.

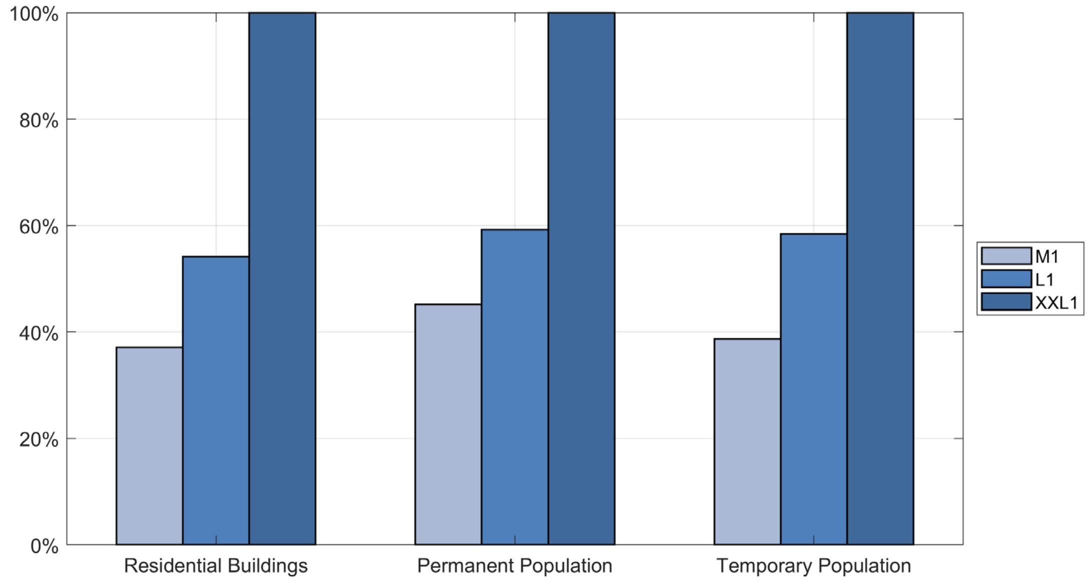


Table LC-2 (and presented graphically in **Figure LC-3**) indicates that the majority (64%) of permanent residents within the Lincoln City tsunami zone (XXL1) occupy single-family residential homes, while ~10% of the population live in manufactured homes. Similarly, a large (65%) portion of the temporary visitor population stay in single-family vacation and second homes (e.g., VRBO), while an additional 23% of visitors are in hotel/motels. These results show the importance of Lincoln City as a major recreational destination, while also highlighting potential challenges that tsunami educators and community leaders need to address. For example, one major challenge with such a dispersed temporary population is ensuring that every vacation home contains appropriate information about the earthquake/tsunami hazard (e.g., warning signs to look out for, response procedures), as well as site-specific information (e.g., tsunami evacuation maps) about where to go if an earthquake occurs.

Table LC-2. Estimates of permanent and temporary population by building type in Lincoln City urban growth boundary XXL1 tsunami zone. Temporary population estimates assume a summer weekend scenario.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single Family Residential	1,375	64%	7,719	65%
Manufactured Housing	215	10%	94	1%
Multi-family Residential	418	19%	858	7%
Hotel/Motel	54	3%	2,732	23%
Mobile (Tents, Rec. Vehicles)	19	1%	441	4%
Other (incl. Mixed-use)	74	3%	0	0%
Total	2,154	100%	11,844	100%

To evaluate time and distance to high ground and thus safety, we assume it takes ~10 minutes for people to mobilize (i.e., milling behavior) prior to evacuating. The tsunami wave fully inundates Lincoln City at 24 minutes; accordingly, people have no more than 14 minutes to reach safety before the wave reaches them. If we assume that people travel at a "walk" speed (i.e., ~4 fps), we can estimate the distance that can be covered (~3,360 ft) within the 14-minute time frame. People whose distances to safety exceed 3,360 ft are assumed to not reach safety in time if we presuppose they maintain an evacuation speed of ≤4 fps. We provide distance to safety statistics using the XXL1 tsunami scenario in **Figure LC-3** for both the permanent and temporary populations, and as a cumulative distribution plot in **Figure LC-4**. Using this approach, we find that for Lincoln City, the median distances to safety for permanent and temporary residents are comparable (1,200 ft and 1,000 feet, respectively, **Figure LC-4**). Furthermore, we find that the majority of hotel/motels in Lincoln City located in the tsunami zone are within ~2,300 ft of safety **Figure LC-3**. Given the threshold of 3,360 ft and assumptions noted previously, our analyses suggest that <10% of the population (permanent and temporary) in the tsunami zone might not reach safety before the tsunami inundates the community (**Figure LC-4**). For people located at distances to safety that are ≥3,360 ft, it is imperative that they leave sooner and travel at speeds faster than 4 fps (e.g., "fast walk" to "jog"). This is reinforced in **Figure LC-4**, which demonstrates that by increasing speed to 6 fps, ~99% of the population (permanent and temporary) could potentially reach safety for an XXL1 tsunami event.

8.3.2 Earthquake and Tsunami Building Damage and Debris Estimates

Within the XXL1 tsunami zone, building repair costs caused by an XXL1 tsunami greatly exceed the repair cost estimated from the earthquake ground motion and earthquake-induced ground deformation (**Table LC-3**). This is primarily due to the prevalence of wood frame, light-frame steel, and manufactured housing types in the community that are unable to withstand the large hydraulic forces of a tsunami. As can be seen from **Table LC-3**, the weight of debris generated by the destruction of the buildings in the tsunami zone is estimated to be ~169,000 tons; note this estimate reflects a minimum estimate since the calculation excludes content in the buildings, vehicles, and other forms of debris. Combined earthquake and tsunami building repair costs are calculated to be ~$536 million, with the bulk of the cost attributed to the destruction caused by the tsunami. However, these costs will almost certainly be higher when communities factor in the added cost to repair buildings and infrastructure located outside the tsunami zone that are also damaged by the earthquake ground motion.

Table LC-3. Building repair costs and debris weight calculated for the Lincoln City urban growth boundary due to a CSZ earthquake and XXL1 tsunami.

Number of Buildings	Building Square Footage (thousand)	Building Value ($ Million)	Natural Hazard	Building Repair Cost ($ Million)	Loss Ratio	Debris from Damaged Buildings (tons)
2,312	5,007	$689	Earthquake	$146	21%	—
			Tsunami	$466	68%	—
			Combined	$536	78%	169,000

Figure LC-3. Distribution of permanent (top) and temporary (bottom) populations relative to tsunami safety within the Lincoln City urban growth boundary XXL1 tsunami zone (Gabel and others, 2019b). Distance to safety is based on a 2 AM scenario, while the temporary population estimates assumes a summer weekend. "Other" category includes mixed-use commercial buildings. See the text for significance of the 4 fps threshold.

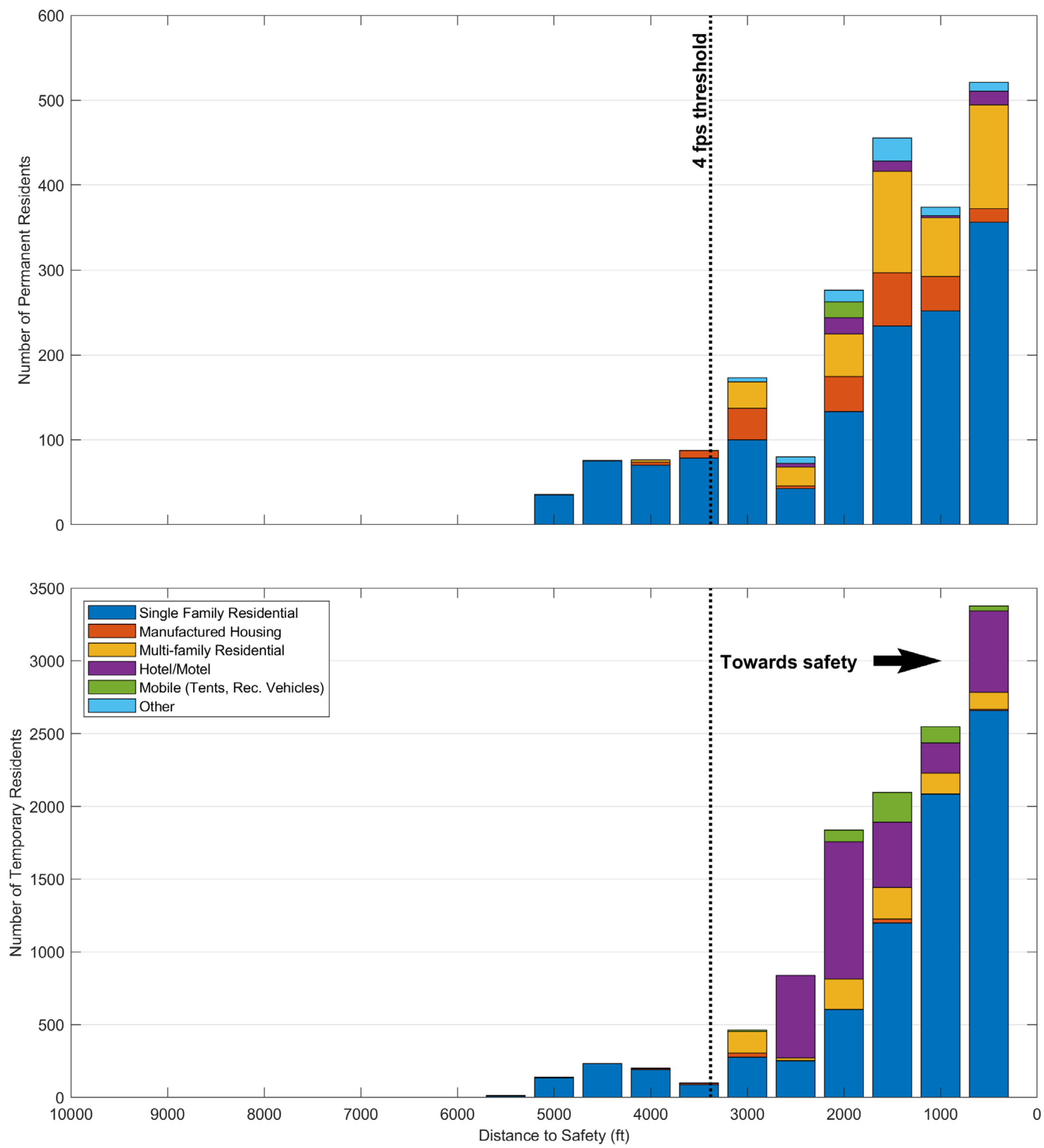
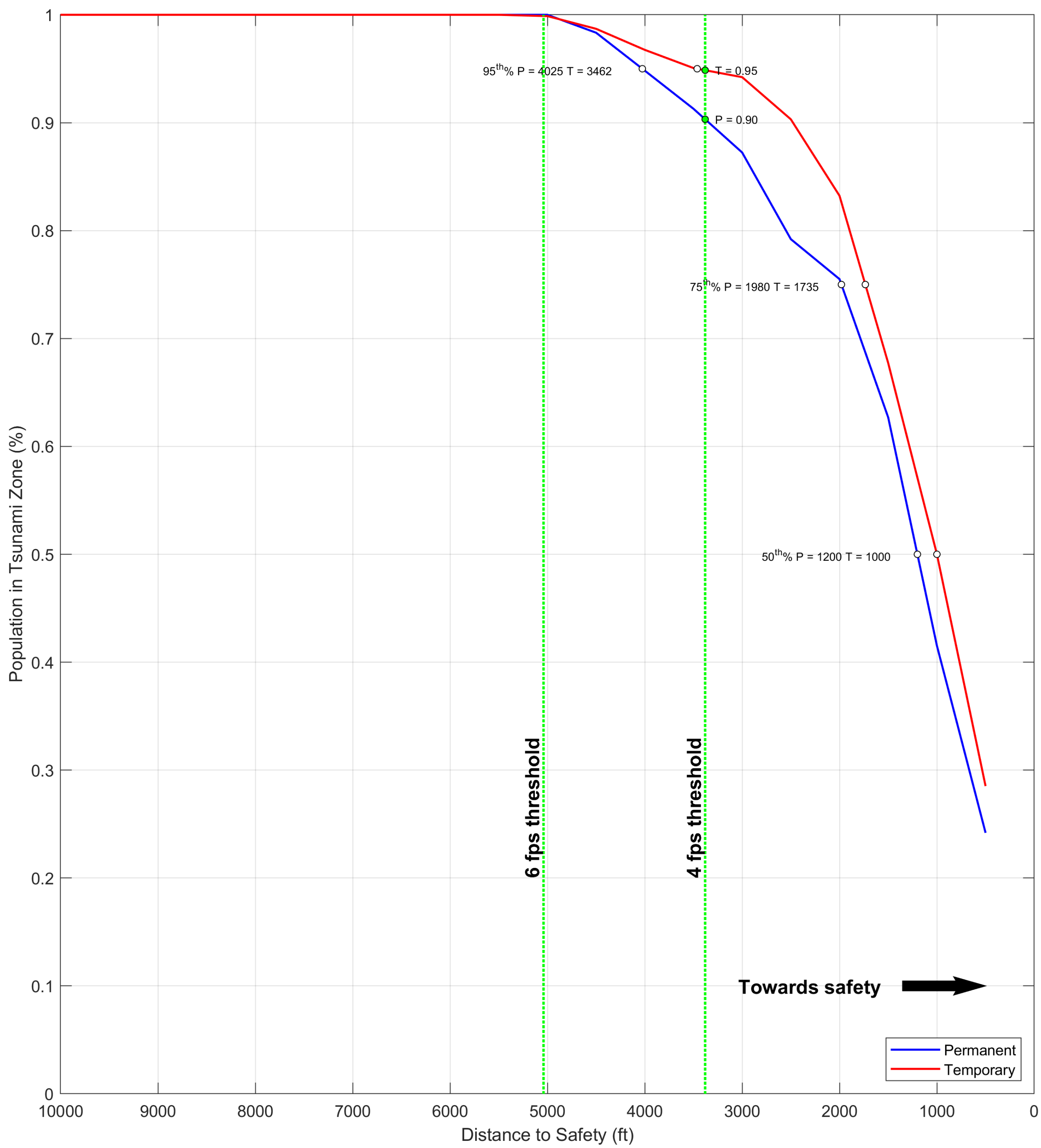


Figure LC-4. Cumulative distribution plot of permanent and temporary populations relative to tsunami safety within the Lincoln City urban growth boundary XXL1 tsunami zone. Figure includes two evacuation reference speed thresholds: 4 fps ("walk") and 6 fps ("fast walk"). Reported values for P and T are, respectively, the permanent and temporary population.



8.3.3 Injury and Fatality Estimates from Earthquake and Tsunami

Injury and fatality estimates for those occupying buildings during the earthquake are low (~1% for both permanent and temporary residents; **Table LC-4**). This is because the majority of residential buildings are wood frame, which is considered to be the most seismically resilient building construction type (FEMA, 2015a). Depending on the extent of a person's injury or how the person responds to the event and injury (i.e., a bookshelf collapses on the person during the earthquake, or the person is unable to open a door to leave the building, or is in shock), it is likely that a portion of the injured population may not be able to evacuate from the tsunami zone in a timely manner and may therefore be killed by the tsunami as the person attempts to evacuate out of the tsunami zone.

Table LC-4. Injuries and fatalities resulting from a CSZ earthquake sustained by resident group in the Lincoln City urban growth boundary, summer weekend 2 AM scenario.

Hazus Injury Severity Level	Permanent Residents	Temporary Residents	Total
Level 1: Minor Injuries	19	93	112
Level 2: Injuries Requiring Hospitalization	4	21	25
Level 3: Life-Threatening Injuries	1	2	3
Level 4: Deaths	1	4	5
Total	25	120	145

Note: See **Table 2-3** for a complete definition of the Hazus injury levels.

In defining the number of casualties caused by the tsunami, we used the XXL1 tsunami evacuation scenario as described by Gabel and others (2019b). As expected, Lincoln City UGB fatality rates associated with the XXL1 scenario are low (**Table LC-5**), approaching 13% for the permanent population and 8% for the temporary population; modeling assumes a 10-minute departure (milling) time. Thus, in this scenario 92% of the combined Lincoln City summer population is expected to survive, with ~8% total fatalities; of those who survive, an estimated ~1% are classified as injured. These results reflect the important fact that high ground is nearby for much of the Lincoln City community (e.g., **Figure LC-3**), allowing more people time to evacuate out of harm's way. Nevertheless, the Lincoln City community should be mindful of the fact that as the group departure time increases (i.e., longer milling, **Table LC-6**) and/or people are unable to evacuate quickly enough along evacuation routes, the number of fatalities could begin to increase significantly. For example, a 15 (20) minute departure time (**Table LC-6**) indicates that 36% (54%) of the population in the tsunami zone could be killed.

The estimated tsunami casualties provided in **Table LC-5** assume a mean departure time of 10 minutes and a group median evacuation walking speed of 4 fps except for individuals ≥65 years in age, who evacuate at 3.2 fps. To better illustrate the evacuation situations and opportunities throughout the Lincoln City UGB, we calculated the likelihood of survival based on distance to safety, walking speed, and tsunami wave arrival time. Survivability was determined using the survival likelihood distance breakpoints from the formula associated with **Table 2-4** for a tsunami wave arrival of 24 minutes, and the results are shown in **Figure LC-5** (north Lincoln City) and **Figure LC-6** (south Lincoln City). Both figures reinforce the point that an XXL1 tsunami is survivable for most residents of Lincoln City, with several notable exceptions. These include the Cutler City area, a small area at Southeast 2nd Court just south of Devils Lake, the Taft

Trailer Park at Southeast 52nd St, and the Taft residences along Southeast 51st Avenue and Southeast Lee Avenue. Of these, the Cutler City area experiences the greatest evacuation challenge.

Table LC-5. Injury and fatality estimates for an XXL1 tsunami in the Lincoln City urban growth boundary. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, 10-minute milling time prior to departure, and wave arrival time at the tsunami runup line of 24 minutes. Injury and fatality estimates are rounded to nearest 10.

				Injury and Fatality Ratio	
Population Segment	**Number of People**	**Fatalities**	**Injuries**	**Fatalities**	**Injuries**
Permanent	2,154	280	30	13%	1%
Temporary	11,844	890	90	8%	1%
Total	13,998	1,170	120	8%	1%

Note: Population and tsunami casualty estimates are limited to people residing in the XXL1 tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Table LC-6. Injury and fatality estimates for an XXL1 tsunami in the Lincoln City urban growth boundary assuming different departure times. Model results assume an average walking speed of 4 fps, summer weekend 2 AM scenario, and wave arrival time at the tsunami runup line of 24 minutes. Injury and fatality estimates are rounded to nearest 10.

		Average Departure Time					
		Injuries and Fatalities			Injury and Fatality Ratio		
Population Segment	**Number of People**	**10 Minutes**	**15 Minutes**	**20 Minutes**	**10 Minutes**	**15 Minutes**	**20 Minutes**
Permanent	2,154	310	880	1,230	14%	41%	56%
Temporary	11,844	970	4,140	6,290	8%	35%	53%
Total	13,998	1,280	5,020	7,520	9%	36%	54%

Note: Population and tsunami casualty estimates are limited to people residing in the XXL1 tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

To better understand the tsunami evacuation limitations and mitigation opportunities at Cutler City, we provide close-up maps showing likelihood of injury and fatality with evacuation speed of 4 fps (**Figure LC-7**), 6 fps (**Figure LC-8**), and a hypothetical tsunami vertical evacuation (**Figure LC-9**, Gabel and others, 2019b). Using this approach, our analyses indicate that the majority of the injuries and fatalities in Lincoln City (**Table LC-5**) can be attributed to the casualties occurring in Cutler City (summarized in **Table LC-7**). Increasing evacuation speed to 6 fps reduces the overall number of fatalities, but residents at the very south end of Cutler City will still be unlikely to reach safety in time (compare **Figure LC-7** with **Figure LC-8**). In contrast, construction of a vertical evacuation structure at the Pacific Baptist Church parking lot (**Figure LC-9**) would significantly help reduce injuries and fatalities (**Table LC-7)**, assuming Cutler City residents evacuate within 10 minutes of the start of earthquake shaking and evacuate at speeds of at least 4 fps or greater.

Table LC-7. Cutler City injury and fatality estimates for an XXL1 tsunami assuming different departure times. Model results assume an average walking speed of 4 fps, summer weekend 2 AM scenario, and wave arrival time at the tsunami runup line of 24 minutes. Injury and fatality estimates are rounded to nearest 10.

			Average Departure Time					
			Injuries and Fatalities			Injury and Fatality Ratio		
Tsunami Evacuation Scenario	Population Segment	Number of People	10 Minutes	15 Minutes	20 Minutes	10 Minutes	15 Minutes	20 Minutes
XXL1 tsunami, present day	Permanent	364	230	300	300	63%	82%	82%
	Temporary	821	580	700	710	71%	85%	86%
	Total	1,185	810	1,000	1,010	68%	84%	85%
XXL1 tsunami with hypothetical tsunami vertical evacuation structure on SW Galley St	Permanent	364	10	110	190	3%	30%	52%
	Temporary	821	20	260	430	2%	32%	52%
	Total	1,185	30	370	620	3%	31%	52%

Note: Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time. Casualties from tsunami are dominated by fatalities, with the injury ratios all less than 10% (**Table 3-6**).

Injuries and fatalities from a tsunami can be significantly lowered if individuals evacuate as soon as possible and travel at faster evacuation speeds (e.g., slow jog to run). We obtained injury and fatality percentages from the Hazus tsunami casualty model for the XXL1 tsunami scenario, varying group departure time and group walking speeds (**Table LC-6**). As expected, injuries and fatalities increase as the departure time increases (i.e., longer milling behavior, **Figure LC-10**) and decrease as speed of travel increases.

Figure LC-5. North Lincoln City evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019b), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 24 minutes.

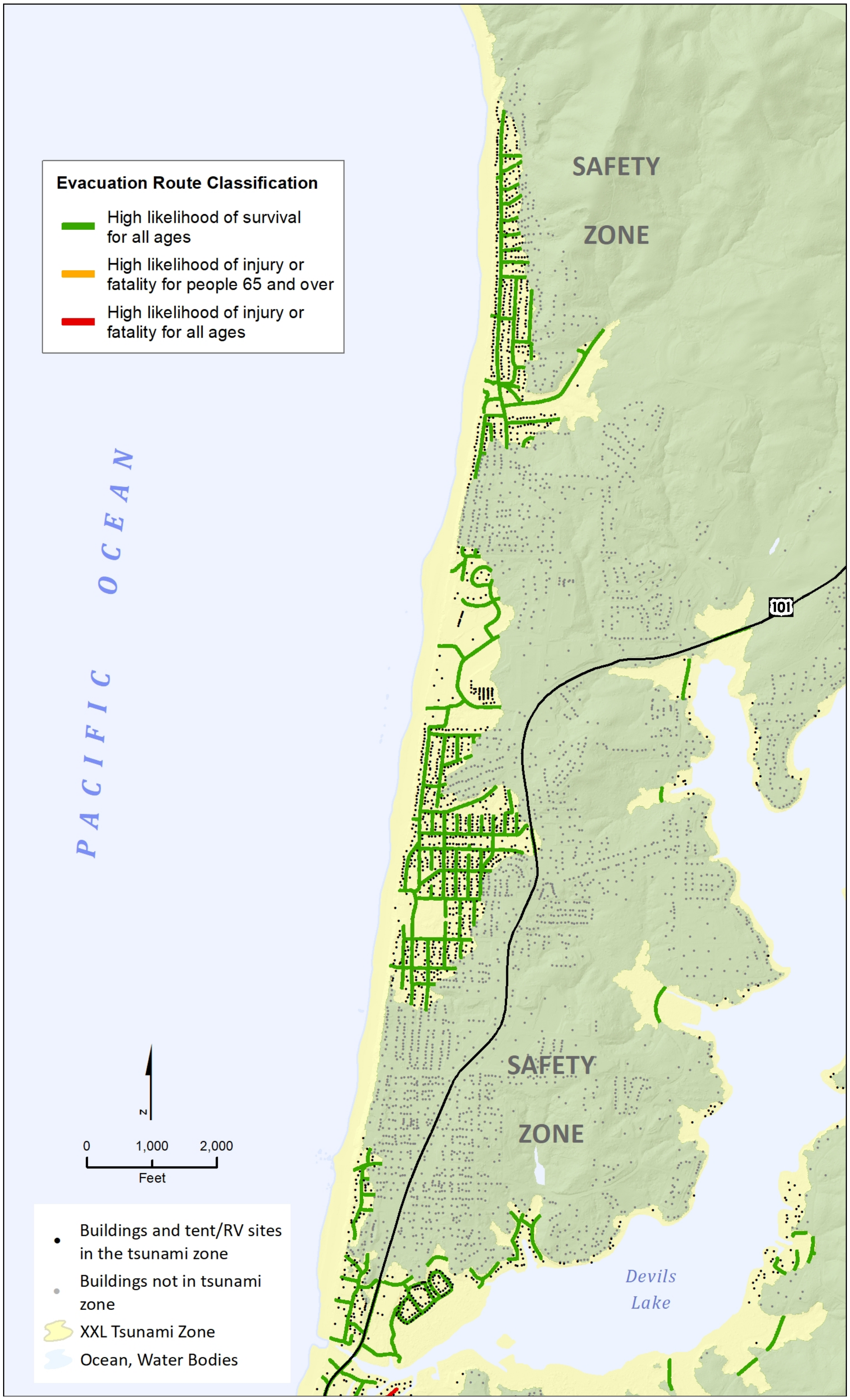


Figure LC-6. South Lincoln City evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019b), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 24 minutes.

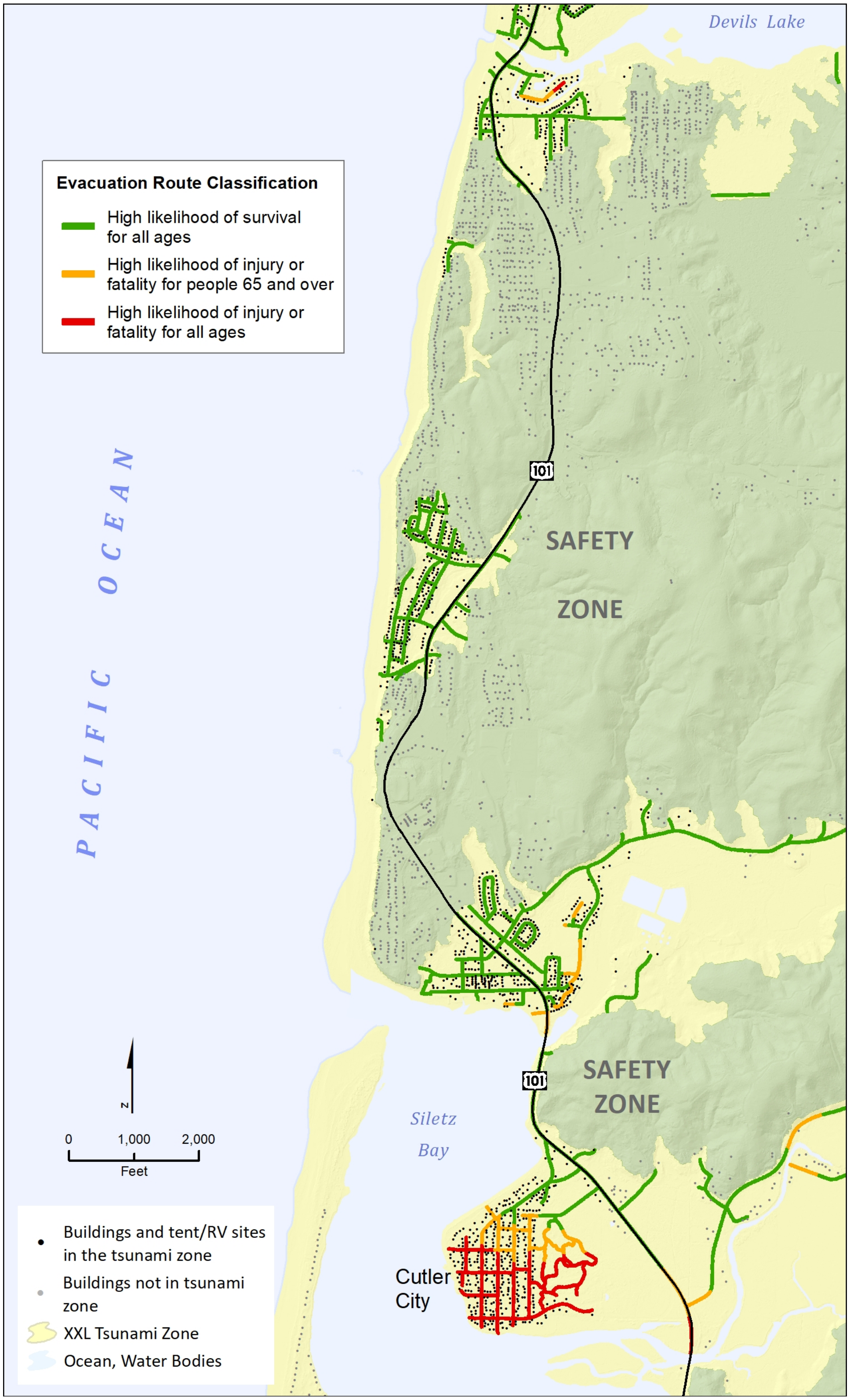
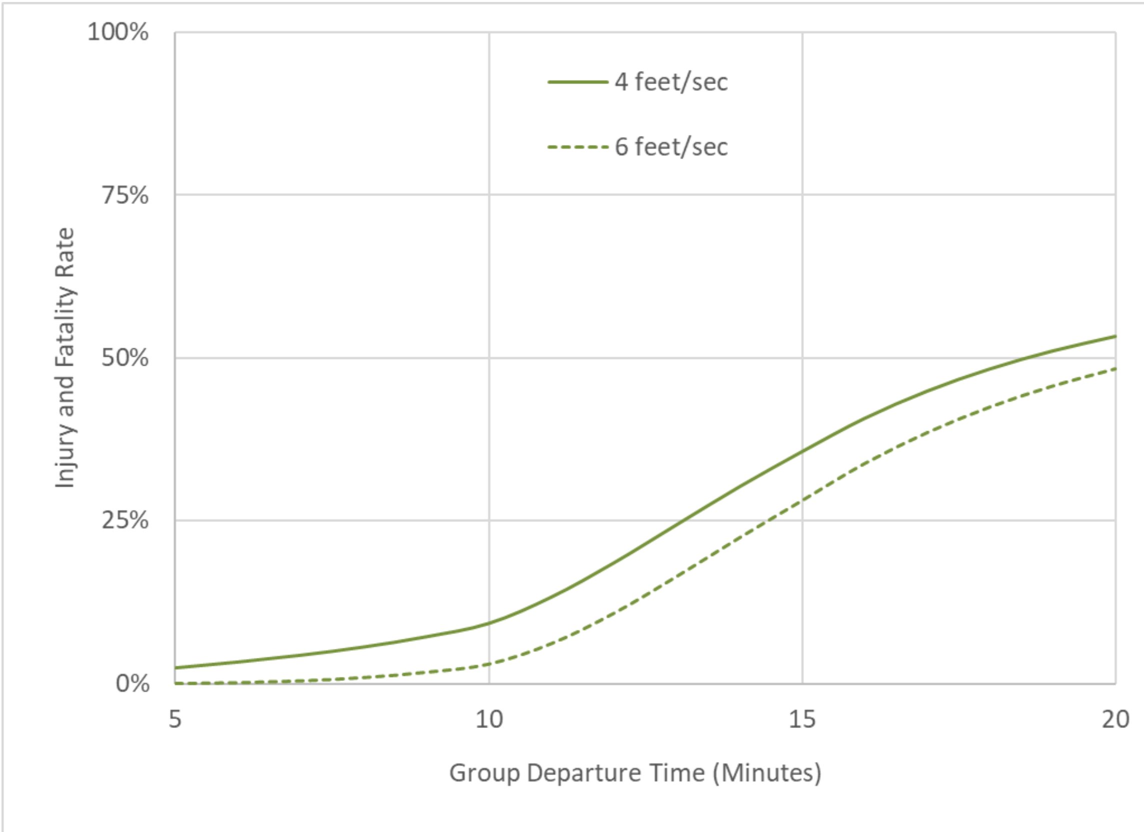


Figure LC-7. Cutler City evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 24 minutes.

Figure LC-8. Cutler City evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 24 minutes.

Figure LC-9. Cutler City evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario and based on the building of a hypothetical vertical evacuation structure (star) on SW Galley Ave (Gabel and others, 2019b), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 24 minutes.

Figure LC-10. Lincoln City injury and fatality rates estimated for the XXL1 tsunami as a function of departure time and two different evacuation speeds. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the tsunami zone at the time of the earthquake. The injury and fatality rate combine both permanent and temporary population groups.



8.3.4 Displaced Population

Permanent and temporary residents who successfully evacuate out of the tsunami zone will require short- to medium-term shelter, given that their residences are presumed destroyed or rendered uninhabitable by the tsunami (**Table LC-1**). Temporary residents will likely not be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017) and that their personal vehicles will likely be destroyed or damaged in the tsunami.

For mass care planning purposes, displaced population estimates can be obtained by subtracting the total injuries and fatalities provided in **Table LC-5** from the total number of people (permanent and temporary) estimated to be in the XXL1 tsunami zone. From those data we estimate that the displaced population in Lincoln City from an XXL1 event could be as low as ~1,800 people and increase to almost 13,000 people. The former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every rental facility at maximum capacity.

We note again that our analysis is limited to the buildings and people in the Lincoln City XXL1 tsunami zone at 2 AM. Some portion of the permanent and temporary residents outside of the tsunami zone can be assumed to need food and shelter if their residential structures were damaged from the earthquake. In addition, extensive development in the tsunami zone currently exists south of Lincoln City, including the unincorporated areas of Gleneden Beach and Salishan Spit, and displaced people in those locations will need local shelter. Further, we reiterate that our analysis does not estimate the number of day visitors to Lincoln City that may be stranded.

A lesser magnitude tsunami event, such as a M1 scenario, will produce fewer tsunami injuries and fatalities. Of the total population in the Lincoln City tsunami zone, we find that 972 permanent and 4,582 temporary residents occupy buildings in the Medium tsunami zone (**Table LC-1**). While more people are expected to survive such an event, a large portion of the population will need post-disaster shelter and care.

8.3.5 Essential Facilities, Special Facilities, and Key Infrastructure

Our research identified no essential facilities or special facilities in the Lincoln City UGB tsunami zone. However, we identified the following *key infrastructure facilities* in the tsunami zone:

- Lift Station, SW Anchor Court
- Lincoln Water Treatment Plant, SE 54th Drive
- Antenna structure, 3277 NE East Devils Lake Road; includes KBCH AM 1400 radio

8.3.6 Employment

Our analyses indicate that ~30% of the jobs in the Lincoln City UGB are within the XXL1 tsunami zone (**Table LC-8**). Of these, the two highest employment sectors are Accommodation and Food Services (NAICS code 72) and Arts, Entertainment, and Recreation (NAICS code 71), which account for 44% and 39% of the jobs, respectively.

Table LC-8. Number of businesses, jobs, and annual wages paid in Lincoln City urban growth boundary XXL1 tsunami zone.

	XXL1 Tsunami Zone	Lincoln City UGB Total
Number of businesses	124	530
Number of jobs	1,803	5,907
Annual wages paid ($ million)	$58	$198

8.3.7 Social Characteristics

We reiterate that the American Community Survey (ACS) social characteristic data span the entire community (and county) and are not at a resolution that would allow us to better define these statistics by tsunami zone. The interested user is encouraged to review the introduction to Appendix A for additional resources on the ACS in order to better understand vulnerable permanent populations living within the tsunami zone.

As noted previously, our analyses indicate that ~30% of the permanent residents in the XXL1 tsunami zone are ≥65 years of age (**Table 3-2**), which is about the same as the Oregon XXL1 tsunami zone average of 27%. We can delve deeper into the social aspect of a local population by evaluating other characteristics such as the number of people who speak Spanish (or other languages) as well as those who may have disabilities. Both datasets are important because they have a direct bearing on basic outreach (e.g., providing material that has been translated) and in terms of identifying those who may need evacuation assistance. The proportion of Spanish-speaking (and other languages) households is presented in **Table LC-9** for both the Lincoln City UGB and the county average. Overall, we find that Spanish-speaking households in the Lincoln City UGB make up ~6.9 % of the local population; including other languages suggests that ~8% of the local population speaks a language other than English.

Table LC-9. Household spoken language statistics for Lincoln City. Data taken from American Community Survey 2013–2017 5-year estimates.

	City of Lincoln City		Lincoln County
	Number of Households	Percent of Households with Margin of Error	Percent of Households with Margin of Error
Households speaking Spanish	260	6.9% ± 3.1%	5.2% ± 0.7%
Households with limited English fluency; Spanish spoken	10	0.3% ± 0.4%	0.5% ± 0.3%
Households with limited English fluency; all languages	46	1.2% ± 0.9%	0.8% ± 0.4%

* Insufficient data

Table LC-10 presents information on the percentages of people with disabilities in the Lincoln City UGB. Overall, these results indicate the proportion of the local population with disabilities is about the same as the county wide average, estimated to be ~21%. Of particular concern are the relatively large numbers of individuals with vision, cognitive, or ambulatory disabilities, who will almost certainly need help evacuating from the tsunami zone. Not all of these individuals may reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

Table LC-10. Number of individuals with disabilities (by type) for Lincoln City and Lincoln County. Data taken from American Community Survey 2013–2017 5-year estimates. An individual with a disability may have more than one difficulty.

	City of Lincoln City		Lincoln County
	Number of Individuals	Percent of Population with Margin of Error	Percent of Population with Margin of Error
Individuals with a disability*	1,784	21.0% ± 2.4%	21.7% ± 1.1%
Difficulty Category			
Hearing	487	5.7% ± 1.4%	6.9% ± 0.7%
Vision	344	4.1% ± 1.3%	3.5% ± 0.5%
Cognitive	690	8.7% ± 1.8%	8.5% ± 0.8%
Ambulatory	962	12.2% ± 2.4%	12.2% ± 1.0%
Self-care	293	3.7% ± 1.3%	4.0% ± 0.5%
Independent Living	716	10.3% ± 2.1%	8.9% ± 0.9%

8.3.8 Discussion and Recommendations

Evacuation Challenges

With several exceptions and concerns, most buildings in Lincoln City are relatively close to safety. This does not preclude the need for preparation and effective messaging. Even if one is occupying a building only 500 feet from tsunami safety, needless delay (i.e., milling behavior) may be deadly.

The areas of Lincoln City where successful tsunami evacuation may be challenging include Cutler City, Southeast 2nd Court just south of Devils Lake, the Taft Trailer Park at Southeast 52nd St, and residences along Southeast 51st Avenue and Southeast Lee Avenue. Landslide failure of the bluffs along Lincoln City may present another factor affecting casualties, although analysis of this hazard is beyond the scope of this paper.

Analyzing daytime evacuation scenarios for Lincoln City was beyond the scope of this paper. Notable concentrations of people are known to gather in the vicinity of the D River Beach Wayside and Siletz Bay Park, including the beach at the mouth of the Siletz River. We note that the D River Beach Wayside is one of the most heavily used state parks in Oregon, with an estimated 1.38 million total visitors in 2016 (White, 2018). We recommend city and emergency managers evaluate whether there is sufficient signage on both sides of the river outlet to help guide the public toward high ground.

Education

Under peak summer circumstances, we estimate that of the ~11,900 temporary visitors who might lodge in the Lincoln City tsunami zone, ~7,700 (65%) of these would stay in single-family vacation and second homes, and another ~2,700 (23%) are likely to spend the night in either a hotel or motel. Our analyses indicate that all motels and hotels in Lincoln City are located close to high ground. As a result, occupants of Lincoln City hotels and motels can survive a tsunami provided they understand the risk and take suitable action immediately following the earthquake shaking. Similarly, people at Devils Lake State Recreation Area can reach safety in sufficient time before the tsunami arrives, provided they understand the risk and take appropriate action (i.e., leave immediately for high ground). Tsunami safety messaging for visitors should therefore include focused outreach to hotel/motels as well as to vacation homes. Besides improving basic hazard awareness, such activities could also include education that local evacuation maps can now be generated for any location on the Oregon coast via the NVS tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac) and smartphone application (http://www.nanoos.org/mobile/tsunami_evac_app.php), enabling users to post appropriate information in their homes. While knowledge of where high ground is located is critical, equally important is the practice of walking one's evacuation route to ensure familiarity with the route and any potential obstacles.

Manufactured homes installed prior to 2003 are subject to slipping off their foundations (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014), potentially compromising the ability to leave the structure quickly. About 300 people in Lincoln City reside in manufactured housing. Although many of these houses are relatively close to high ground (**Figure LC-3**), the compromised egress may hinder timely evacuation by the occupants. Seismic upgrades of such structures to current Oregon building standards (Oregon BCD, 2010) may be cost-prohibitive. FEMA (2012, Section D) advises having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting. Such tools may provide a low-cost solution for rapidly exiting their structures in the critical time interval after the earthquake ends and before the tsunami arrives.

Planners should also consider developing appropriate hazard information and messaging to account for the linguistic diversity in their community (**Table LC-9**). As noted previously, an estimated 8% of the Lincoln City local population speaks a language other than English.

Our model results demonstrate that loss of life can be minimized for *all* residents, permanent and temporary, if individuals evacuate as soon as possible after earthquake cessation and walk as fast as possible (**Figure LC-10**).

Mitigation

Our evacuation simulations suggest that improving existing evacuation trails for unimpeded passage, along with increased saturation of tsunami wayfinding signage will help reduce the potential for large numbers of casualties. Of particular importance is having a sufficiently dense network of signs (either posted and/or thermoplastic on road/path surfaces) that direct people along core routes to areas outside of the tsunami zone. Signs of this nature need to be spaced appropriately far apart so that they can be easily viewed (and read) at any time of the day or night.

Additional site-specific mitigation in the form of a vertical evacuation structure has been evaluated for Cutler City. Such a structure will save lives as demonstrated in our casualty analyses. However, in the absence of such a structure now we encourage the community to undertake the following:

1) establish additional wayfinding signage in the community to guide people toward high ground east of Highway 101; and,
2) practice evacuation routes.

Finally, as noted by McCaughey and others (2017), if a structural solution is eventually adopted, it should be accompanied by a well thought out education campaign.

We recommend and encourage local communities to practice periodic (annual) tsunami evacuation drills. In order to instill a culture of awareness of the tsunami hazard facing the Oregon coast, residents (and visitors) must periodically practice their evacuation routes. Studying an evacuation map is not the same as actually walking an evacuation route. Although we recognize that such an approach may be disruptive to the local economy, holding periodic drills will save lives. Such a culture is entrenched in Japanese way of life and helped save many thousands of lives during the catastrophic tsunami event on the Sendai coast on March 11, 2011. This culture is highlighted in several recent studies (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Response

Depending on the time of year a CSZ earthquake and tsunami strike, Lincoln City is likely to experience an acute short- to medium-term sheltering need after a tsunami. Should an XXL1 tsunami occur, we estimate that the displaced population in Lincoln City could range from a winter low of ~1,800 people to almost 13,000 people in the peak of summer. Even a lesser magnitude tsunami will result in significant destruction of residential property, with a Medium (M1) tsunami potentially displacing ~5,500 people at mid-summer.

Although neither of the US Highway 101 bridges at D River or Drift Creek within Lincoln City are used in our pedestrian evacuation model, their role in aiding post-disaster response and recovery services after an earthquake and tsunami will be important.

Lincoln City (and Lincoln County) will need to prepare for potentially large numbers of casualties. Overall, injuries caused by the tsunami were found to be ~9% of the affected community. This outcome is because the majority of people who are unable to evacuate in time and are caught by the tsunami are killed. Combined earthquake and tsunami related injuries presented for Lincoln City are estimated to reach ~260 people for an XXL1 event (**Table LC-4** and **Table LC-5**). However, because the numbers of injured are calculated for just those in the tsunami zone, incorporating earthquake related injuries outside of the tsunami zone will almost certainly increase the overall number, potentially approaching many hundreds of people. Further work is required to better refine these numbers, especially by incorporating earthquake related injuries from outside the tsunami zone. Total fatalities calculated for the XXL tsunami scenario are estimated to be ~1,200 people. However, this number is likely high, as it assumes 100% occupancy throughout the community.

Wang (2018) examined a number of considerations for coastal hospitals to take in order to prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for needed fuel and water needs. According to the Oregon Resilience Plan documents (OSSPAC, 2013), there are about 483 licensed beds at the 11 coastal hospitals. Combined earthquake and tsunami related injuries in Lincoln City is estimated to be ~260 people; total injuries for the five communities could approach 900, exceeding existing hospital capacity on the coast. Hence, coastal hospitals will need to prepare for a surge in injuries (as well as large numbers of fatalities) that could well exceed existing capacity.

Recovery

An XXL1 tsunami will have a large impact on local employment and ultimately on the local economy. Tourism-driven services, which make up of 83% of the jobs in the Lincoln City tsunami zone, will be significantly impacted.

About 2,000 permanent residents in Lincoln City reside in buildings within the tsunami zone (**Table LC-1**). Given the predominance of wood frame construction, nearly all the buildings will likely be destroyed in an XXL1 tsunami. Many of these buildings are not in coastal flooding zones, and thus the owners are not currently required by federally backed mortgage lenders to carry flood insurance for buildings outside of a designated flood zone. However, flood insurance is available to all building owners through the National Flood Insurance Program, which covers building loss due to a tsunami (FEMA, 2018c). More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

8.4 Newport

The Newport urban growth boundary (UGB) includes the following areas that are outside city limits: Idaho Point, the neighborhood of Holiday Beach, and the commercial areas of South Beach near SE 42nd St (**Figure NP-1**).

Figure NP-1. Newport urban growth boundary, city limits, and XXL1 tsunami zone. Buildings inside the tsunami zone and urban growth boundary are shown as black points; all other buildings shown as grey points. Figure includes tent, boat slips, and recreational vehicle sites in the tsunami zone as black points.

8.4.1 Building and Population Characteristics

Our analyses indicate that only certain areas throughout the Newport UGB are directly impacted by the XXL1 tsunami (e.g., from south to north: South Beach State Park, Newport Bayfront, Nye Beach, and Agate Beach, **Figure NP-1**); most of the area is located outside the tsunami zone. This is because large parts of the Newport area are located on marine terraces, well outside of the tsunami zone. As of July 1, 2018, the City of Newport had 10,125 permanent residents (PSU PRC, 2019), of which ~11% live in the XXL1 tsunami zone (**Table NP-1**). An additional ~8,300 temporary residents potentially may visit the community on a summer weekend and would be located within the tsunami zone; the latter estimate assumes that every facility is at maximum capacity. Thus, the local population within the XXL1 tsunami zone could potentially increase by ~7 times under the most ideal circumstances in the summer. Clearly, numbers of this magnitude would place a very large burden on the local community in the hours to days following a major earthquake and accompanying tsunami. Our analyses also reveal that ~41% of the permanent residents in the XXL1 zone are ≥65 years of age (**Table 3-2**), which is significantly higher when compared with the XXL1 average of 27% calculated for the entire Oregon coast. Temporarily occupied households (referred to as "seasonal" in the U.S. Census database) make up 36% of the residential households in the XXL1 tsunami zone (**Figure NP-2**). Finally, it is worth noting in **Table NP-1** and **Figure NP-2** that both the permanent resident and temporary populations roughly double in number from an L1 event to an XXL1 event.

Table NP-1. Newport urban growth boundary tsunami zone building statistics and demographics for three tsunami zones.

Tsunami Zone	Number of Buildings	Number of Residential Buildings	Building Replacement Cost ($ Million)	Total Number of Households (2010 Census)	Number of Seasonal Households (2010 Census)
M1[1]	487	245	379	432	159
L1[1]	652	355	441	663	268
XXL1[1]	1,071	727	638	1,035	377

Tsunami Zone	Permanent Resident Population Estimate			Temporary Resident Population Estimate, Summertime Weekend			Population Total, Summertime Weekend
	Under 65 Years Old	65 Years and Older	Total	Under 65 Years Old	65 Years and Older	Total	
M1[1]	235	225	460	2,420	867	3,287	3,747
L1[1]	337	287	620	3,286	1,138	4,423	5,047
XXL1[1]	678	482	1,160	5,471	1,701	7,171	8,332

Notes: The U.S. Census refers to temporarily occupied households such as vacation and second homes as "seasonal households." Temporary population estimates are based on a summer weekend scenario.

[1]M1, L1, and XXL1 (Priest and others, 2013e)

Figure NP-2. Newport urban growth boundary tsunami zone building statistics and demographics for three tsunami zones expressed as percentages relative to the XXL1 zone. Temporary population estimates assume a summer weekend scenario.

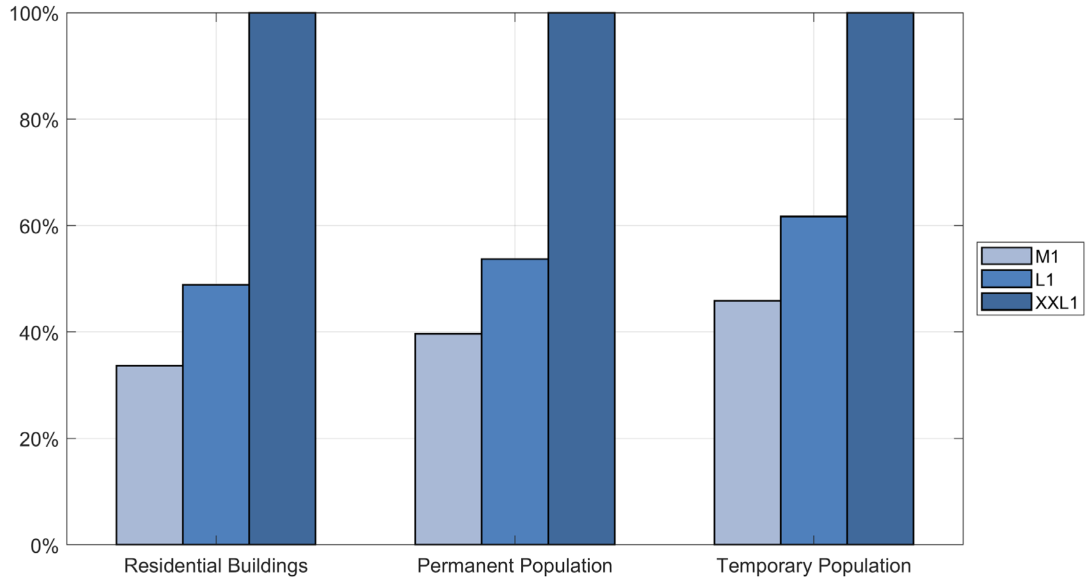


Table NP-2 (and presented graphically in **Figure NP-3**) indicates that the majority of the permanent residents within the Newport tsunami zone (XXL1) occupy either single-family residential homes (38%), or multi-family residential homes (30%). The remaining population is distributed across a wide variety of housing classifications that include manufactured housing (7%), mobile (9%, i.e., recreational vehicles, boats), and mixed-use (14%). Conversely, while half of the temporary visitor population stays in single-family vacation and second homes (26%), and hotel/motels (27%) (**Table NP-2**), almost one-third of the population stays in mobile housing (29%, i.e., tents, recreational vehicles, boats). These results demonstrate the importance of Newport as a major recreational destination, while also highlighting potential challenges that tsunami educators and community leaders need to address. For example, the majority of the "mobile" visitor population tends to be concentrated at the popular South Beach State Park campground (**Figure NP-1**). Thus, a major challenge with such a dispersed temporary population is ensuring that campgrounds as well as vacation homes contain appropriate information about the earthquake/tsunami hazard (e.g., warning signs to look out for, response procedures), as well as site-specific information (e.g., tsunami evacuation maps) about where to go if an earthquake occurs. This information must be accompanied by a sufficiently dense network of evacuation signage along core evacuation routes in order to quickly guide people out of the inundation zone.

To evaluate time and distance to high ground and thus safety, we assume it takes ~10 minutes for people to mobilize (i.e., milling behavior) prior to evacuating, while the tsunami wave fully inundates Newport in 30 minutes. Accordingly, people have no more than 20 minutes to reach safety before the wave reaches them. If we assume that people travel at a "walk" speed (i.e., ~4 fps), we can estimate the distance of ground that can be covered (~4,800 ft) within the 20 minute time frame; people whose distances to safety exceed 4,800 ft would thus not reach safety in time assuming they maintain (or travel more slowly than) an evacuation speed of ≤4 fps. We provide distance to safety statistics using the XXL1 tsunami scenario in **Figure NP-3** for both the permanent and temporary population, and as a cumulative distribution plot in **Figure NP-4.** Using this approach, we find that for Newport, the median distances to safety for permanent (970 ft) and temporary (1,300 ft) residents are comparable (**Figure NP-4**). Furthermore, we find that the majority of hotel and motels in Newport located in the tsunami zone are within ~1,500 ft of safety (**Figure NP-3**). Given the threshold of 4,800 ft and assumptions noted previously, our analyses suggest that <2% (<9%) of the permanent (temporary) population in the tsunami zone might not reach safety in time before the tsunami inundates the community. Thus, for people located at distances to safety that are ≥4,800 ft, it is imperative that they leave sooner and travel at speeds faster than 4 fps (e.g., "fast walk" to "jog"). This is reinforced in **Figure NP-4**, which demonstrates that by increasing evacuation speed to 6 fps, 100% (~99%) of the permanent (temporary) population could potentially reach safety for an XXL1 tsunami event.

Table NP-2. Estimates of permanent and temporary population by building type in Newport urban growth boundary XXL1 tsunami zone. Temporary population estimates are based on a summer weekend scenario; Tent occupancy limited to temporary residents.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single-family Residential	443	38%	1,845	26%
Manufactured Housing	85	7%	38	1%
Multi-family Residential	343	30%	1,080	15%
Hotel/Motel	32	3%	1,921	27%
Mobile (Tents, Recreational Vehicles, Boats)	101	9%	2,097	29%
Other (incl. Mixed-use)	158	14%	250	3%
Total	1,160	100%	7,231	100%

8.4.2 Earthquake and Tsunami Building Damage and Debris Estimates

Within the XXL1 tsunami zone, building repair costs caused by an XXL1 tsunami greatly exceed the repair cost estimated from the earthquake ground motion and earthquake-induced ground deformation (**Table NP-3**). This is primarily due to the prevalence of wood frame, light-frame steel, and manufactured housing types in the community that are unable to withstand the large hydraulic forces of a tsunami. As can be seen from **Table NP-3**, the weight of debris generated by the destruction of the buildings in the tsunami zone is estimated to be ~195,000 tons; note this estimate reflects a minimum estimate, as the calculation excludes content in the buildings, vehicles, and other forms of debris. Combined earthquake and tsunami building repair costs are calculated to be ~$558 million, with the bulk of the cost attributed to the destruction caused by the tsunami. However, these costs will almost certainly be higher when communities factor in the added cost to repair buildings and infrastructure located outside of the tsunami zone that are also damaged by the earthquake ground motion.

Table NP-3. Building repair costs and debris weight calculated for the Newport urban growth boundary due to a CSZ earthquake and XXL1 tsunami.

Number of Buildings	Building Square Footage (thousand)	Building Value ($ Million)	Natural Hazard	Building Repair Cost ($ Million)	Loss Ratio	Debris from Damaged Buildings (tons)
1,071	5,007	$638	Earthquake	$231	36%	—
			Tsunami	$494	77%	—
			Combined	$558	87%	195,000

Figure NP-3. Distribution of permanent (top) and temporary (bottom) populations relative to tsunami safety within the Newport urban growth boundary XXL1 tsunami zone (Gabel and others, 2019b). Distance to safety is based on a 2 AM scenario, while the temporary population estimates assumes a summer weekend. "Other" category includes mixed-use commercial buildings. See the text for significance of the 4 fps threshold.

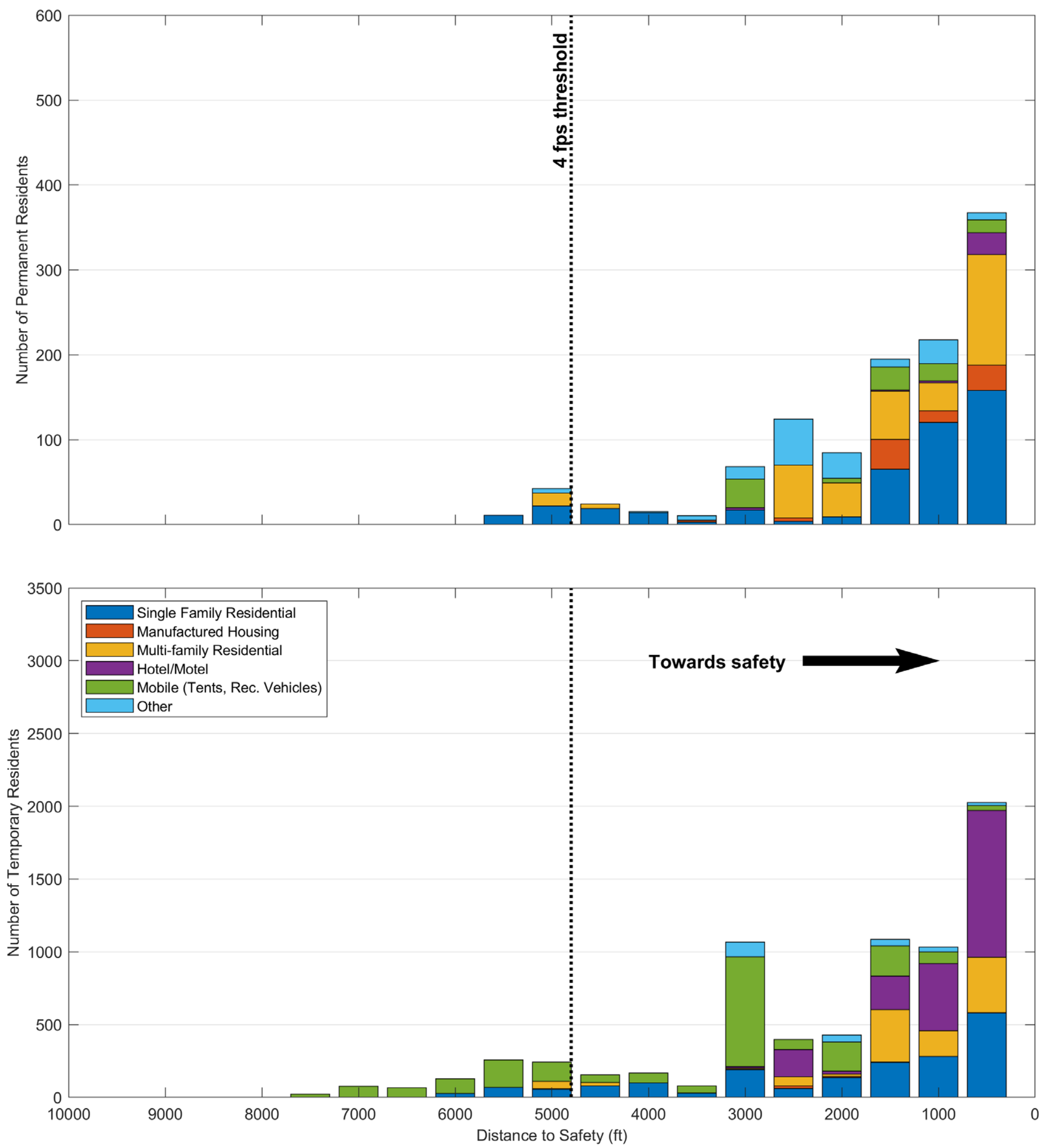
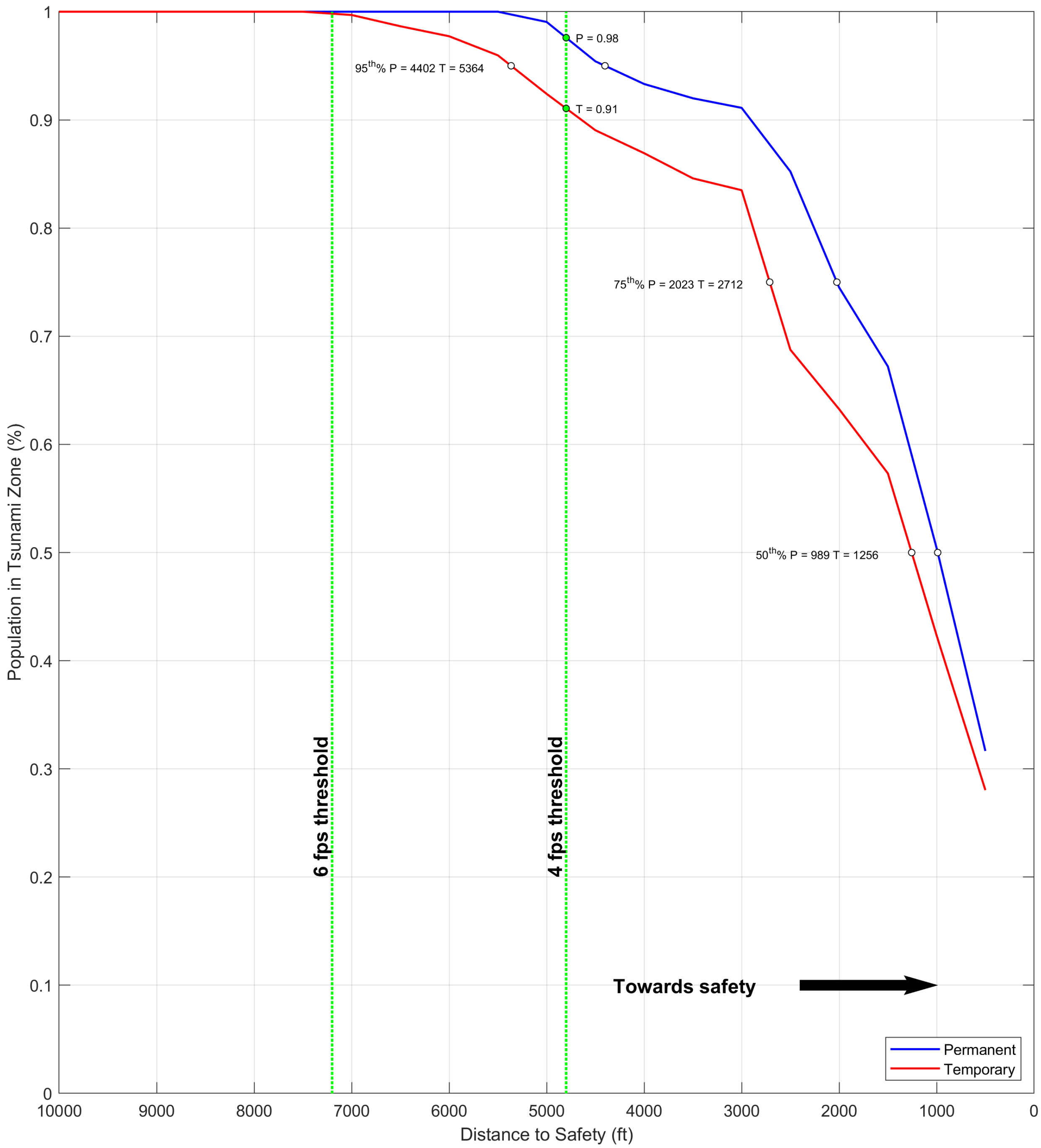


Figure NP-4. Cumulative distribution plot of permanent and temporary populations relative to tsunami safety within the Newport urban growth boundary L1 tsunami zone. Figure includes two evacuation reference speed thresholds: 4 fps ("walk") and 6 fps ("fast walk"). Reported values for P and T are, respectively, the permanent and temporary population.



8.4.3 Injury and Fatality Estimates from Earthquake and Tsunami

Injury and fatality estimates for those occupying buildings during the earthquake are low (~1.5% and 1.3% for permanent and temporary residents, respectively; **Table NP-4**), given the overall population in the XXL1 tsunami zone. This is because the majority of residential buildings are wood frame, which is considered to be the most seismically resilient building construction type (FEMA, 2015a). Depending on the extent of a person's injury or how they respond to the event and injury (i.e., a bookshelf collapses on the person during the earthquake, or the person is unable to open a door to leave the building, or is in shock), it is likely that a portion of the injured population may not be able to evacuate from the tsunami zone in a timely manner and may therefore be killed by the ensuing tsunami as they attempt to evacuate out of the tsunami zone.

Table NP-4. Injuries and fatalities resulting from a CSZ earthquake sustained by resident group types in Newport urban growth boundary, summer weekend 2 AM scenario.

Hazus Injury Severity Level	Permanent Residents	Temporary Residents	Total
Level 1: Minor Injuries	14	59	73
Level 2: Injuries Requiring Hospitalization	3	14	17
Level 3: Life-Threatening Injuries	1	2	3
Level 4: Deaths	1	3	4
Total	19	78	97

Note: See **Table 2-3** for a complete definition of the Hazus injury levels.

In defining the number of casualties caused by the tsunami, we used the XXL1 tsunami evacuation scenario as described by Gabel and others (2019b) that includes the new Oregon State University tsunami vertical evacuation structure (Marine Studies Building). As expected, Newport UGB fatality rates associated with the XXL1 scenario are low (**Table NP-5**), approaching 7% for the permanent population and 9% for the temporary population when modeled using a 10-minute departure (milling) time. Hence, in this scenario 91% of the combined Newport summer population is expected to survive, with ~9% total fatalities; of those who survive, an estimated ~1% are classified as injured. These results highlight the important fact that high ground is nearby for much of the Newport community (e.g., **Figure NP-4**), allowing people more time to evacuate out of harm's way. Nevertheless, the Newport community should be mindful of the fact that as the group departure time increases (i.e., longer milling, **Table NP-6**) and/or people are unable to evacuate quickly enough along evacuation routes, the number of fatalities could increase significantly. For example, a 15 (20) minute departure time (**Table NP-6**) indicates that 27% (45%) of the population in the tsunami zone could be killed.

The estimated tsunami casualties provided in **Table NP-5** assume a mean departure time of 10 minutes and a group median evacuation walking speed of 4 fps except for individuals ≥65 years in age, who evacuate at 3.2 fps. To better illustrate the evacuation situations and opportunities throughout the Lincoln City UGB, we calculated the likelihood of survival based on distance to safety, walking speed, and tsunami wave arrival time. Survivability was determined using the survival likelihood distance breakpoints from the formula associated with **Table 2-4** for a tsunami wave arrival of 30 minutes. These data are shown in **Figure NP-5** for areas north of Yaquina Bay and **Figure NP-6** for south of the bay. **Figure NP-5** demonstrates that an XXL1 tsunami is survivable for most residents north of Yaquina Bay.

Conversely, those areas that are likely to experience the greatest number of fatalities include South Beach State Park and the Southshore neighborhood located on the south side of Yaquina Bay (**Figure NP-6**). **Figure NP-7** provides a close-up of the South Beach area, highlighting the challenges of evacuating from an XXL1 tsunami. Even with an increase in the evacuation speed to 6 fps, it is apparent that visitors camping at the South Beach State Park campground will be challenged to reach safety in time (**Figure NP-8**). Using these data, our analyses confirm that the majority of the injuries and fatalities shown in **Table NP-5** can be attributed to casualties occurring at South Beach State Park (**Figure NP-7**). These data are evaluated in more detail in Section 8.4.3.1.

Table NP-5. Injury and fatality estimates for an XXL1 tsunami in the Newport urban growth boundary. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, 10-minute milling time prior to departure, and wave arrival time at the tsunami runup line of 30 minutes. Injury and fatality estimates are rounded to nearest 10.

				Injury and Fatality Ratio	
Population Segment	**Number of People**	**Fatalities**	**Injuries**	**Fatalities**	**Injuries**
Permanent	1,160	80	10	7%	1%
Temporary	7,171	670	50	9%	1%
Total	8,331	750	60	9%	1%

Note: Population and tsunami casualty estimates are limited to people residing in the XXL1 tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Table NP-6. Injury and fatality estimates for an XXL1 tsunami in the Newport urban growth boundary assuming different departure times. Model results assume an average walking speed of 4 fps, summer weekend 2 AM scenario, and wave arrival time at the tsunami runup line of 30 minutes. Injury and fatality estimates are rounded to nearest 10.

		Average Departure Time					
		Injuries and Fatalities			Injury and Fatality Ratio		
Population Segment	**Number of People**	**10 Minutes**	**15 Minutes**	**20 Minutes**	**10 Minutes**	**15 Minutes**	**20 Minutes**
Permanent	1,160	80	260	490	7%	23%	42%
Temporary	7,171	720	1,960	3,300	10%	27%	46%
Total	8,331	800	2,220	3,790	10%	27%	45%

Note: Population and tsunami casualty estimates are limited to people residing in the XXL1 tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Finally, injuries and fatalities from a tsunami can be significantly lowered if individuals evacuate as soon as possible and travel at faster evacuations speeds (e.g., slow jog to run). We obtained injury and fatality percentages from the Hazus tsunami casualty model for the XXL1 tsunami scenario, varying group departure time and group walking speeds (**Table NP-6**). As expected, injuries and fatalities increase as the departure time increases (i.e., longer milling behavior, **Figure NP-9**) and decrease as the speed of travel increases.

Figure NP-5. North Newport evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

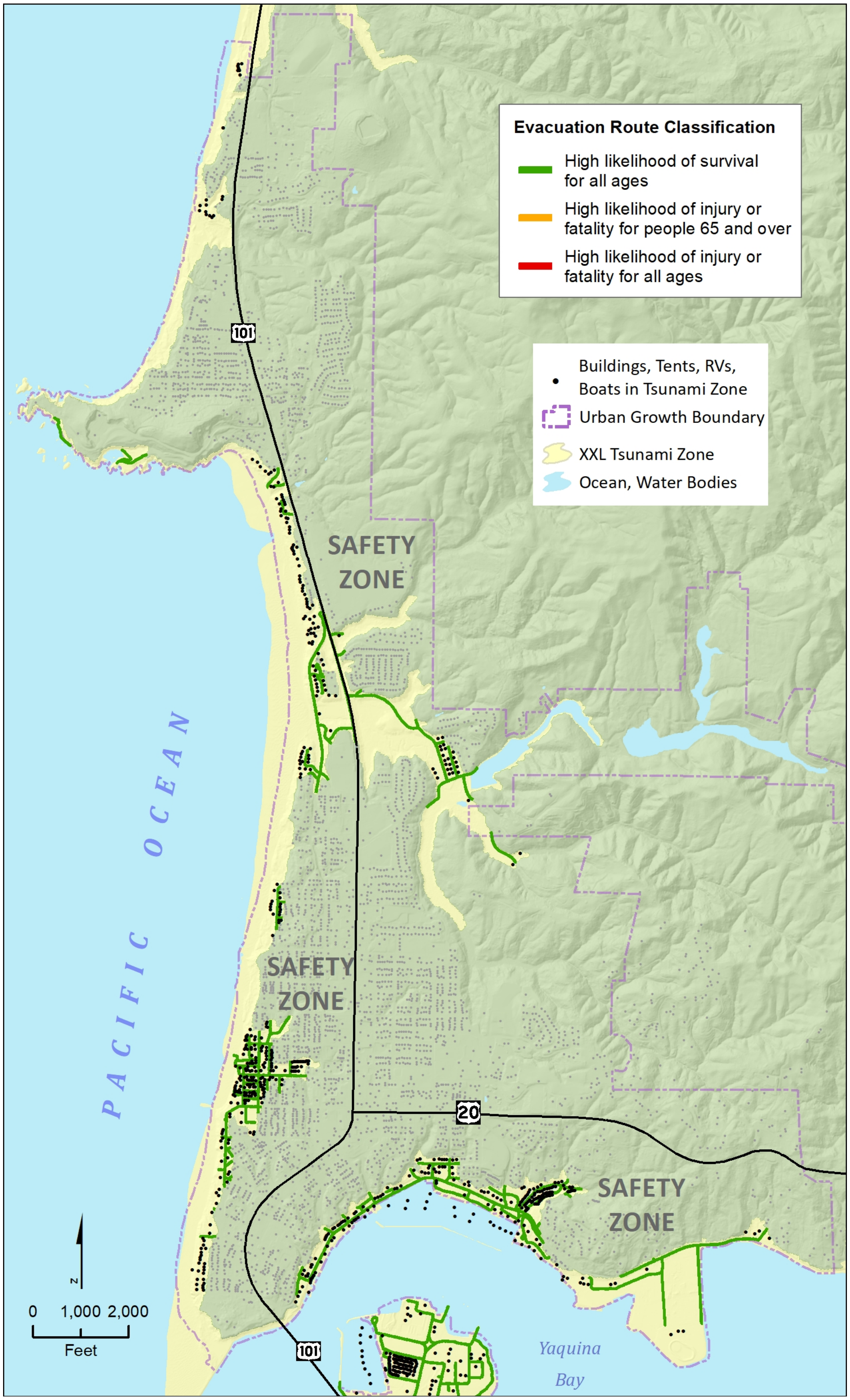


Figure NP-6. South Newport evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

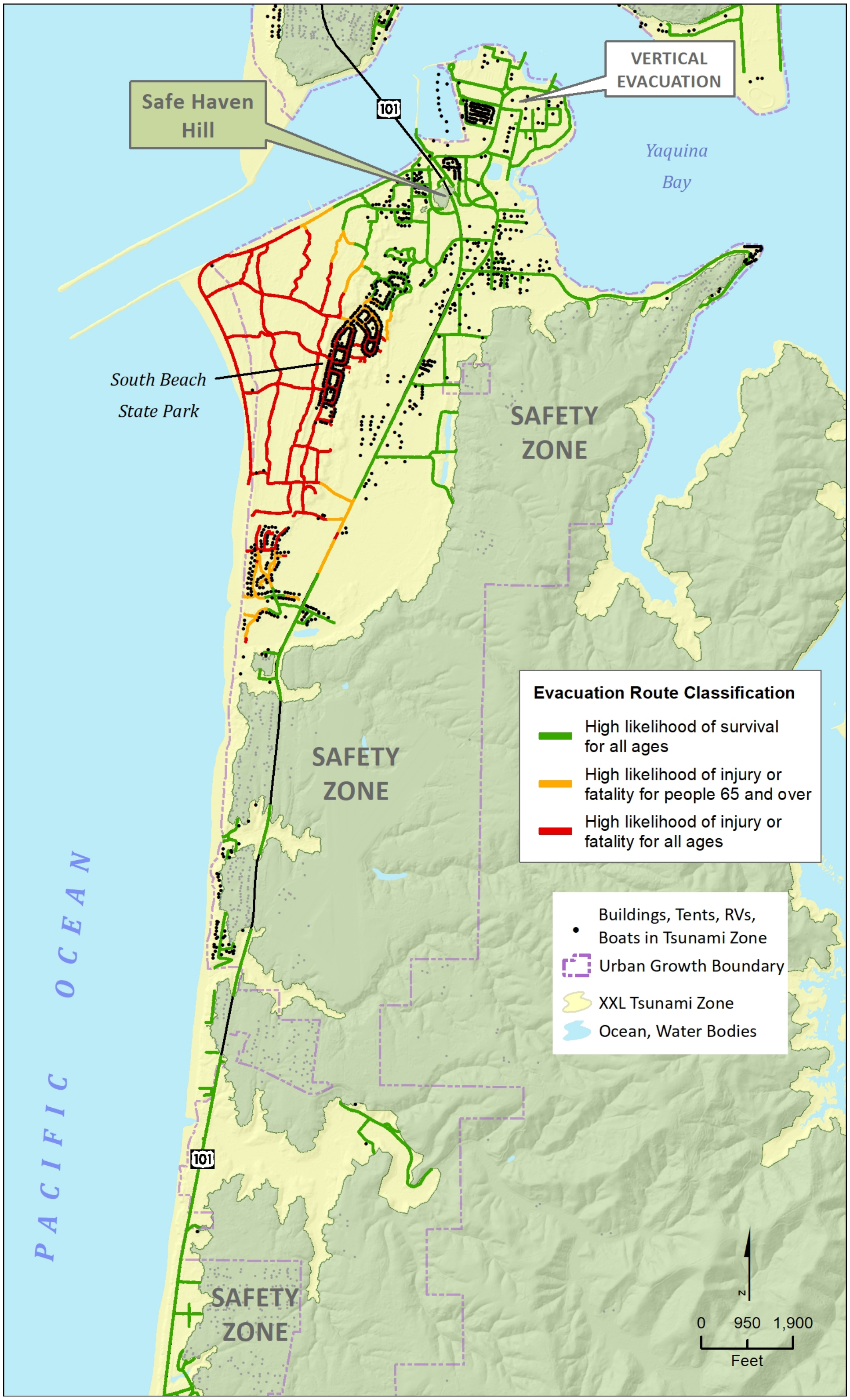


Figure NP-7. Close-up of South Newport evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

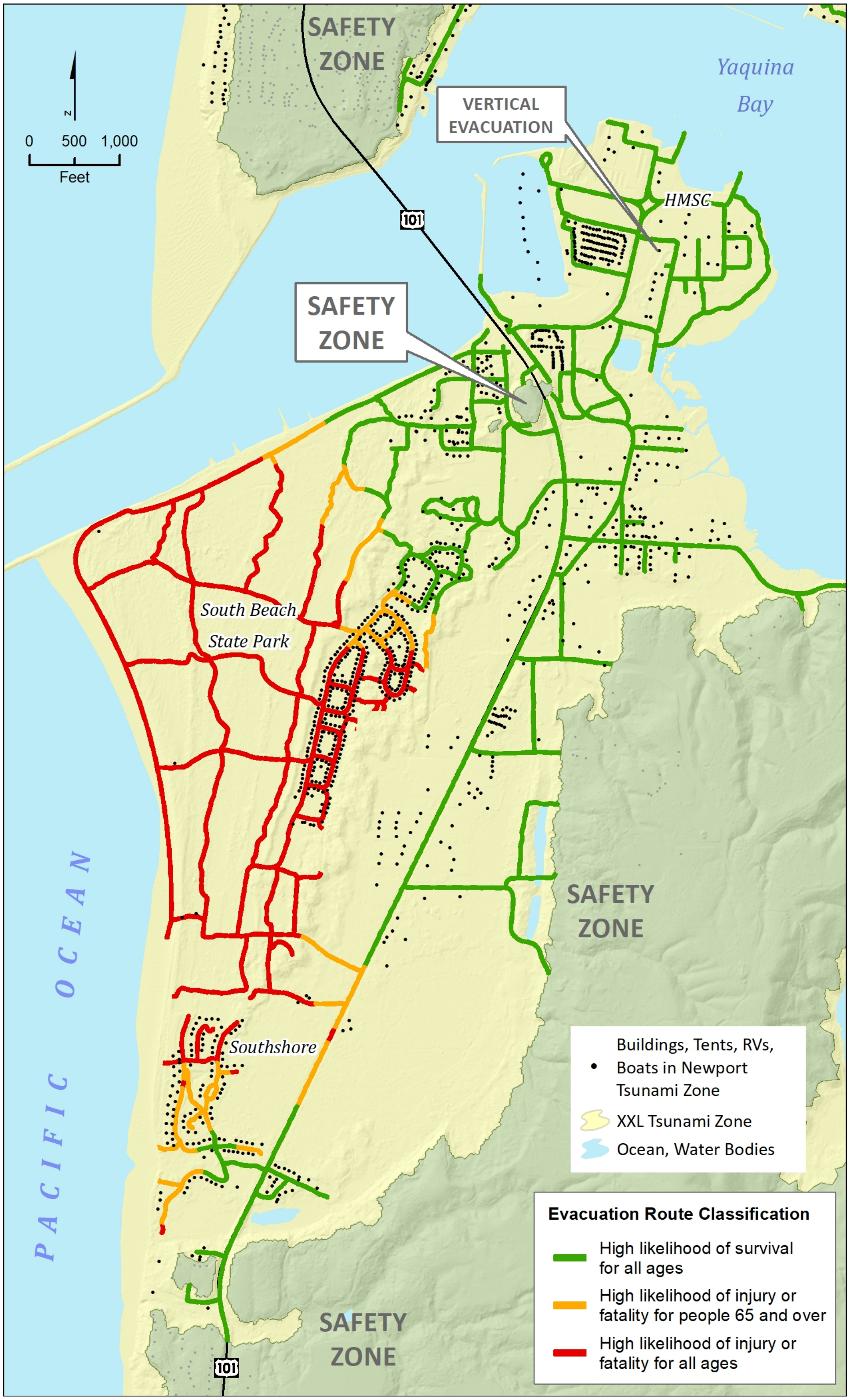


Figure NP-8. South Newport evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

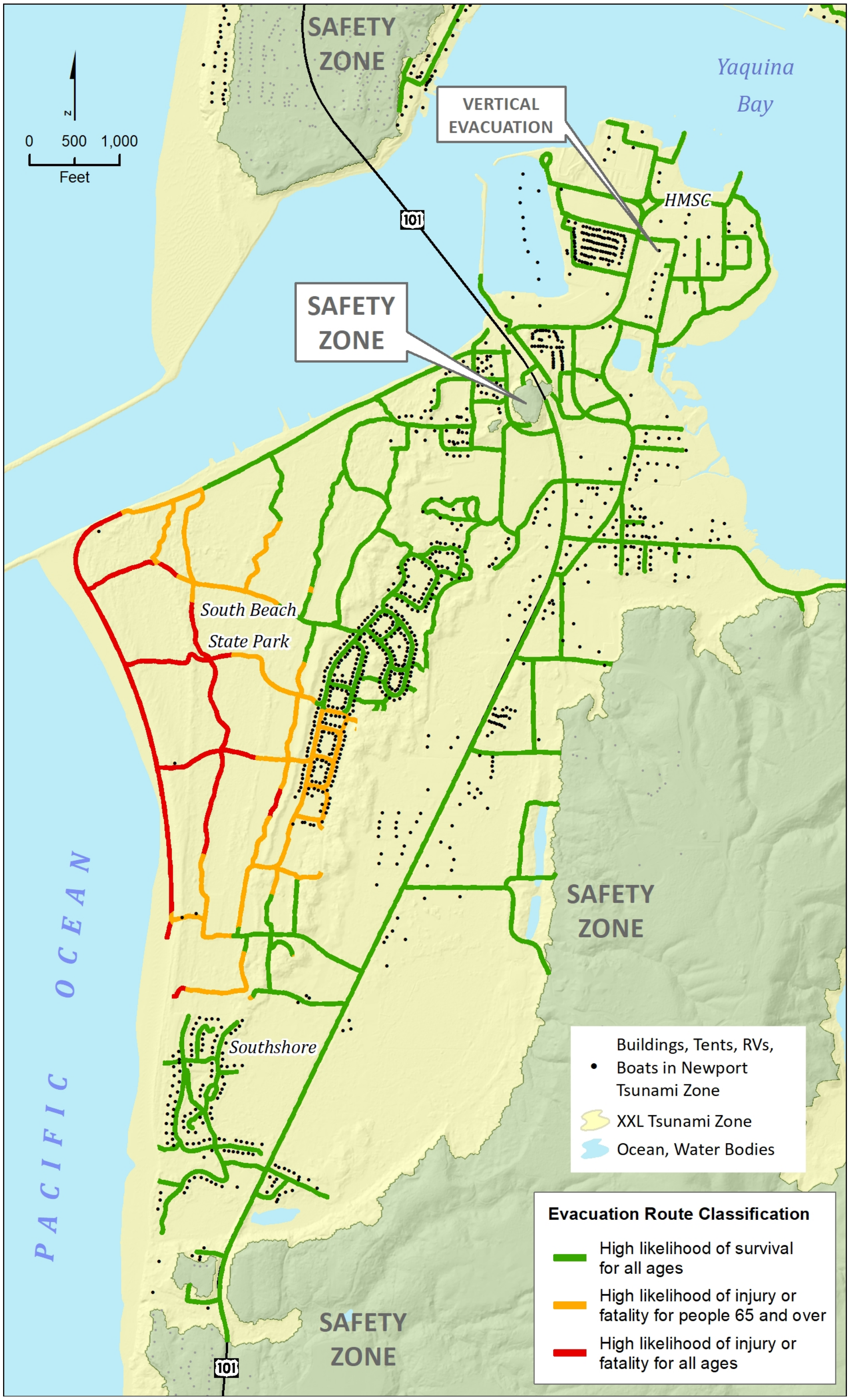
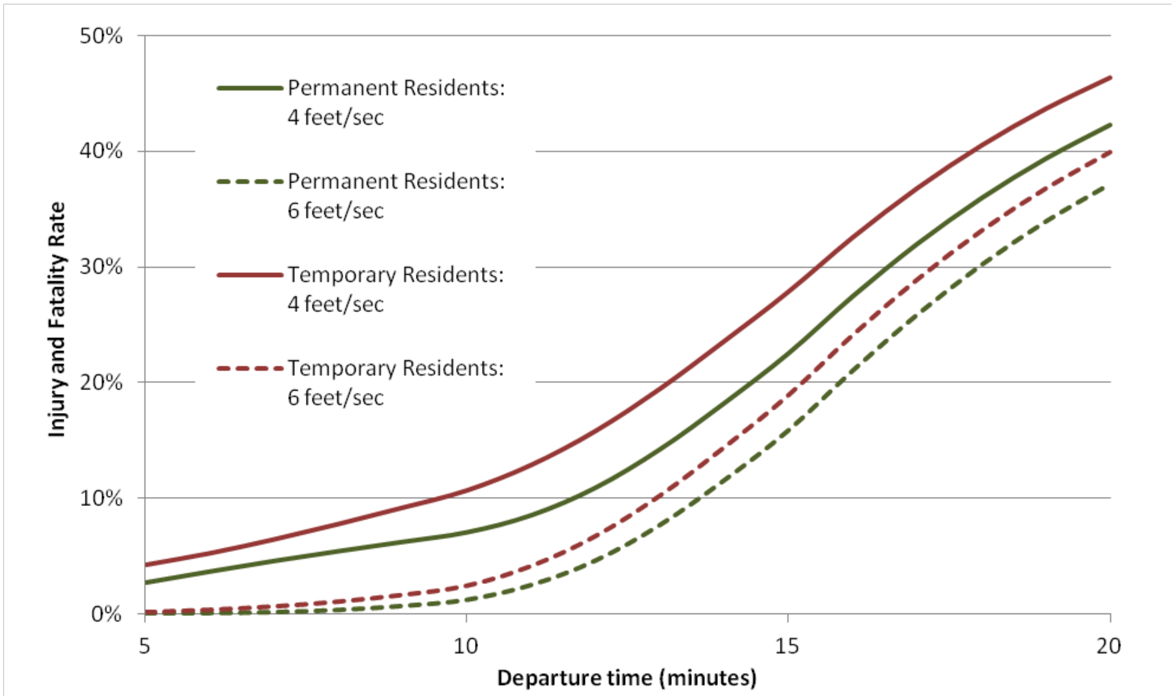


Figure NP-9. Newport injury and fatality rates estimated for the XXL1 tsunami as a function of departure time and two different evacuation speeds. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the XXL1 tsunami zone. Scenario includes the Oregon State University tsunami vertical evacuation structure (Gabel and others, 2019a).



8.4.3.1 South Newport: L1 Tsunami Scenario

Hazus analyses using the XXL1 CSZ tsunami scenario clearly indicate that the bulk of the casualties in the Newport area are likely to be from South Beach State Park. Here, we evaluate the L1 tsunami inundation scenario (Gabel and others, 2019a), which covers 95% of the expected range of possible tsunami inundation scenarios (Witter and others, 2011). The L1 analyses indicates that virtually all campground residents and most residents in the Southshore Beach Homes neighborhood can evacuate safely to the various island safety zones (**Table NP-7**, **Figure NP-10**). These results improve even more if evacuees increase their evacuation speed to 6 fps. As can be seen in **Figure NP-11**, evacuation using this higher speed results in virtually all of the South Beach campground and neighborhood residents reaching safety. The analysis assumes that South Beach State Park campground residents optimally evacuate to the closest identified safety "island," including, where appropriate, the "island" of Safe Haven Hill. However, in the event of a real earthquake and tsunami, temporary residents at the state park, OPRD officials, and individual resident evacuees must weigh the risk between trying to reach the XXL1 high ground in time, versus evacuating to a lower "L1" elevation island of high ground with the hope that inundation dos not exceed the L1 inundation line.

Table NP-7. Injury and fatality estimates for an XXL1 and an L1 tsunami in the South Beach area assuming different departure times. Model results assume an average walking speed of 4 fps, summer weekend 2 AM scenario, and wave arrival time at the tsunami runup line of 30 minutes. Injury and fatality estimates are rounded to nearest 10.

			Average Departure Time					
			Injuries and Fatalities			Injury and Fatality Ratio		
Tsunami Evacuation Scenario	Population Segment	Number of People	10 Minutes	15 Minutes	20 Minutes	10 Minutes	15 Minutes	20 Minutes
XXL1 Tsunami	Permanent	402	81	170	240	20%	42%	60%
	Temporary	3,522	710	1,500	2,100	20%	43%	60%
	Total	3,924	791	1,670	2,340	20%	43%	60%
L Tsunami	Permanent	402	21	130	210	5%	32%	52%
	Temporary	3,522	71	860	1,600	2%	24%	45%
	Total	3,924	92	990	1,810	2%	25%	46%

8.4.3.2 South Beach Day Use Study

For a daytime tsunami evacuation scenario we assume beach visitors are able to mobilize immediately (~5 minutes rather than 10 minutes) after the strong earthquake ground motion ceases. However, even with a 5-minute departure time, because of the relatively large travel distances required to reach safety in the XXL1 scenario, nearly all beach visitors in our simulation are unable to reach safety at a speed of 4 fps before being inundated by the tsunami (**Table NP-8**, **Figure NP-12**). It is apparent in **Figure NP-13** that at a speed of 6 fps there is still insufficient time for many beach occupants to reach safety. These data are in stark contrast with the same analyses using the L1 tsunami scenario, which indicates that distance to safety is significantly lowered (i.e., closer) for all beach visitors (**Figure NP-10**). It is important to note these results assume that every beach visitor is aware of, and will take, the optimal route to safety. In reality, beach visitors will not necessarily evacuate via their closest entry point to the beach, nor will they necessarily know the optimal route through the beachgrass-covered undulating sand dunes to a tsunami safety zone.

Table NP-8. Injury and fatality estimates for an XXL1 and L1 tsunami in the South Beach State Park day-use area assuming different departure times. Injury and fatality estimates are constrained to two significant digits. Model results based on a group average walking speed of 4 fps and wave arrival time of 30 minutes.

		Average Departure Time					
		Injuries and Fatalities			Injury and Fatality Ratio		
Tsunami Evacuation Scenario	Number of People	5 Minutes	10 Minutes	20 Minutes	5 Minutes	10 Minutes	20 Minutes
XXL1 tsunami	554	510	540	550	92%	97%	99%
L tsunami		21	95	360	4%	17%	65%

Figure NP-10. South Beach evacuation routes and distance to tsunami safety for the L1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

Figure NP-11. South Beach evacuation routes and distance to tsunami safety for the L1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

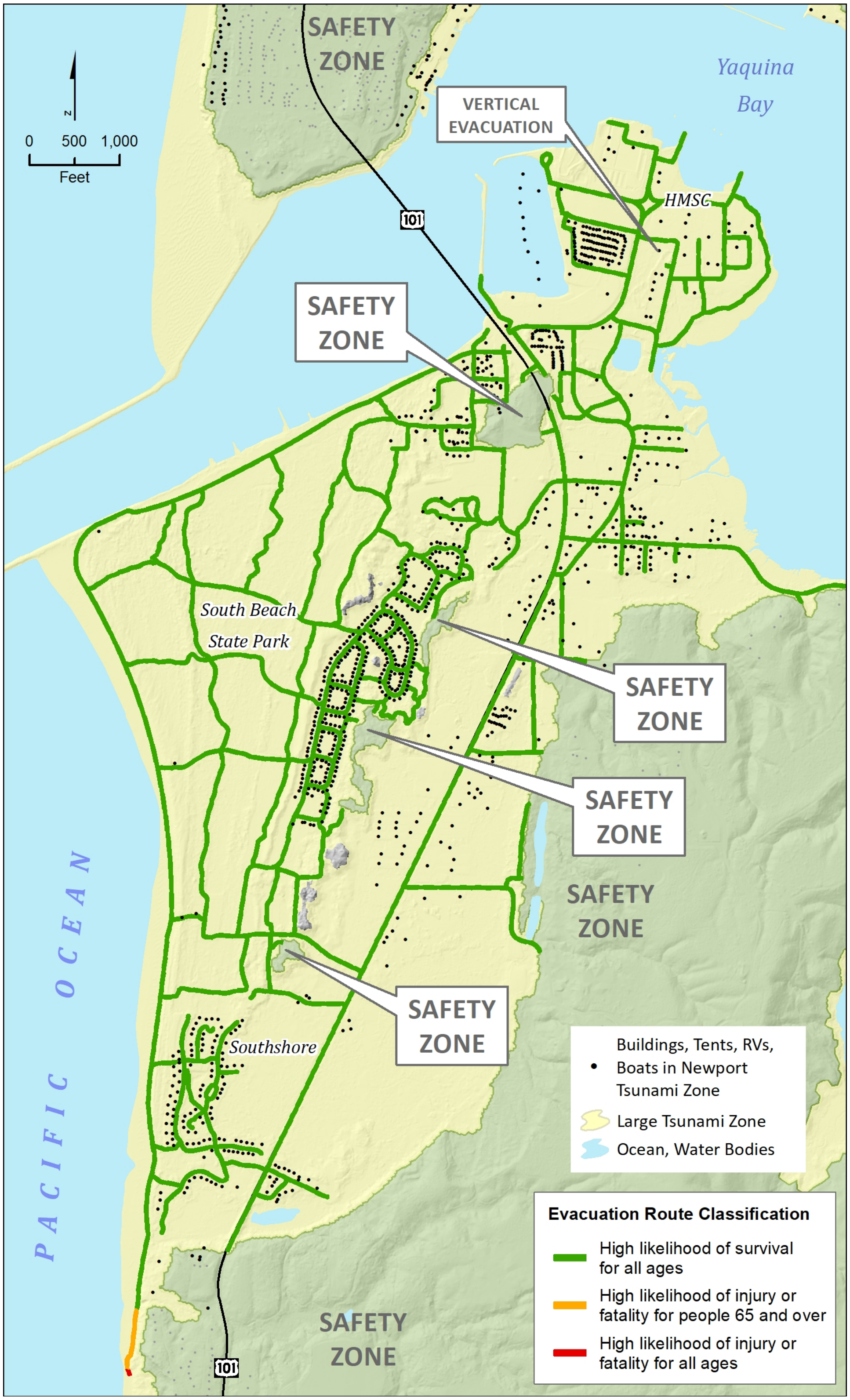


Figure NP-12. South Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 5 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes. The 168 parties comprise 554 individuals; see Table NP-8 and Section 9.3.

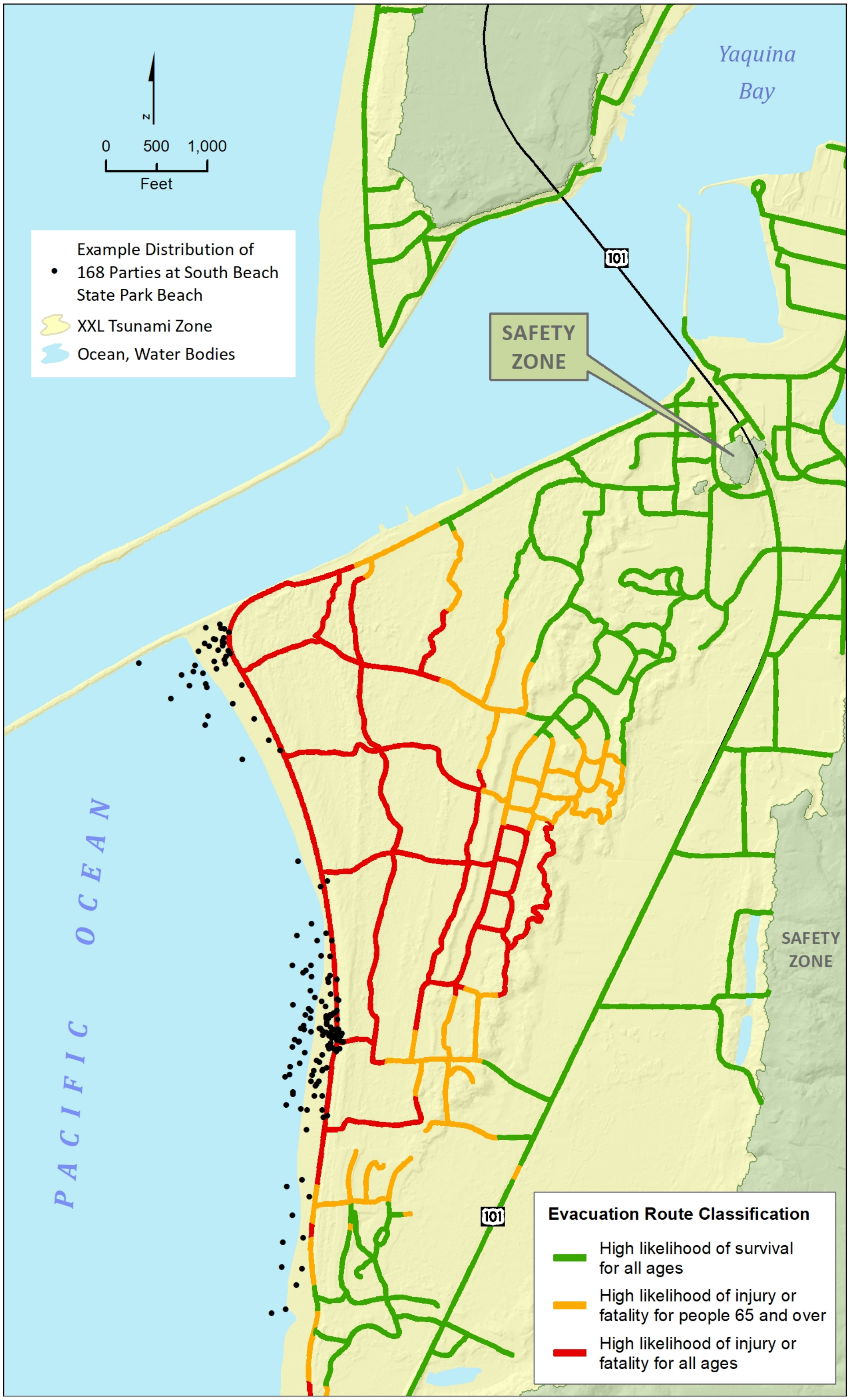
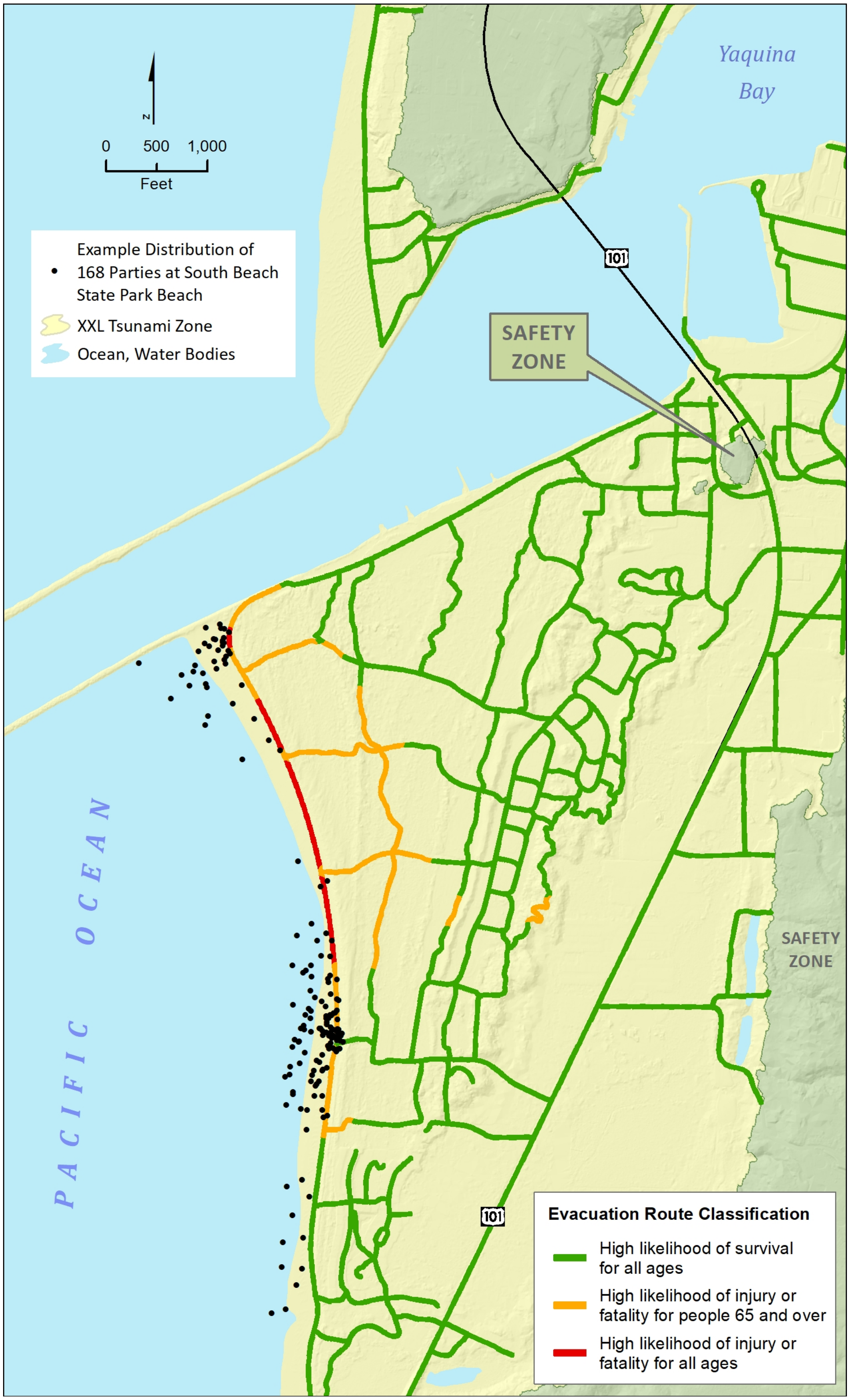


Figure NP-13. South Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), symbolized into survivability classes. Symbology assumes a departure time of 5 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes. The 168 parties comprise 554 individuals; see Table NP-8 and Section 9.3.



8.4.3.3 Impact of Tsunami Vertical Evacuation Structure at Hatfield Marine Science Center

We evaluate the added benefit of a tsunami vertical evacuation structure (Oregon Marine Sciences Building) at the Hatfield Marine Science Center (HMSC) shown in **Figure NP-14**, when compared with not having the structure and evacuating everyone to Safe Haven Hill (**Figure NP-15**). For a daytime earthquake scenario we assume that HMSC building occupants and people in or adjacent to the complex (e.g., from the nearby RV park) are able to mobilize immediately after the earthquake ground motion ceases (~5 minutes after the start of earthquake shaking). Further, we assume occupants of the older buildings at HMSC are able to evacuate their buildings quickly with minimal egress restrictions. Weekday daytime population estimates were estimated to range from ~1,100 people during the week, to ~680 on the weekend; the majority are visitors and workers at HMSC along with a number of people who live on their boats. Furthermore, the daytime population estimate assumes a fully occupied Marine Science Building with 300 faculty and students, nearly all of whom are under 65 years of age. With these assumptions in mind, our analyses indicate that the vertical evacuation structure provides some benefit to the broader community (**Table NP-9**). If we assume that people are able to evacuate immediately (e.g., within 5 minutes), then differences in fatalities (evacuate to Safe Haven Hill versus to the vertical evacuation structure) are likely to range from ~5 to 20 people. In practice, however, occupants of the large buildings at HMSC may need several minutes to successfully evacuate the buildings, so a 10-minute departure may be a more reasonable assumption. Using this scenario, it can be seen in **Table NP-9** that the number of fatalities could increase substantially (to ~290 people), assuming the tsunami were to occur on a weekday. Increasing a person's speed of travel (e.g., walk to jog) would almost certainly increase the chance of survival, thereby reducing the estimated fatalities. However, when compared with not having a vertical evacuation structure, it is evident from **Table NP-9** that ~170 to 290 more people could perish.

Table NP-9. Injury and fatality estimates for an XXL1 tsunami affecting northeast South Beach (i.e., HMSC) assuming different departure times. Injury and fatality estimates are constrained to two significant digits. Number of people is limited to those occupying buildings, boats, and recreational vehicles within the evacuation watershed outline shown in Figure NP-14. Model results based on a group average walking speed of 4 fps and wave arrival time of 30 minutes.

			Average Departure Time			
			Injuries and Fatalities		Injury and Fatality Ratio	
Tsunami Evacuation Scenario	Day of Week Scenario	Number of People	5 Minutes	10 Minutes	5 Minutes	10 Minutes
XXL1 tsunami: Without tsunami vertical evacuation structure	Weekday	1,096	17	380	2%	35%
	Weekend	681	0	240	0%	35%
XXL1 tsunami: With tsunami vertical evacuation structure at HMSC	Weekday	1,096	4	93	0%	8%
	Weekend	681	0	67	0%	10%

Figure NP-14. Northeast South Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), with the inclusion of the new OSU Marine Science Building vertical evacuation structure. Purple dash highlights the local evacuation community (area of "watershed"). Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes. The model assumes people within the evacuation watershed outline evacuate to the Marine Science Building, while people outside of the area evacuate to Safe Haven Hill.

Figure NP-15. Northeast South Beach evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario (Gabel and others, 2019a), excluding the new OSU Marine Science Building vertical evacuation structure. In this scenario, everyone evacuates to Safe Haven Hill. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 30 minutes.

8.4.4 Displaced Population

Permanent and temporary residents who successfully evacuate out of the tsunami zone will require short- to medium-term shelter, given that their residences are presumed destroyed or rendered uninhabitable by the tsunami (**Table NP-1**). Temporary residents will likely not be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017) and that their personal vehicles will likely be destroyed or damaged in the tsunami.

For mass care planning purposes, displaced population estimates can be obtained by subtracting the total injuries and fatalities in **Table NP-5** from the total number of people (permanent and temporary) estimated to be in the XXL1 tsunami zone. From those data, we estimate that the displaced population in Newport from an XXL1 event could be as low as ~1,100 people and as high as almost 7,600 people. The former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every rental facility at maximum capacity. If we assume the earthquake rupture is closer to an L1 event, from **Table NP-1** we estimate that the displaced population could range from as few as ~600 people to as many as 4,500 people in need of shelter. As with the XXL1 scenario, the former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every rental facility at maximum capacity.

We note again that our analysis is limited to the buildings and people in the Newport XXL1 tsunami zone at 2 AM. Some portion of the permanent and temporary residents outside of the tsunami zone can be assumed to need food and shelter if their residential structures, including motels and hotels, are heavily damaged from the earthquake.

A lesser magnitude tsunami event, such as a M1 scenario, will result in even fewer tsunami injuries and fatalities, the bulk of whom are likely to come from a few discrete areas, such as the Newport bayfront, and the South Beach area. However, even with an M1 earthquake scenario there will be considerable building destruction as the tsunami is expected to severely damage the bayfront, and portions of the South Beach area, thereby impacting the local economy.

8.4.5 Essential Facilities, Special Facilities, and Key Infrastructure

Our analyses indicate the following *essential facilities* in the Newport UGB tsunami zone:

- U.S. Coast Guard Station Yaquina Bay

Special facilities located in the Newport UGB tsunami zone are:

- Oregon Coast Aquarium ("Sleep in the Deep" program, up to 80 children)
- Camp Gray (up to 140 children in dormitories and classrooms)
- Bayside at South Beach Memory Care Facility, 411 SE 35th St (42 beds)

We identified the following *key infrastructure facilities* in the Newport UGB tsunami zone:

- U.S. Customs and Border Protection Port of Entry, 610 SE Bay Blvd.
- Electrical Substation, S.E. 40th St east of SE Ash St
- Cellular tower, Verizon Wireless, 3087 SE Ash St
- FM Transmission towers, Northwest Natural Gas Company, Callsigns WCE997, WCE 998, near McClean Point
- Lift Station ("HMSC Pump Station"), SE Marine Science Drive
- Lift Station ("Bay Front Pump Station"), SW Bay Blvd.
- Lift Station ("Nye Beach Pump Station"), NW Beach Dr.
- Cell Tower, 4627 S Coast Highway
- Big Creek Reservoir and Newport Water Treatment Plant, 2810 NE Big Creek Rd

8.4.6 Employment

Our analyses indicate that ~27% of the jobs in the Newport UGB are within the tsunami zone (**Table NP-10**). Of these, the two highest employment sectors in the tsunami zone are Accommodation and Food Services (NAICS code 72) and Manufacturing (NAICS code 31), which account for 42% and 11% of the 2,814 jobs, respectively.

Table NP-10. Number of businesses, jobs, and annual wages paid in Newport urban growth boundary XXL1 tsunami zone.

	XXL1 Tsunami Zone	Newport Urban Growth Boundary
Number of businesses	201	731
Number of jobs	2,814	10,550
Annual wages paid ($ million)	$98	$411

8.4.7 Social Characteristics

We reiterate that the American Community Survey (ACS) social characteristic data span the entire community (and county) and are not at a resolution that would allow us to better define these statistics by tsunami zone. The interested user is encouraged to review the introduction to Appendix A for additional resources on the ACS in order to better understand vulnerable permanent populations living within the tsunami zone.

As noted previously, our analyses indicate that ~42% of the permanent residents in the XXL1 tsunami zone are ≥65 years of age (**Table 3-2**), which is significantly higher than the Oregon XXL1 tsunami zone average of 27%. We can delve deeper into the social aspect of a local population by evaluating other characteristics such as the number of people who speak Spanish (or other languages) as well as those who may have disabilities. Both datasets are important because they have a direct bearing on basic outreach (e.g., providing material that has been translated) and in terms of identifying those who may need evacuation assistance. The proportion of Spanish-speaking (and other languages) households in the City of Newport is double (at ~11%) the overall Lincoln County average of ~5% (**Table NP-11**). If we include other languages, we find that ~13% of the local population speaks a language other than English. Given this high percentage, tsunami awareness and evacuation materials by emergency managers could be developed in other languages (especially Spanish) would be especially useful.

Table NP-11. Household spoken language statistics for the City of Newport and Lincoln County. Data taken from American Community Survey 2013–2017 5-year estimates.

	City of Newport		Lincoln County
	Number of Households	Percent of Households with Margin of Error	Percent of Households with Margin of Error
Households speaking Spanish	500	11.1% ± 2.3%	5.2% ± 0.7%
Households with limited English fluency; Spanish spoken	85	1.9% ± 1.4%	0.5% ± 0.3%
Households with limited English fluency; all languages	94	2.1% ± 1.4%	0.8% ± 0.4%

Table NP-12 presents information on the percentages of people with disabilities in the Newport area. Overall, these results indicate the proportion of the local population with disabilities, ~15.4%, is less than the county wide average, ~21.7%, Of particular concern is the relatively large number of individuals with vision, cognitive, or ambulatory disabilities, as well as a large number of people classified as experiencing independent living difficulty, all of whom will need help evacuating from the tsunami zone. Not all of these individuals may reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

Table NP-12. Number of individuals with disabilities (by type) for City of Newport and Lincoln County. Data taken from American Community Survey 2013–2017 5-year estimates. An individual with a disability may have more than one difficulty.

	City of Newport		Lincoln County
	Number of Individuals	Percent of Population with Margin of Error	Percent of Population with Margin of Error
Individuals with a disability	1,544	15.4% ± 1.8%	21.7% ± 1.1%
Difficulty Category			
Hearing	510	5.1% ± 1.2%	6.9% ± 0.7%
Vision	333	3.3% ± 1.0%	3.5% ± 0.5%
Cognitive	609	6.4% ± 1.4%	8.5% ± 0.8%
Ambulatory	923	9.8% ± 1.7%	12.2% ± 1.0%
Self-care	353	3.7% ± 1.1%	4.0% ± 0.5%
Independent Living	636	8.0% ± 1.9%	8.9% ± 0.9%

8.4.8 Discussion and Recommendations

Evacuation Challenges

Aside from a few notable areas of concern (e.g., South Beach), the majority of the buildings in the Newport area are either located close to high ground or are located outside of the tsunami inundation zone. This does not preclude the need for preparation and effective messaging. Even if one is occupying a building only 500 feet from tsunami safety, needless delay (i.e., milling behavior) may be deadly.

The most significant evacuation challenges can be found south of Yaquina Bay in the South Beach area, which includes South Beach State Park and the Southshore neighborhood. At South Beach State Park, Safe Haven Hill is the locally identified tsunami safety destination. However, distances to Safe Haven Hill from many campground sites are typically a mile or more away and as much as 1.7 miles for day-use visitors recreating in the vicinity of the South Beach State Park day-use area. As a result, Oregon State Parks and community leaders should evaluate additional trails leading out of the campground toward the hills located on the east side of Highway 101. Such options have been evaluated by Gabel and others (2019a) and have demonstrable benefits over directing everyone solely toward Safe Haven Hill.

In the Newport tsunami zone, temporary residents greatly outnumber the permanent residents at peak season. Temporary residents typically reside in structures that are closer to the ocean and thus farther from tsunami safety. This strongly suggests that more effort should be directed at working with the hospitality industry to educate both staff and the public. We strongly encourage the hospitality industry to include tsunami hazard information and evacuation maps in every room.

Finally, local emergency managers and community leaders should be mindful of the fact that ~42% of the permanent residents in the tsunami zone are ≥65 years of age and therefore are likely to evacuate at slower speeds compared with those <65 years. Thus, for this demographic group it is perhaps even more important that they evaluate their evacuation routes and regularly practice evacuation "walk-outs" so that the routes become instinctive.

Education

We estimate that of the 7,000 temporary visitors who lodge in the Newport XXL1 tsunami zone, a significant portion (~1,900, 27%), spend the night in either a hotel or motel. Although many of the motels and hotels in the Newport UGB are located close to high ground, many visitors to the coast are probably unaware of the tsunami hazard, let alone where to evacuate to should a CSZ earthquake occur. Due to the relative closeness of the hotels and motels to high ground, it is very clear that occupants can survive the event provided they are aware of the hazard and take appropriate action at the time. Accordingly, tsunami safety messaging for visitors should include focused outreach to hotel/motels as well as to vacation homes. Besides improving basic hazard awareness, such activities could also include education that local evacuation maps can be generated for any location on the Oregon coast via the NVS tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac) and smartphone application (http://www.nanoos.org/mobile/tsunami_evac_app.php), enabling users to post appropriate information in their homes or in every motel/hotel room. Familiarity and use of the mobile app would also allow for increased awareness of where high ground is located, not just for Newport, but also for other areas on the Oregon Coast. While knowledge of where high ground is located is critical, equally important is the practice of walking one's evacuation route to ensure familiarity with the route and any potential obstacles.

Similarly, our analyses indicate that the majority of Newport permanent residents are located either close to tsunami safety (**Figure NP-3**) or are outside of the inundation zone. However, any delay in evacuation could quickly become problematic and lead to increased fatalities (**Figure NP-9**). Our Hazus simulations demonstrate that loss of life can be minimized for *all* residents, permanent and temporary, if individuals evacuate as soon as possible after the earthquake stops and travel on foot as quickly as possible.

Visitors to Newport spending the night in the tsunami zone occupy diverse housing types (**Figure NP-3**). Educational material can be developed to target all types of visitors, including second-home owners, vacation homes, condominium units, campers and recreational vehicles, manufactured housing, and overnight boaters at the marina.

Three manufactured housing ("mobile home") parks are located in the tsunami zone. These are Surf Sounds Court (4623 Oregon Coast Highway), Harbor Village RV Park (923 SE Bay Blvd., which includes a mixture of recreational vehicles and manufactured housing), and Surfside Mobile Village (392 NW 3rd St). All three mobile home parks are located relatively close to high ground and hence tsunami safety. However, manufactured homes installed prior to 2003 are subject to slipping off their foundations (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014), potentially compromising the ability to leave the structure quickly. The compromised egress may hinder timely evacuation by the occupants. Seismic upgrades of such structures to current building standards may be cost-prohibitive. FEMA (2012, Section D) advises having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting. Such tools may provide a low-cost solution for rapidly exiting their structures in the critical time interval after the earthquake ends and before the tsunami arrives. Manufactured housing occupants can first be educated about the potential situation, and then given the information on tools that they can obtain to mitigate it.

Mitigation

Our evacuation simulations suggest that improving existing evacuation trails for unimpeded passage, along with increased saturation of tsunami wayfinding signage will help reduce the potential for a large number of casualties. Of particular importance is having a sufficiently dense network of signs (either posted and/or thermoplastic on road/path surfaces) that direct people along core routes to areas outside the tsunami zone. Signs of this nature need to be spaced appropriately far apart so that they can be easily viewed (and read) at any time of the day or night.

Additional site-specific mitigation needs are warranted for the South Beach area, particularly in the vicinity of South Beach State Park. At minimum, this could include developing additional trails that direct people near the south end of the campground toward Highway 101 and to the eastern foothills. In developing such trails, additional consideration should be given to areas of wetland that are established adjacent to Highway 101. In these areas, further engineering may be required in order to address potential liquefaction concerns. Such trails should be accompanied by sufficient signage that will help guide people out of harm's way under all lighting conditions. Another option for consideration is the construction of a tsunami vertical evacuation structure. Although we did not evaluate this option for the park, it remains a viable consideration.

An alternate mitigation solution could include planning for evacuating from an L1 tsunami event compared to an XXL1 tsunami event. Recall that the L1 scenario covers an estimated 95% of the possible tsunami inundation and is founded on strong geologic science. Were Oregon State Parks to adopt such an approach, it would require additional work to prepare various islands of high ground that are outside of the L1 inundation zone as evacuation sites (**Figure NP-10**), along with accompanying changes in evacuation brochures and messaging.

Finally, we recommend and encourage local communities to practice periodic (annual) tsunami evacuation drills. In order to instill a culture of awareness of the tsunami hazard facing the Oregon coast, residents (and visitors) must periodically practice their evacuation routes. Studying an evacuation map is not the same as actually walking an evacuation route. Although we recognize that such an approach may be disruptive to the local economy, holding periodic drills will save lives. Such a culture is entrenched in Japanese way of life and helped save many thousands of lives during the catastrophic tsunami event on the Sendai coast on March 11, 2011. This culture is highlighted in several recent studies (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Response

Depending on the time of year a CSZ earthquake and tsunami strike, Newport is likely to experience an acute short- to medium-term sheltering need after a tsunami. Should an XXL1 tsunami occur, we estimate that the displaced population in Newport could range from a winter low of ~1,000 people to almost 8,300 people in the peak of summer. Even a lesser magnitude tsunami will result in significant destruction of residential property, with a Medium (M1) tsunami potentially displacing ~3,700 temporary residents and 450 permanent residents (**Table NP-1**), assuming most of the residents safely evacuate from the M1 tsunami zone.

Besides addressing shelter needs, coastal communities such as Newport (and Lincoln County) will need to attend to both fatalities and injuries caused by the tsunami (**Table NP-5**) and earthquake (**Table NP-4**). As noted previously, injuries in the Newport area are relatively low, ranging from a few tens of people to as many as ~150, while numbers of fatalities could reach several hundred. Local hospitals and emergency services will need to be prepared to respond to such challenges.

Wang (2018) examined a number of considerations for coastal hospitals to take in order to prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for needed fuel and water needs. According to the Oregon Resilience Plan documents (OSSPAC, 2013), there are about 483 licensed beds at the 11 coastal hospitals. Combined earthquake and tsunami related injuries in Newport is estimated to be ~140 people; total injuries for the five communities could approach 900, exceeding existing hospital capacity on the coast. Hence, coastal hospitals will need to prepare for a surge in injuries (as well as large numbers of fatalities) that could well exceed existing capacity. Although a new hospital has been constructed in Newport to modern seismic code and contains state of the art facilities, the expected surge in injuries from the surrounding Newport area following Cascadia will almost certainly place a significant burden on the hospital.

Recovery

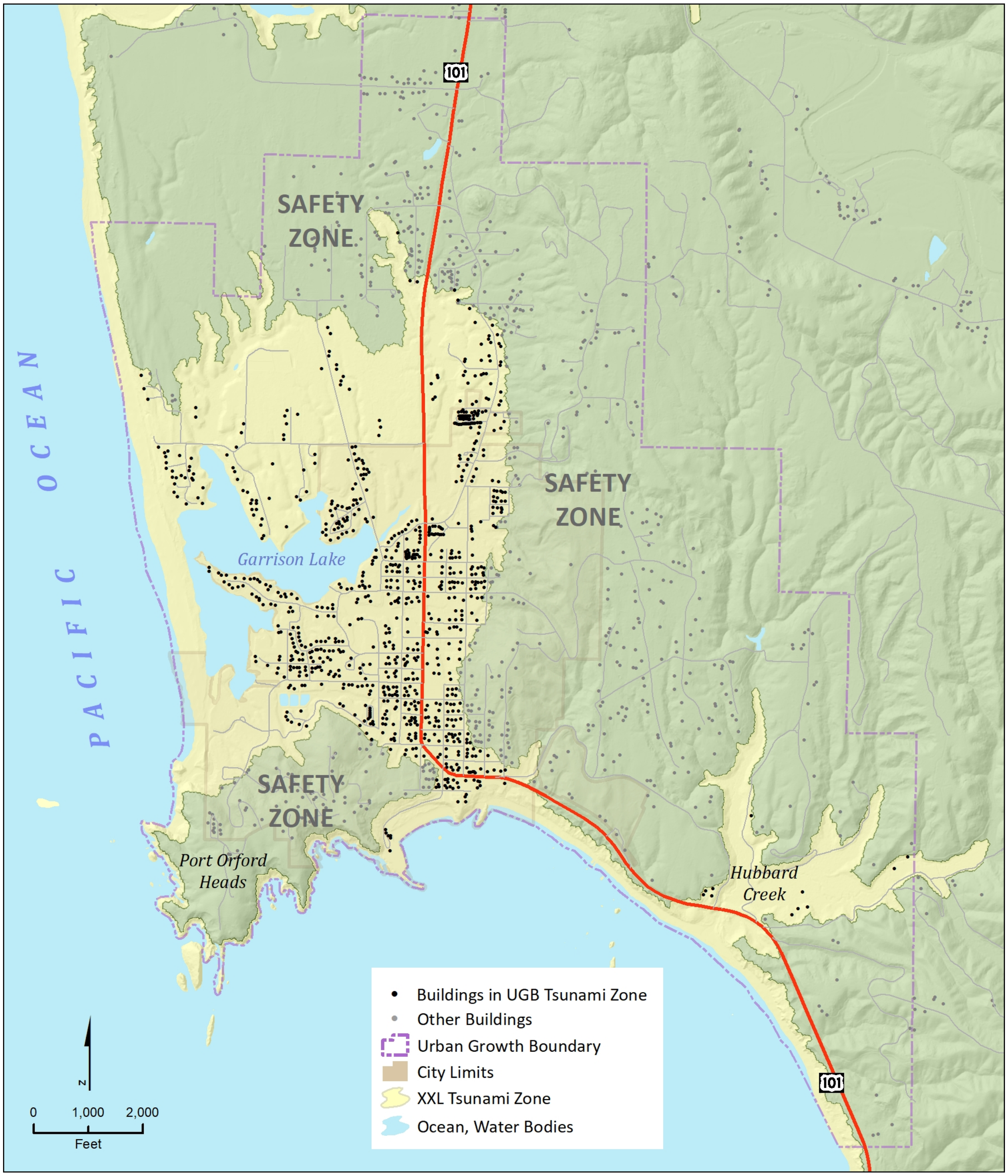
An XXL1 tsunami will have a significant impact on local employment and ultimately on the Newport economy. Tourism-driven services, which account for 42% of the jobs in the Newport tsunami zone, will be seriously impacted. This is especially the case given the number of motels and vacation and second homes located in the XXL1 tsunami zone. The situation improves somewhat if the earthquake shaking and accompanying tsunami are closer to an M1 scenario. Although fewer businesses (and hence jobs) are likely to be directly impacted by the tsunami, the potential disruption to transportation networks leading into Newport will almost certainly impact the local economy in the short term. Conversely, recovery of the commercial fishing fleet could take longer due to the need to undertake dredging of the Yaquina Bay navigation channel, rebuilding of the Yaquina bridge, and needed remediation of the jetties that fix the estuary mouth in place. The fleet itself may need to be rebuilt, given most fishing boats will be lost or destroyed.

About 1,100 permanent residents in Newport reside in buildings within the tsunami zone (**Table NP-1**). Given the predominance of wood frame construction in the tsunami zone, nearly all the buildings will likely be destroyed in an XXL1 tsunami. Many of these buildings are not in coastal flooding zones, and thus the owners are not currently required by federally backed mortgage lenders to carry flood insurance for buildings outside of a designated flood zone. However, flood insurance is available to all building owners through the National Flood Insurance Program, which covers building loss due to a tsunami (FEMA, 2018c). More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

8.5 Port Orford

The Port Orford urban growth boundary (UGB) includes the neighborhoods north of Garrison Lake and the Hubbard Creek areas outside the Port Orford city limits in the southeast (**Figure PO-1**).

Figure PO-1. Port Orford urban growth boundary (UGB), city limits, and XXL1 tsunami zone. Buildings inside the tsunami zone and UGB are shown as black points; all other buildings shown as grey points. Figure includes tent and recreational vehicle sites in the tsunami zone as black points.



8.5.1 Building and Population Characteristics

Of the total number of permanent population in a tsunami zone (895 permanent versus an estimated 2,077 temporary), ~3% (6%) of the permanent (temporary) Port Orford population is located within the M1 tsunami inundation scenario (**Table PO-1**, **Figure PO-2**). Recall, the M1 scenario accounts for an estimated 79% of the expected inundation from CSZ earthquakes. The number of permanent (temporary) residents in the L1 tsunami zone increases to ~32% (26%) (**Table PO-1**). As a reminder, the L1 scenario accounts for ~95% of the expected inundation from CSZ earthquakes (i.e., may be exceeded by ~5%). For the XXL1 scenario, virtually the entire Port Orford UGB is in the tsunami zone (**Figure PO-1**). Those not in a tsunami zone are located on high ground to the east and northeast of town, as well as on Port Orford Heads (**Figure PO-1**). As of July 1, 2018, the City of Port Orford had 1,145 permanent residents (PSU PRC, 2019) of which 895 people were identified as living in the XXL1 tsunami inundation zone. An additional 2,077 temporary residents may visit the community on a summer weekend and would be located within the XXL1 tsunami zone (**Table PO-1**); the latter estimate assumes that every residential facility and RV spot is at maximum capacity. Thus, the local population within the Port Orford XXL1 tsunami zone could potentially increase by ~2.3 times under the most ideal circumstances in the summer. Clearly, numbers of this magnitude would place a large burden on the local community in the hours to days following a major earthquake and accompanying tsunami. Our analyses also reveal that ~37% of the permanent residents are ≥65 years of age (**Table 3-2**), which is 10% higher than the overall Oregon XXL1 tsunami zone average of 27%. Temporarily occupied households (referred to as "seasonal" in U.S. Census database) make up 8% of the residential households in the XXL1 tsunami zone (**Figure PO-2**).

Table PO-1. Port Orford urban growth boundary tsunami zone building statistics and demographics for three tsunami zones.

Tsunami Zone	Number of Buildings	Number of Residential Buildings	Building Replacement Cost ($ Million)	Total Number of Households (2010 Census)	Number of Seasonal Households (2010 Census)
M1[1]	44	29	9	71	3
L1[1]	275	182	59	192	15
XXL1[1]	833	552	183	593	45

Tsunami Zone	Permanent Resident Population Estimate			Temporary Resident Population Estimate, Summertime Weekend			Population Total, Summertime Weekend
	Under 65 Years Old	65 Years and Older	Total	Under 65 Years Old	65 Years and Older	Total	
M1[1]	15	14	29	59	15	74	103
L1[1]	164	126	290	248	62	310	600
XXL1[1]	562	333	895	875	307	1,181	2,077

Notes: The U.S. Census refers to temporarily occupied households such as vacation and second homes as "seasonal households." Temporary population estimates are based on a summer weekend scenario.

[1]M1, L1, and XXL1 (Priest and others, 2013e)

Figure PO-2. Port Orford urban growth boundary tsunami zone building statistics and demographics for three tsunami zones expressed as percentages relative to the XXL1 zone. Temporary population estimates assume a summer weekend scenario.

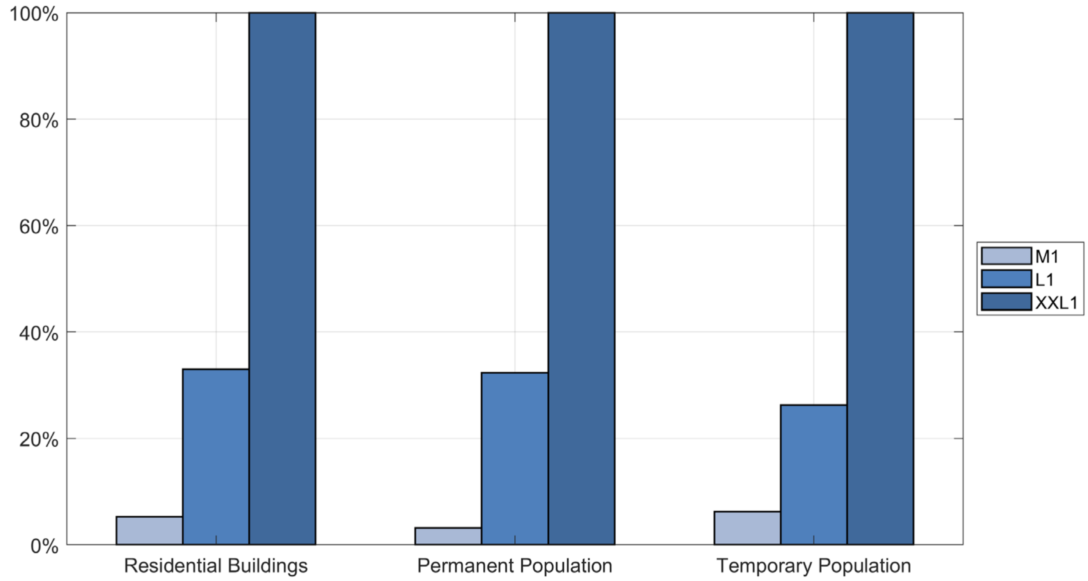


Table PO-2 (and presented graphically in **Figure PO-3**) indicates that the majority of the permanent residents within the Port Orford tsunami zone (XXL1) occupy either single-family residential homes (62%) or manufactured housing (17%). The remaining population is distributed across a wide variety of housing classifications that include multi-family residential (8%) and other (9%). Similarly, our analyses indicate that temporary residents are predominantly located in single-family vacation homes (73%), while hotel/motel lodging make up 6% of the accommodation in the XXL1 tsunami zone (**Table PO-2**). Finally, about 11% of the temporary visitor population stay in tents and recreational vehicles.

Table PO-2. Estimates of permanent and temporary population by building type in Port Orford urban growth boundary XXL1 tsunami zone. Temporary population estimates are based on a summer weekend scenario.

Housing Type	Permanent Population	Permanent Population Percentage	Temporary Population	Temporary Population Percentage
Single-family Residential	560	62%	862	73%
Manufactured Housing	151	17%	38	3%
Multi-family Residential	73	8%	82	7%
Hotel/Motel	7	1%	69	6%
Mobile (Recreational Vehicles)	20	2%	130	11%
Other (incl. Mixed-use)	84	9%	0	0%
Total	895	100%	1,181	100%

To evaluate time and distance to high ground and thus safety, we assume it takes ~10 minutes for people to mobilize prior to evacuating, while the tsunami wave fully inundates Port Orford in 17 minutes.

Accordingly, people have no more than 7 minutes to reach safety before the tsunami reaches them. If we assume that people travel at a "walk" speed (i.e., ~4 fps), we can estimate the distance of ground that can be covered (~1,680 ft) within the 7-minute time frame; people whose distances to safety exceed 1,680 ft would thus not reach safety in time assuming they maintain (or travel more slowly than) an evacuation speed of ≤4 fps. We provide distance to safety statistics using the XXL1 tsunami scenario in **Figure PO-3** for both the permanent and temporary population and as a cumulative distribution plot in **Figure PO-4**. Using this approach, we determine that for Port Orford the median distances to safety for permanent (1,900 ft) and temporary (2,064 ft) residents are comparable (**Figure PO-4**). Furthermore, we find that the majority of hotel and motels in the Port Orford UGB located in the tsunami zone are generally within ~1,680 ft of safety (**Figure PO-3**). Given the threshold of 1,680 ft and assumptions noted previously, our analyses suggest that ~55% to 60% of the population (permanent and temporary) in the tsunami zone might not reach safety before the tsunami inundates the community (**Figure PO-4**). Thus, for people located at distances to safety that are ≥1,680 ft, it is imperative that they leave sooner and travel at speeds faster than 4 fps (e.g., "fast walk" to "jog"). This is reinforced in **Figure PO-4**, which demonstrates that by increasing speed to 6 fps, ~65% of the population (permanent and temporary) could potentially reach safety in an XXL1 tsunami event.

8.5.2 Earthquake and Tsunami Building Damage and Debris Estimates

Within the XXL1 tsunami zone, building repair costs caused by an XXL1 tsunami greatly exceed the repair cost estimated from the earthquake ground motion and earthquake-induced ground deformation (**Table PO-3**). This is primarily due to the prevalence of wood frame, light-frame steel, and manufactured housing types in the community that are unable to withstand the large hydraulic forces of a tsunami. As can be seen from **Table PO-3**, the weight of debris generated by the destruction of the buildings in the tsunami zone is estimated to be ~61,000 tons; note this estimate reflects a minimum estimate, because the calculation excludes content in the buildings, vehicles, and other forms of debris. Combined earthquake and tsunami building repair costs are calculated to be ~$175 million, with the bulk of the cost attributed to the destruction caused by the tsunami. However, these costs will almost certainly be higher when communities factor in the added cost to repair buildings and infrastructure located outside of the tsunami zone that are also damaged by the earthquake ground motion.

Table PO-3. Building repair costs and debris weight calculated for the Port Orford urban growth boundary due to a CSZ earthquake and XXL1 tsunami.

Number of Buildings	Building Square Footage (thousand)	Building Value ($ Million)	Natural Hazard	Building Repair Cost ($ Million)	Loss Ratio	Debris from Damaged Buildings (tons)
833	1,547	$183	Earthquake	$47	26%	—
			Tsunami	$173	95%	—
			Combined	$175	96%	61,000

Figure PO-3. Distribution of permanent (top) and temporary (bottom) populations relative to tsunami safety within the Port Orford urban growth boundary XXL1 tsunami zone. Distance to safety is based on a 2 AM scenario, while the temporary population estimate assumes a summer weekend. "Other" category includes mixed-use commercial buildings. See the text for significance of the 4 fps threshold.

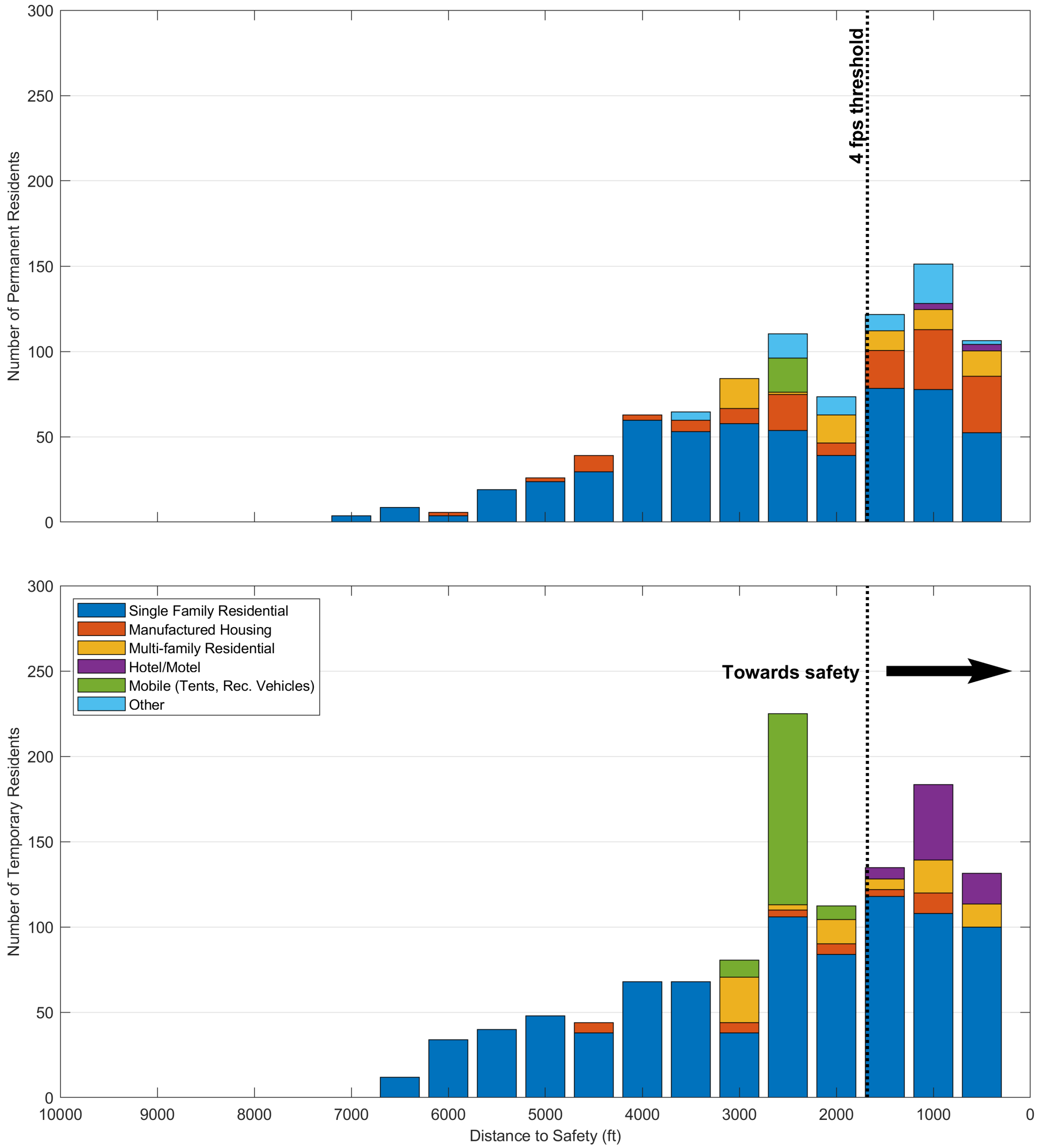
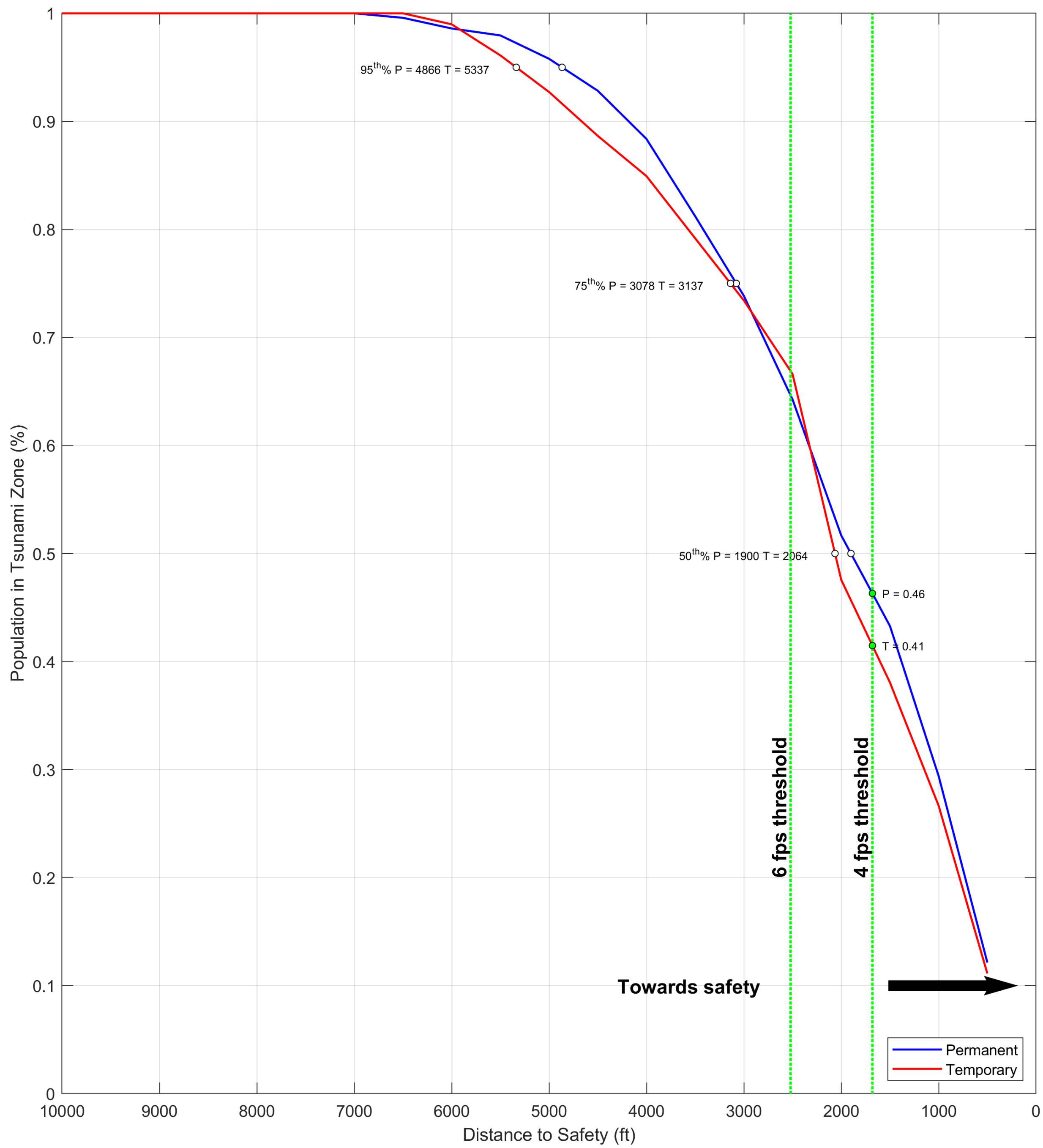


Figure PO-4. Cumulative distribution plot of permanent and temporary populations relative to tsunami safety within the Port Orford urban growth boundary XXL1 tsunami zone. Figure includes two evacuation reference speed thresholds: 4 fps ("walk") and 6 fps ("fast walk"). Reported values for P and T are, respectively, the permanent and temporary population.



8.5.3 Injury and Fatality Estimates from Earthquake and Tsunami

Building occupant injury and fatality estimates due to earthquake ground motion are low (~1.5% and 1.3% for permanent and temporary residents, respectively; **Table PO-4**), given the overall population in the XXL1 tsunami zone. This is because the majority of residents occupy wood-frame buildings. This building type is considered to be the most seismically resilient building construction type (FEMA, 2015a). Depending on the extent of a person's injury or how the person responds to the event and injury (i.e., shock), it is likely that a portion of the injured population may not be able to evacuate from the tsunami zone in a timely manner and may therefore be killed by the ensuing tsunami as they attempt to evacuate out of the tsunami zone.

Table PO-4. Injuries and fatalities resulting from a CSZ earthquake sustained by resident group types in Port Orford urban growth boundary, summer weekend 2 AM scenario.

Hazus Injury Severity Level	Permanent Residents	Temporary Residents	Total
Level 1: Minor Injuries	9	11	20
Level 2: Injuries Requiring Hospitalization	2	2	4
Level 3: Life-Threatening Injuries	1	1	2
Level 4: Deaths	1	1	2
Total	13	15	28

Note: See **Table 2-3** for a complete definition of the Hazus injury levels.

In defining the number of casualties caused by the tsunami at Port Orford (**Table PO-5**), we analyzed four tsunami evacuation scenarios. The four scenarios included:

- An XXL1 scenario that assumes "non-retrofitted bridges fail" due to earthquake ground motion. A levee/culvert on Paradise Point Road was also removed in this scenario. In this scenario, the Hazus tsunami casualty model assumes evacuees have prior knowledge that the specified bridges are likely impassable and seek an alternate optimal route for evacuation;
- An XXL1 scenario that assumes all evacuation routes are intact and usable (i.e., bridges are seismically retrofitted);
- An XXL1 scenario that includes a hypothetical vertical evacuation structure. Again, the Hazus tsunami casualty model assumes that people nearby are aware of, and are willing to use, the vertical evacuation structure; and,
- An L1 scenario that assumes "non-retrofitted bridges fail" due to the earthquake ground motion (Paradise Point Road culvert also removed for this scenario).

As expected, the fatality rates associated with the XXL1 scenario are significant, reaching 58% for the permanent population and 60% for the temporary population (**Table PO-5**), while injuries make up a very small portion (~3%) of this scenario. Thus, for a worst-case XXL1 scenario only about 40% of the combined population would survive the event. Again, it is important to stress that these numbers assume that every person evacuates at 4 fps ("walk") speed. As a result, evacuees traveling at speeds greater than a walk (i.e., fast walk to jog to run) will significantly increase their chance of surviving an XXL1 event, reducing the overall casualty numbers.

Our analyses indicate that seismically reinforcing two bridges in the Port Orford area (Highway 101 and Arizona St, both over Mill Creek) as well as Paradise Point Rd, results in no reduction in the number of fatalities. This is because the distance to safety is equidistant on both sides of the bridges and high ground is much closer in other locations. In contrast, construction of a hypothetical vertical evacuation structure at Buffington Memorial Park will save lives. As can be seen in **Table PO-5**, building a single vertical evacuation structure results in ~100 fewer deaths in an XXL1 scenario (i.e., saves an additional 5% of the combined population).

The injury and casualty estimates in **Table PO-5** for the XXL1 tsunami scenarios are very high primarily due to the early wave arrival time of 17 minutes, the earliest of the five communities in this study (**Table 2-1**). Injuries and fatalities decrease significantly (~75% less) for the "L1" tsunami scenario, largely due to there being fewer people in the tsunami zone. However, the number of fatalities in the L1 scenario remains about 50% of the population in the L1 tsunami zone.

Table PO-5. Injury and fatality estimates for several CSZ tsunami scenarios in the Port Orford area. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, a 10-minute milling time prior to departure, and wave arrival time at the tsunami runup line of 17 minutes. Injury and fatality estimates are rounded to nearest 10.

Tsunami Scenario	Population Segment	Number of People	Fatalities	Injuries	Injury and Fatality Ratio	
					Fatalities	Injuries
XXL1 tsunami, non-retrofitted bridges fail	Permanent	895	520	30	58%	3%
	Temporary	1,181	710	30	60%	3%
	Total	2,076	1,230	60	59%	3%
XXL1 tsunami, bridges seismically reinforced	Permanent	895	520	30	58%	3%
	Temporary	1,181	710	30	60%	3%
	Total	2,076	1,230	60	59%	3%
XXL1 tsunami, non-retrofitted bridges fail, hypothetical vertical evacuation structure at Buffington Memorial Park	Permanent	895	470	30	53%	3%
	Temporary	1,181	660	30	56%	3%
	Total	2,076	1,130	60	54%	3%
L1 tsunami, non-retrofitted bridges fail	Permanent	290	140	10	48%	3%
	Temporary	310	170	10	55%	3%
	Total	600	310	20	52%	3%

Note: Population and tsunami casualty estimates are limited to people residing in the respective tsunami zone within the designated UGB (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

The estimated tsunami injury and fatalities provided in **Table PO-5** assume a mean departure time of 10 minutes, group median evacuation walking speed of 4 fps, with individuals ≥65 years in age evacuating at 3.2 fps. To better illustrate the evacuation situations and planning opportunities, we symbolize the distance to safety for the four scenarios using two different walking speeds (4 and 6 fps, adjusted to 3.2 and 4.8 fps, respectively, for people ≥65), using the survival likelihood distance breakpoints identified by the formula accompanying **Table 2-4** for a tsunami wave arrival of 17 minutes. Using this approach, **Figure PO-5** indicates that the bulk of the injuries and fatalities are primarily in the northern and western parts of Port Orford, especially around the shores of Garrison Lake. If we assume people are able to evacuate at faster speeds of >6 fps (fast walk), we find that the bulk of the fatalities is concentrated in the west-central area of Port Orford, nearest to Garrison lake (**Figure PO-6**). The retrofitted bridges scenario

(**Figure PO-7**) provides an effective shorter escape route only for a very small fraction of the population, located near the intersection of Garrison Lake Road and Paradise Point Road in the northwest corner of Garrison Lake. However, our Hazus analyses indicates that retrofitting the bridge results in no change in the calculated fatalities, **Table PO-5**, when compared with the bridge out scenario. This is entirely due high ground being roughly equidistant on either side of both bridges, meaning it is not necessary for anyone to cross the bridges to reach their closest point of high ground. The lack of change in fatality estimates is because there are no buildings in the immediate vicinity of either bridge. As a result, retrofitting the bridge will not directly save lives for those trying to escape the tsunami; such remediation will, however, be very important for post-disaster recovery. Conversely, construction of a tsunami vertical evacuation structure at Buffington Memorial Park (**Figure PO-8**) will save lives, enabling more people in its immediate vicinity a much better chance at reaching safety in time. This is especially the case if residents and visitors located nearest to Garrison Lake travel at speeds greater than a fast walk (i.e., >6 fps). In the Large (L1) scenario (**Figure PO-9**), injuries and fatalities are primarily concentrated in the central-west portion of Port Orford, and if people travel faster to safety, injuries and fatalities are further reduced (**Figure PO-10**).

Finally, injuries and fatalities from a tsunami can be significantly lowered if individuals evacuate as soon as possible and travel at faster evacuations speeds (e.g., slow jog to run). We obtained injury and fatality percentages from the Hazus tsunami casualty model, varying group departure time and group walking speeds (**Table PO-6**). As expected, injuries and fatalities increase as the departure time increases (i.e., longer milling behavior) (**Figure PO-11**) and decrease as the speed of travel increases.

Table PO-6. Combined injury and fatalities for several tsunami scenarios in the Port Orford area. Model results assume summer weekend 2 AM scenario, average walking speed of 4 fps, various milling times, and wave arrival time at the tsunami runup line of 17 minutes. Injury and fatality estimates are rounded to nearest 10.

			Average Departure Time			
			Injuries and Fatalities		Injury and Fatality Ratio	
Tsunami Evacuation Scenario	Population Segment	Number of People	10 Minutes	15 Minutes	10 Minutes	15 Minutes
XXL1 tsunami, non-retrofitted bridges fail	Permanent	895	540	710	60%	79%
	Temporary	1,181	740	950	63%	80%
	Total	2,076	1,280	1,660	62%	80%
XXL1 tsunami, bridges seismically reinforced	Permanent	895	540	710	60%	79%
	Temporary	1,181	740	950	63%	80%
	Total	2,076	1,280	1,660	62%	80%
XXL1 tsunami, non-retrofitted bridges fail, hypothetical vertical evacuation structure at Buffington Memorial Park	Permanent	895	490	690	55%	77%
	Temporary	1,181	690	930	58%	79%
	Total	2,076	1,180	1,620	57%	78%
L1 tsunami, non-retrofitted bridges fail	Permanent	290	150	220	52%	76%
	Temporary	310	170	240	55%	77%
	Total	600	320	460	53%	77%

Note: Population and tsunami casualty estimates are limited to people residing in the respective tsunami zone within the designated urban growth boundary (DLCD, 2017). Injury and fatality ratio is a percentage of the people who were in the tsunami zone at the time of the earthquake who do not evacuate to safety in time.

Figure PO-5. Port Orford evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

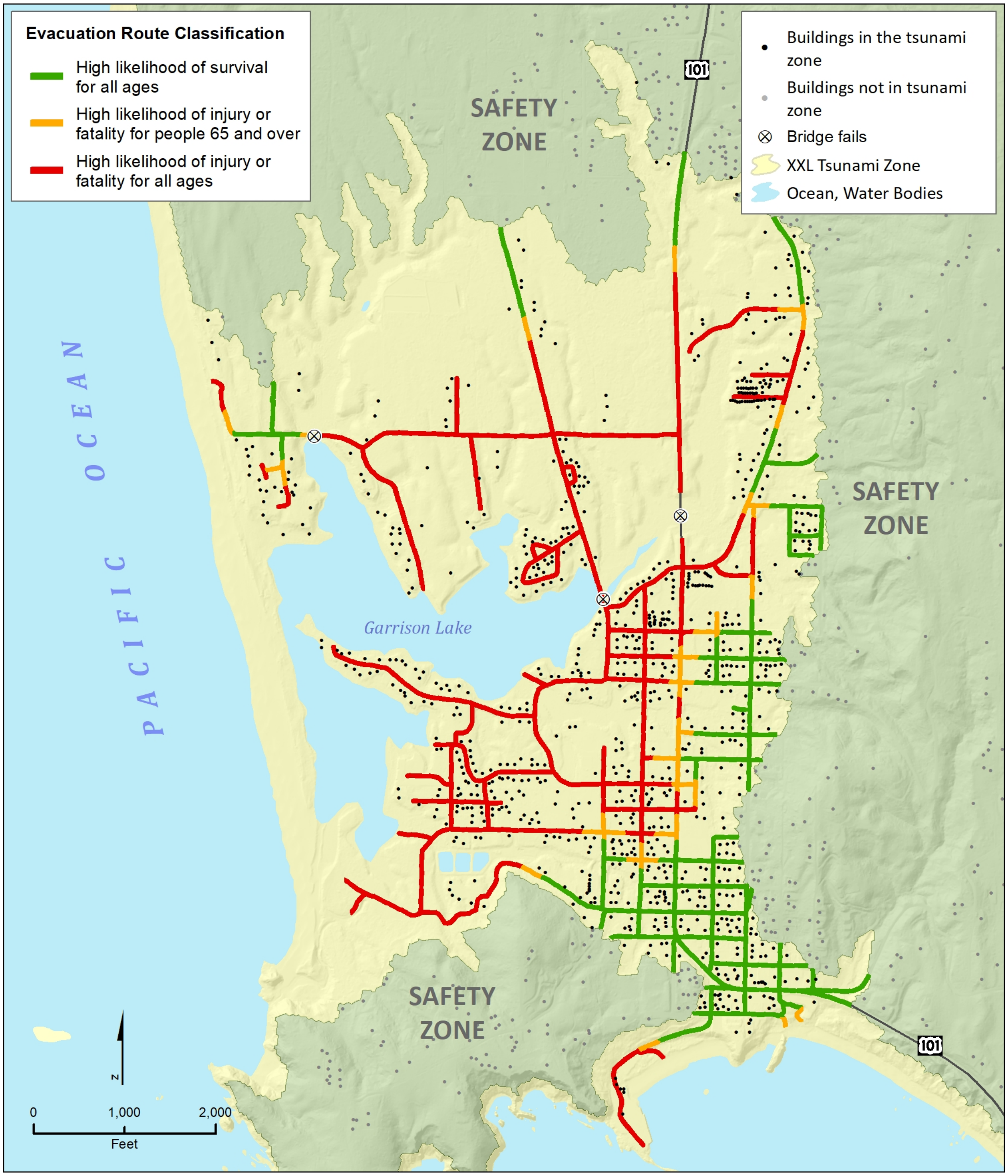


Figure PO-6. Port Orford evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

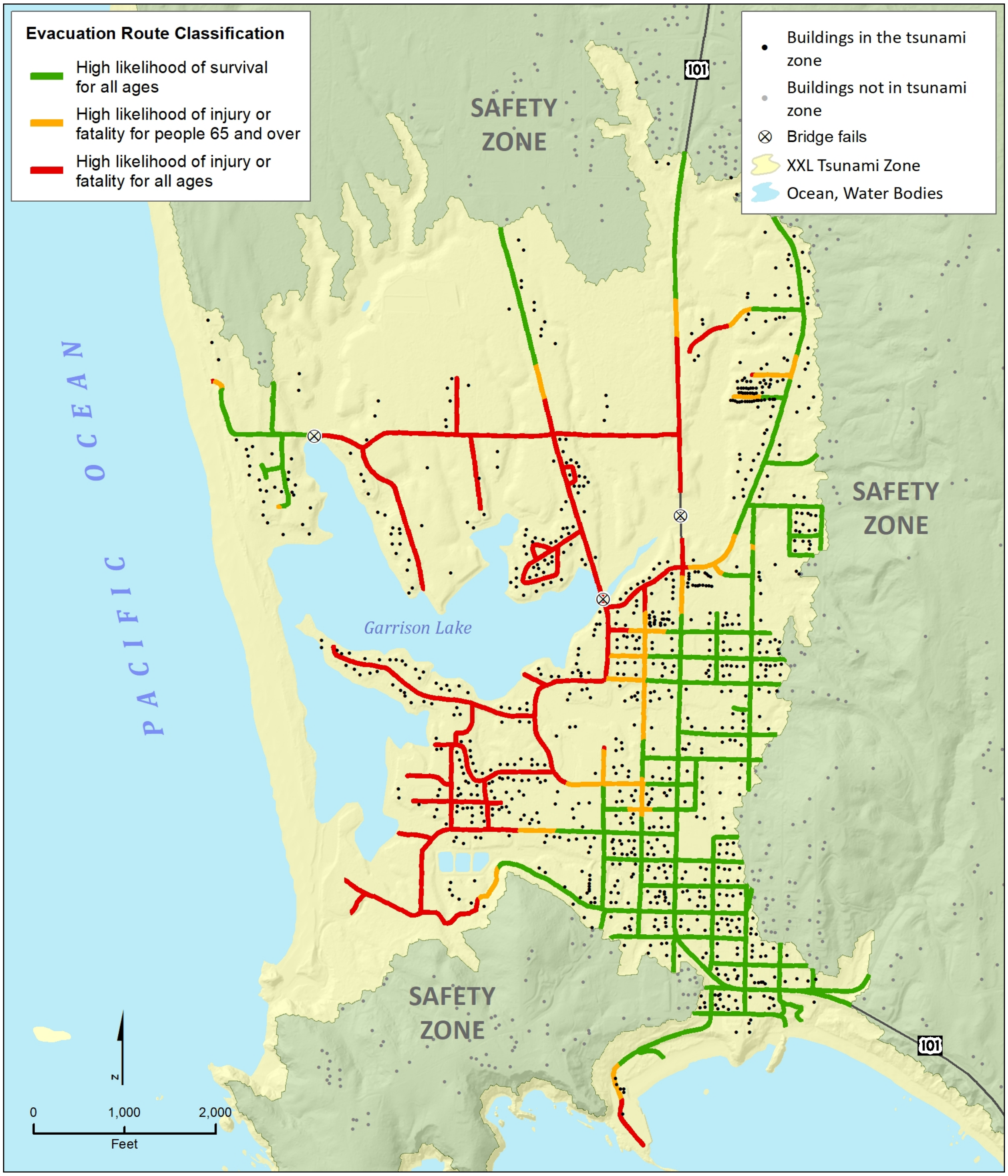


Figure PO-7. Port Orford evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario with seismically reinforced bridges, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

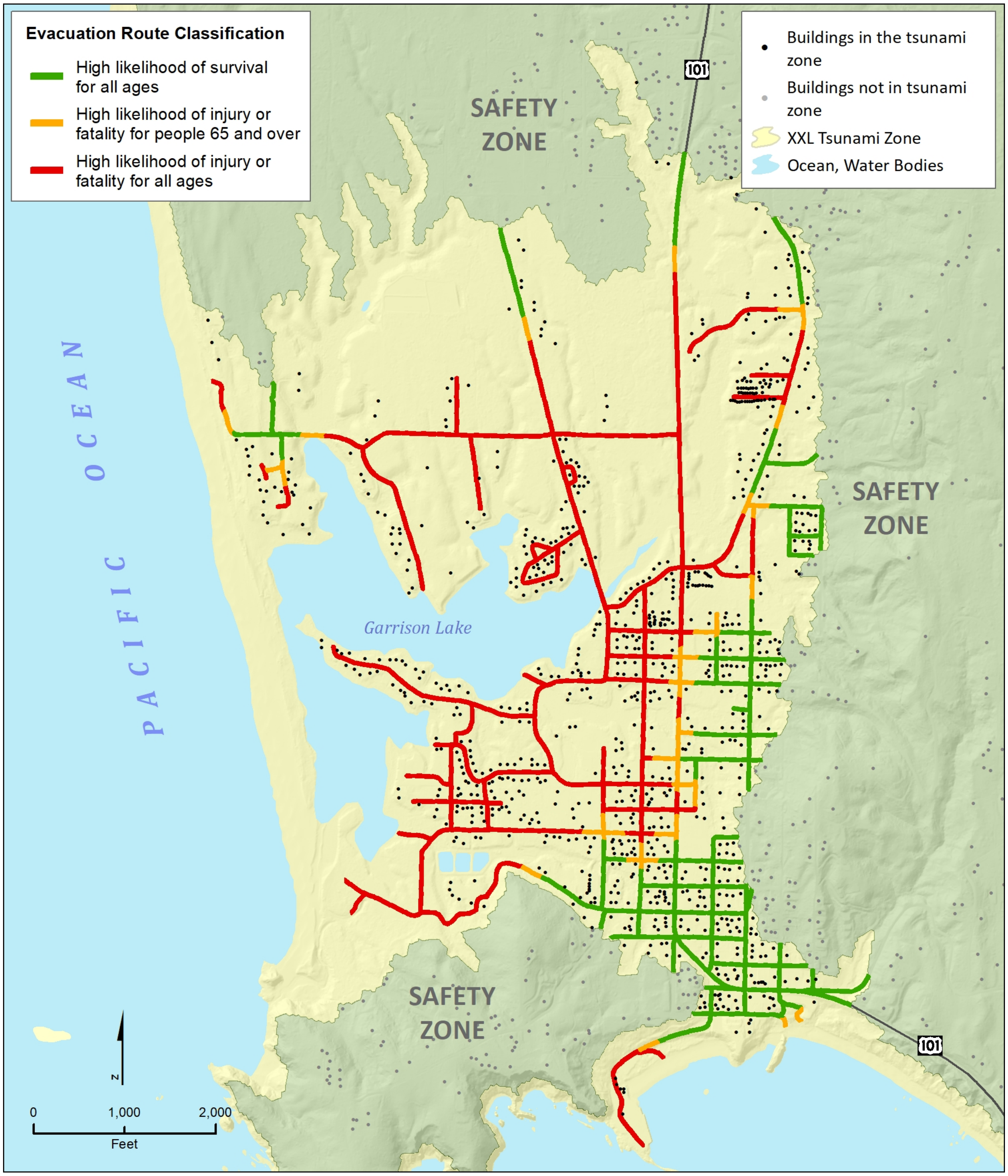


Figure PO-8. Port Orford evacuation routes and distance to tsunami safety for the XXL1 tsunami scenario with a hypothetical tsunami vertical evacuation structure (star in figure) at Buffington Memorial Park, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

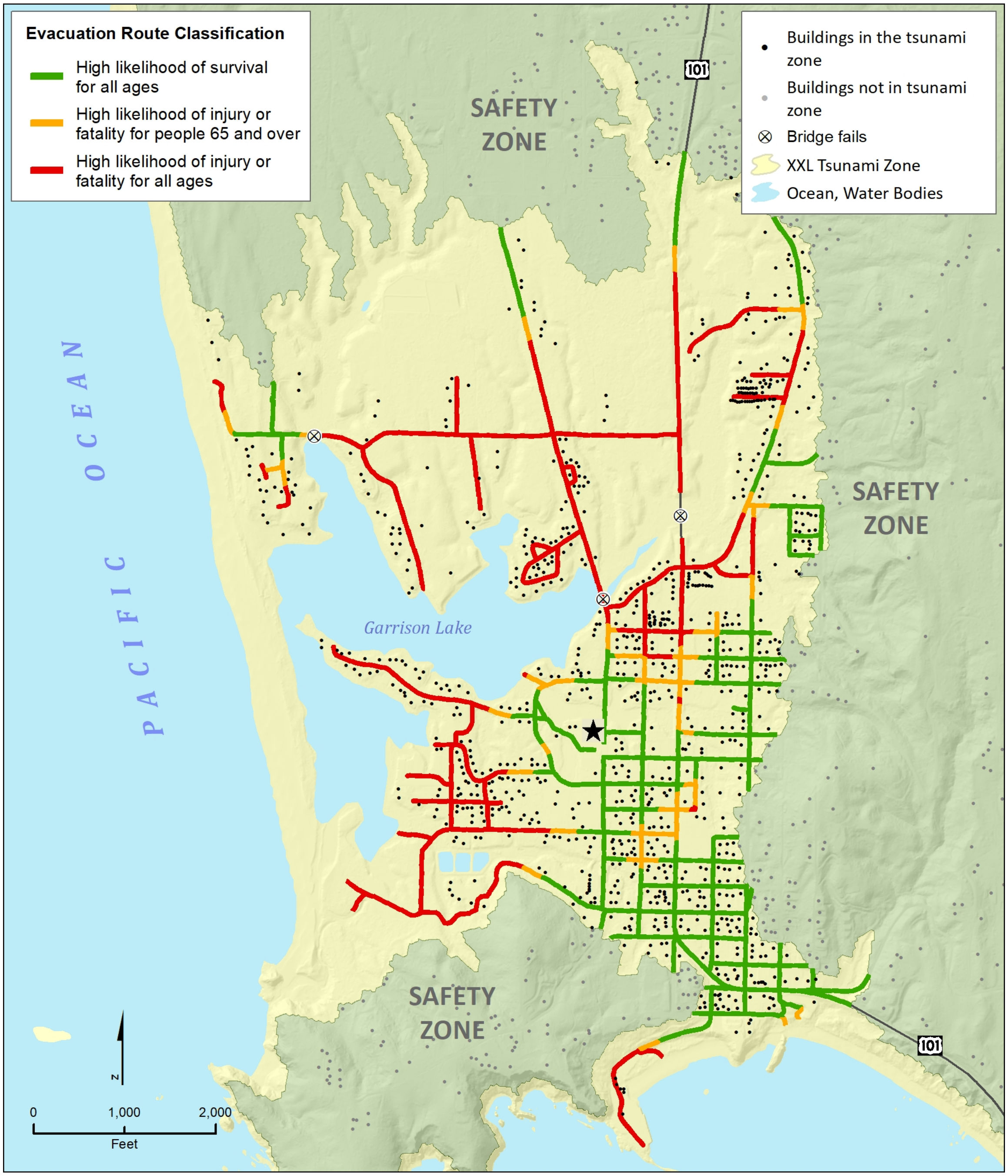


Figure PO-9. Port Orford evacuation routes and distance to tsunami safety for the L1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 4 fps for <65 years of age (3.2 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

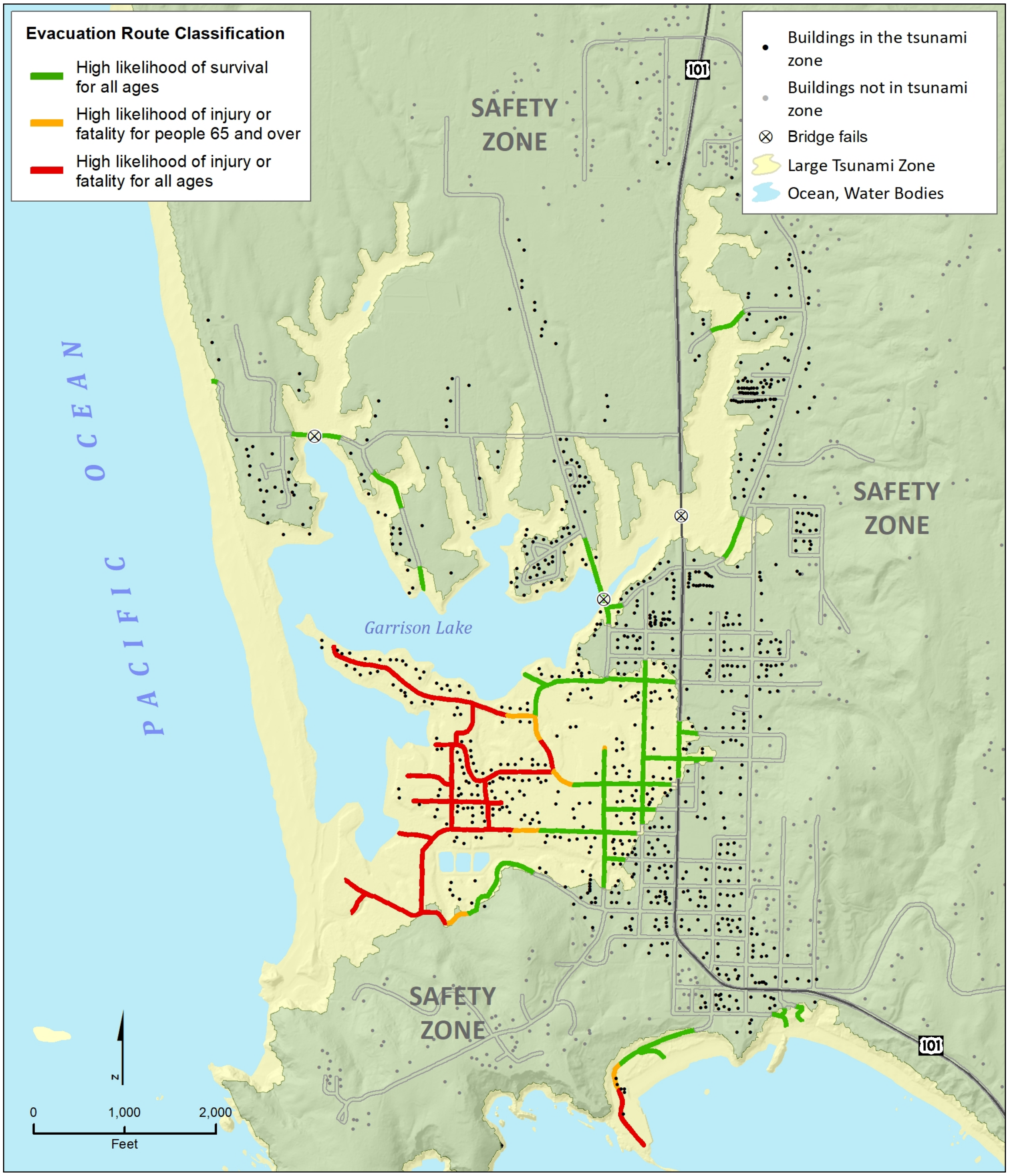


Figure PO-10. Port Orford evacuation routes and distance to tsunami safety for the L1 tsunami scenario, symbolized into survivability classes. Symbology assumes a departure time of 10 minutes after the earthquake begins, a group walking speed of 6 fps for <65 years of age (4.8 fps for people ≥65 years), and a wave arrival time at the tsunami runup line of 17 minutes.

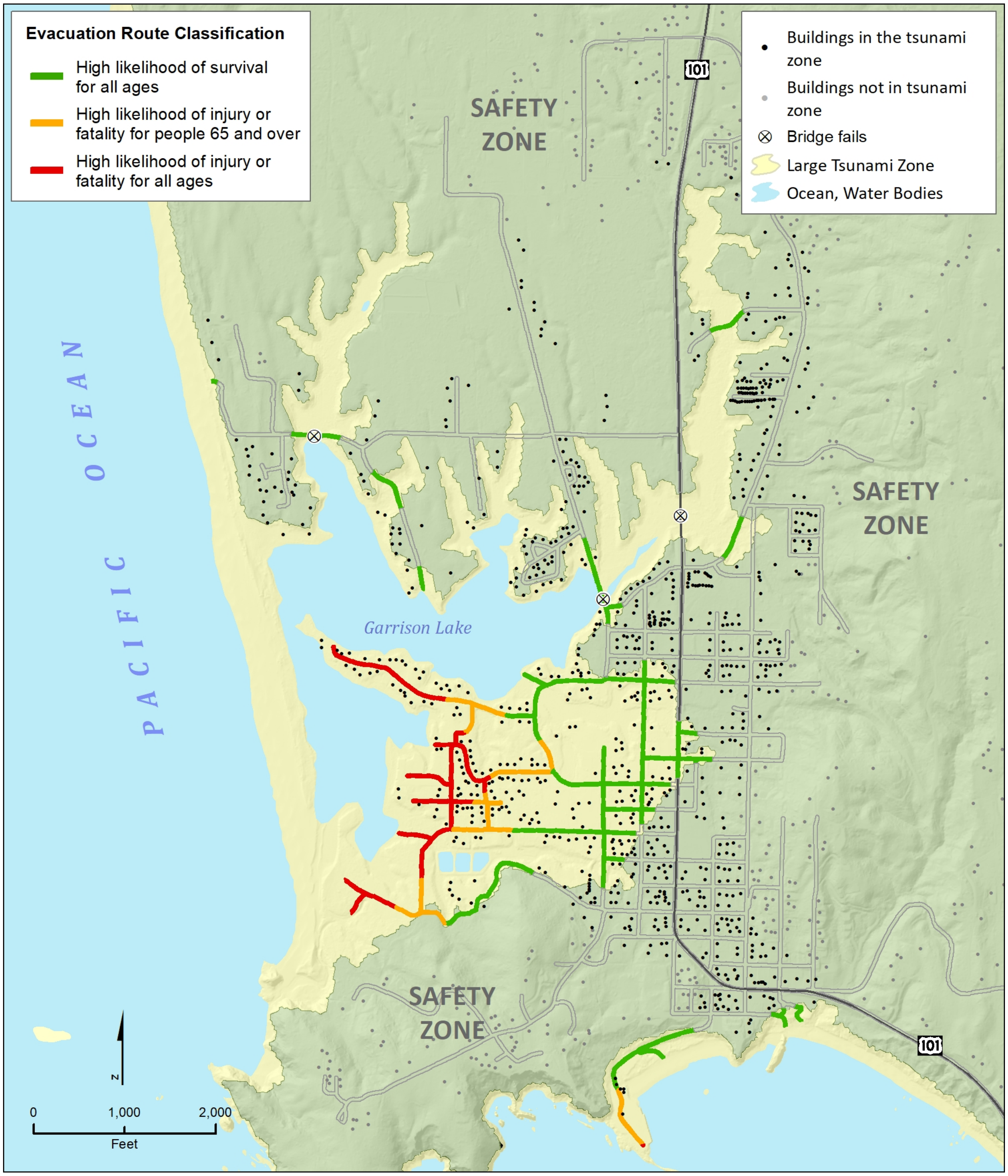
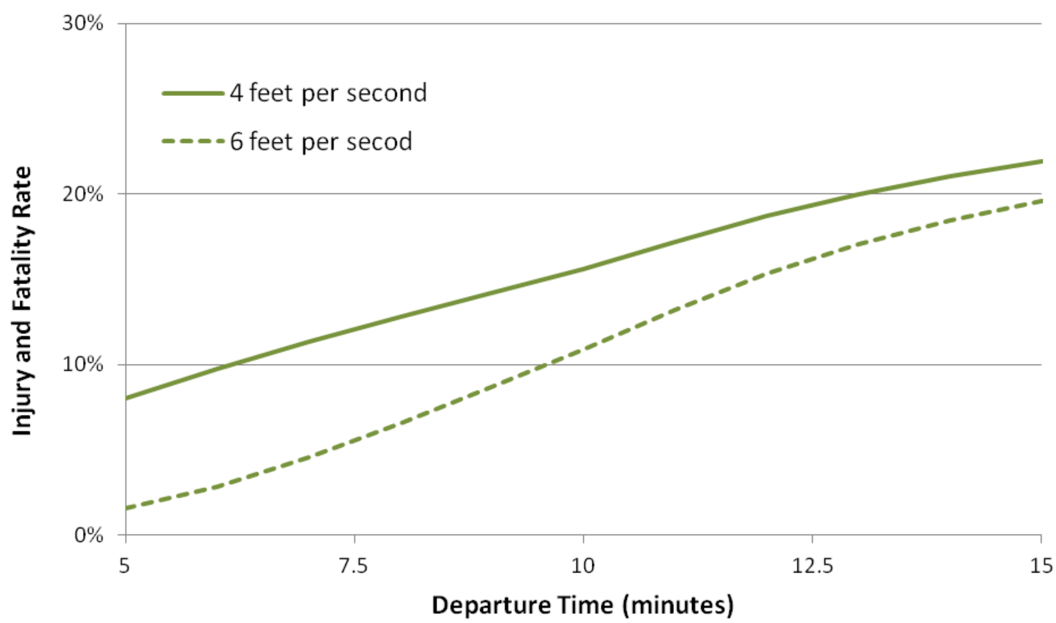


Figure PO-11. Port Orford injury and fatality rates estimated for the L1 tsunami as a function of departure time and two different walking speeds. Departure time is the time in minutes after the beginning of the earthquake. Injury and fatality rate is the number of individuals who did not evacuate in time divided by all individuals in the XXL1 tsunami zone. Injury and fatality rate for permanent and temporary residents is the same, for a given departure time and evacuation speed (Figure PO-4).



8.5.4 Displaced Population

Permanent and temporary residents who successfully evacuate out of the tsunami zone will very likely require short- to medium-term shelter, given that their residences are presumed destroyed or rendered uninhabitable (**Table PO-1**). Temporary residents will likely not be able to return to their permanent homes for at least several weeks, given the anticipated disruption to the regional transportation network and fuel supply (ODOT, 2014; ODOE, 2017) and that their personal vehicles will likely be destroyed or damaged in the tsunami.

For mass care planning purposes, displaced population estimates can be obtained by subtracting the total injuries and fatalities in **Table PO-5** from the total number of people (permanent and temporary) estimated to be in the XXL1 tsunami zone. From those data, we estimate that the displaced population in Port Orford from an XXL1 event could be as low as ~375 people and as high as almost 850 people. The former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every rental facility at maximum capacity. If we assume the tsunami is closer to an L1 event, from **Table PO-5** we estimate that the displaced population could range from as little as ~150 people to as many as 290 people in need of shelter. As with the XXL1 scenario, the former reflects a low-end mid-winter estimate, while the latter reflects a peak summer weekend situation, with every rental facility at maximum capacity.

We note again that our analysis is limited to the buildings and people in the Port Orford XXL1 tsunami zone. Some portion of the permanent and temporary residents outside of the tsunami zone can be assumed to need food and shelter, as their residential structures, including motels and hotels, may have been heavily damaged from the earthquake ground motion.

A lesser magnitude tsunami event, such as a M1 scenario, will likely result in few tsunami injuries and fatalities, the bulk of which are likely to come from a few discrete areas (e.g., adjacent to Garrison Lake or potentially the Port dock facilities). However, even with an M1 earthquake scenario there will be considerable building destruction as the tsunami is expected to severely damage the Port facilities and residential structures nearest to Garrison Lake, thereby impacting the local economy.

8.5.5 Essential Facilities, Special Facilities, and Key Infrastructure

Our analyses indicate the following *essential facilities* in the Port Orford UGB tsunami zone:

- Port Orford Fire Station and Police Station (contained within the same structure)
- Driftwood Elementary School

Our analyses revealed no *special facilities* in the Port Orford UGB tsunami zone. However, we did identify the following *key infrastructure facilities*:

- City of Port Orford Wastewater Plant, 913 12th St
- City of Port Orford Water Treatment Plant
- City of Port Orford Garrison Lake Intake water source (backup)

8.5.6 Employment

Our analyses indicate that ~60% of the jobs in the Port Orford UGB are within the tsunami zone (**Table PO-7**). Of these, the highest employment sector in the tsunami zone is based in retail trade (NAICS codes 44 and 45), which accounts for 38% of the 248 jobs.

Table PO-7. Number of businesses, jobs, and annual wages paid in the Port Orford urban growth boundary XXL1 tsunami zone.

	XXL1 Tsunami Zone	Port Orford Urban Growth Boundary
Number of businesses	53	68
Number of jobs	248	409
Annual wages paid ($ million)	$6.25	$18.80

8.5.7 Social Characteristics

We reiterate that the American Community Survey (ACS) social characteristic data span the entire community (and county) and are not at a resolution that would allow us to better define these statistics by tsunami zone. The interested user is encouraged to review the introduction to Appendix A for additional resources on the ACS in order to better understand vulnerable permanent populations living within the tsunami zone.

As noted previously, our analyses indicate that ~37% of the permanent residents in the tsunami zone are ≥65 years of age (**Table 3-2**), which is significantly higher than the Oregon XXL1 tsunami zone average of 27%. We can delve deeper into the social aspect of a local population by evaluating other characteristics such as the number of people who speak Spanish (or other languages) as well as those who may have disabilities. Both datasets are important because they have a direct bearing on basic outreach (e.g., providing material that has been translated) and in terms of identifying those who may need evacuation assistance. The proportion of Spanish-speaking households in the City of Port Orford is smaller than the overall Curry County average of 2.9% (**Table PO-8**). Insufficient sample size prevents an estimate for households with limited English fluency regardless of language.

Table PO-8. Household spoken language statistics for City of Port Orford. Data taken from American Community Survey 2013–2017 5-year estimates.

	City of Port Orford		Curry County
	Number of Households	Percent of Households with Margin of Error	Percent of Households with Margin of Error
Households speaking Spanish	5	0.9% ± 1.3%	2.9% ± 1.2%
Households with limited English fluency; Spanish spoken	*	*	0.3% ± 0.4%
Households with limited English fluency; all languages	*	*	0.8% ± 0.6%

* Insufficient data

Table PO-9 presents information on the percentages of people with disabilities in the Port Orford area. Overall, these results indicate the proportion of the local population with disabilities (~40%) is significantly higher than the county wide average (~23%); the number of people with disabilities in Port Orford is the highest percentage of the five communities studied. Of particular concern is the relatively large number of individuals with ambulatory, cognitive, or vision disabilities, as well as a large number of people classified as experiencing independent living difficulty, all of whom are likely to need significant help evacuating from the tsunami zone. Not all of these individuals may reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

Table PO-9. Number of individuals with disabilities (by type) for City of Port Orford and Curry County. Data taken from American Community Survey 2013–2017 5-year estimates. An individual with a disability may have more than one difficulty.

	City of Port Orford		Curry County
	Number of Individuals	Percent of Population with Margin of Error	Percent of Population with Margin of Error
Individuals with a disability	438	39.9% ± 9.2%	23.4% ± 2.1%
Difficulty Category			
Hearing	129	11.7% ± 4.7%	8.5% ± 1.2%
Vision	45	9.5% ± 4.2%	5.7% ± 1.3%
Cognitive	149	14.1% ± 5.2%	8.2% ± 1.5%
Ambulatory	293	27.8% ± 7.2%	14.1% ± 1.8%
Self-care	87	8.3% ± 4.2%	5.0% ± 1.1%
Independent Living	70	20.1% ± 6.8%	9.0% ± 1.5%

8.5.8 Discussion and Recommendations

Evacuation Challenges

The greatest challenge facing the community of Port Orford is that the tsunami (irrespective of the size of the scenario) strikes the area quickly (~17 minutes) after earthquake shaking has commenced. Immediate community wide evacuation is key to surviving this event, as there is effectively no time to "mill" prior to evacuating. Our estimates of fatalities and injuries described above assume at minimum a 10-minute delay prior to evacuation, allowing people time to collect their belongings ("go-kits") and evacuate from any buildings. This reduces the actual time to evacuate to ~7 minutes in order to reach the nearest point of high ground. Accordingly, if people are able to reduce their milling time and evacuate faster, the chances of surviving a local Cascadia event improve.

Another major challenge facing the community of Port Orford is the relatively high percentage of people with an ambulatory difficulty. Knowing where these people are located prior to the event and developing appropriate response plans to get them out of harm's way during an event is essential for minimizing fatalities.

Education

Our model results demonstrate that loss of life can be minimized for *all* residents, permanent and temporary (e.g., **Figure PO-11**), if individuals evacuate as soon as possible after the earthquake stops and travel as quickly as possible toward high ground. Educational material can be developed to further emphasize this point. Besides improving basic hazard awareness, such activities could also include education that local evacuation maps can be generated for any location on the Oregon coast via the NVS tsunami evacuation portal (http://nvs.nanoos.org/TsunamiEvac) and smartphone application (http://www.nanoos.org/mobile/tsunami_evac_app.php), enabling users to post appropriate information in their homes or in every motel/hotel room. Importantly, awareness of where high ground is located and actually practicing evacuation drills will help improve an individual's chance of surviving the event. Familiarity and use of the mobile app would also allow for increased awareness of where high ground is located, not just for Port Orford, but for other areas on the Oregon Coast.

An estimated 17% of permanent residents in Port Orford live in manufactured housing (**Table PO-2**). Manufactured homes installed prior to 2003 are subject to slipping off their foundations (Oregon BCD, 2002; SPA Risk, 2014; Maison and Cobeen, 2016; EERI, 2014), potentially compromising the ability to leave a structure quickly. Although many of the manufactured houses are relatively close to high ground (**Figure PO-3**), the compromised egress may hinder timely evacuation. Seismic upgrades of such structures to current building standards may be cost-prohibitive. FEMA (2012, Section D) advises having large crowbars and sledgehammers stored near potentially compromised primary door(s) to facilitate emergency exiting. Such tools may provide a low-cost solution for rapidly exiting structures in the critical time interval after the earthquake ends and before the tsunami arrives.

Mitigation

Of the coastal communities studied here, Port Orford is characterized with the fewest options to mitigate for the tsunami event and reduce the number of fatalities. The two most obvious approaches are, first, to implement an aggressive education campaign to highlight that speed of evacuation is key to surviving the event and, second, to increase people's awareness of where to go. To that end, we emphasize the need for a sufficiently dense network of signs (either posted and/or thermoplastic on road/path surfaces) that direct people along core routes to areas outside the tsunami zone. Signs of this nature need to be spaced appropriately far apart so that they can be easily viewed (and read) at any time of the day or night. Knowing exactly where the optimal routes to safety are and removing much of the guesswork on where to go will help save lives.

Our tsunami Hazus modeling indicated that seismic retrofit of the U.S. 101 and Arizona St bridges spanning Mill Creek and the Paradise Point Road causeway will result in little improvement in reducing fatalities and injuries. This is because the distance to safety is approximately the same on both sides of the bridges and, importantly, high ground is much closer in other locations. However, retrofitting the Highway 101 bridge will almost certainly assist with needed post-disaster recovery.

Our analyses suggest that constructing vertical evacuation structures in key locations in the community could help save lives. In the example presented here, we evaluated a vertical evacuation structure established at Buffington Memorial Park (**Figure PO-8**), which resulted in ~100 fewer casualties in the XXL1 scenario (**Table PO-5**); such a structure built in the same location was found to provide minimal benefits when evaluating an L1 tsunami scenario. Construction of additional vertical evacuation structure (e.g., west of Buffington Memorial Park) near Garrison Lake would almost certainly address most of the potential deaths that would be attributed to the tsunami. Because of the very limited responses times prior to the tsunami inundating the community, we recommend the City of Port Orford evaluate further the possibility of establishing vertical evacuation structures throughout the community. However, this approach must be accompanied by an aggressive education campaign.

Finally, we recommend and encourage that local communities practice periodic (annual) tsunami evacuation drills. In order to instill a culture of awareness of the tsunami hazard facing the Oregon coast, residents (and visitors) must periodically practice their evacuation routes. Studying an evacuation map is not the same as actually walking an evacuation route. Although we recognize that such an approach may be disruptive to the local economy, holding periodic drills will save lives. Such a culture is entrenched in Japanese way of life: drills helped save many thousands of lives during the catastrophic tsunami event on the Sendai coast on March 11, 2011. This culture is highlighted in several recent studies (e.g., Nakaya and others, 2018; Sun and Yamori, 2018).

Response

Relative to other communities, Port Orford can be expected to have a modest short- to medium-term sheltering need following the earthquake and tsunami. Our analyses indicate that for an XXL1 event, the displaced population could range from a low of ~375 people in the winter to ~850 people in summer (**Table PO-5**); for an L1 earthquake event and tsunami, these numbers are reduced to a low of ~150 people in the winter, increasing to ~290 people in the peak of summer.

Besides addressing shelter needs, coastal communities such as Port Orford will need to attend to both fatalities and injuries caused by the tsunami (**Table PO-5**) and earthquake (**Table PO-4**). As noted previously, injuries in the Port Orford area are relatively low at ~40, while numbers of fatalities could reach as many as 1,200 for an XXL1 tsunami; the latter number drops significantly to ~300 fatalities for the L1 scenario. Local hospitals and emergency services will need to be prepared to respond to such challenges.

Wang (2018) examined a number of considerations for coastal hospitals to take in order to prepare for Cascadia, including improving building seismic resiliency, establishing a resilience network where knowledge and training could be shared, and evaluating and planning for needed fuel and water needs. According to the Oregon Resilience Plan documents (OSSPAC, 2013), there are about 483 licensed beds at the 11 coastal hospitals. Combined earthquake and tsunami related injuries in Port Orford are estimated to be ~40 people; total injuries for the five communities could approach 900, exceeding existing coast-wide hospital capacity. Hence, coastal hospitals will need to prepare for a surge in injuries (as well as large numbers of fatalities) that could well exceed existing capacity.

Finally, although the bridge seismic retrofits analyzed in this report provide minimal improvements to life safety (**Table PO-5**), the role of the Highway 101 bridge in aiding key post-disaster response and recovery services after an earthquake and tsunami will be significant.

Recovery

An XXL1 tsunami will have a significant impact on local employment and ultimately on the Port Orford local economy. Our analyses indicate that ~900 permanent residents in the community reside in buildings within the tsunami zone (**Table PO-1**). Given the predominance of wood frame construction in the tsunami zone, nearly all the buildings will likely be destroyed in an XXL1 tsunami. Our analyses indicate that only six of the residential buildings in the Port Orford UGB are in a FEMA-designated flood hazard zone. Homeowners outside of a FEMA-designated flood hazard zone are not currently required by federally backed mortgage lenders to carry flood insurance. Homeowners and businesses in the tsunami zone are encouraged to pursue flood insurance coverage for a tsunami event through the National Flood Insurance Program. More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/national-flood-insurance-program/How-Buy-Flood-Insurance.

9.0 APPENDIX B: POPULATION MODELS

9.1 Permanent Residents at 2 AM

Geocoded Oregon Department of Motor Vehicles (DMV) driver license data were obtained from Oregon Health Authority (E. Main, written communication, June 2018), representing records on file at the end of 2017. The dataset included all driver license classes, including identification cards. Year of birth ranged from 1932 to 1999; records with individuals over 85 years and less than 18 years of age were excluded. We used the birth year 1952 to identify individuals 65 years of age and over.

The geocoded records were spatially associated with a nearby residential structure, using the FEMA Hazus occupancy class designation (e.g., "RES1", "RES2"). Where a residential structure was not available, the record was manually associated with another building occupancy type, typically a retail commercial ("COM1"). The situation occurs when the primary usage of the building is retail, and thus designated a commercial use building, but contains residential quarters. Occasionally DMV records were associated with a recreational vehicle park. The situation is not uncommon in Oregon coastal communities, given the recent limited housing situation (czb, 2017). In this case, the DMV records were assigned to individual spots in the park; the remaining spots were populated with temporary residents.

Not all adult residents of the state obtain a driver's license or state-issued identification card. We used several data sources to quantify the potential undercounting, which we estimate at ~8.8%:

Oregon 2018 population estimate (PSU PRC, 2018):	4.195 million
Oregon DMV database number of individuals (OHA, 2018):	2.970 million
Percent of total Oregon population ages 0–17 (PSU PRC, 2018):	20.7%
Percent of total Oregon population ages 85 and greater (ACS, 2018):	2.1%

Percent of population in Oregon ages 18–84 accounted for in DMV records:

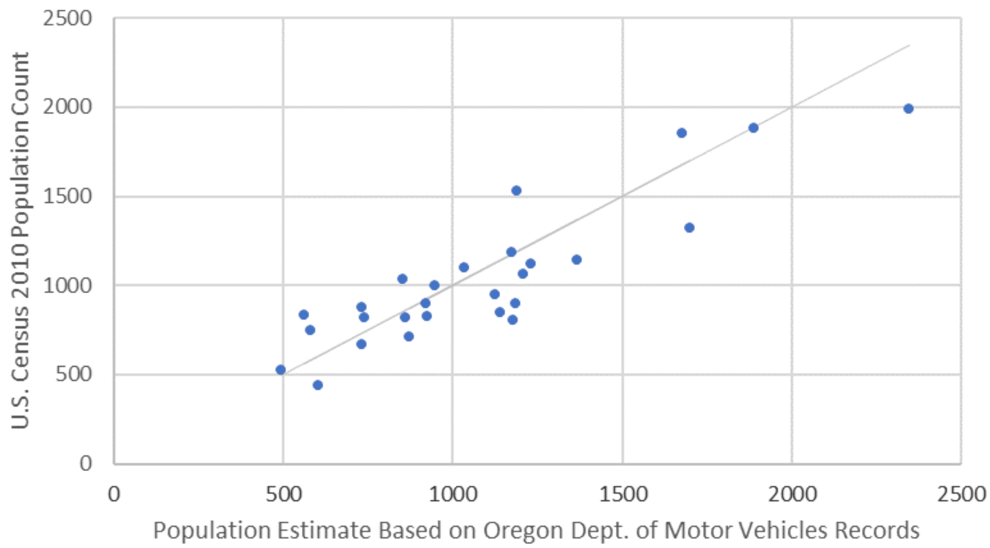
2.970 million / (4.195 million * [100% − 20.7%] * [100% − 2.1%]) = 91.2%

Assuming the statewide 8.8% undercounting applies to permanent residents in the community tsunami zones, the impact of the undercounting is that our automated spatial association procedures may have occasionally designated a single-family residential structure as temporarily occupied, when in fact someone lives there on a permanent basis. We made no adjustment to the permanent population estimate for this undercounting.

We adjusted individual permanent population assignments to account for the exclusion of minors in the Oregon DMV database. We assumed people aged 0–17 live with an adult aged 18–64 and that people ≥65 years do not have a minor in their home. We multiplied each individual in the 18–64 age group by 1.318 to obtain an overall 64 and under population estimate. The percentage was calculated by dividing the 0–17 age group population count by the 18–64 age group population count using the age group estimates by PSU PRC (2018) for the seven Oregon coastal counties. For example, two permanent residents between 18 and 65 years of age at a home have 0.636 minors living with them.

The process of geocoding individual driver license addresses is imperfect; note that Oregon DMV rules do not permit the usage of post office box or equivalent as a residential address. To establish further confidence in our usage of Oregon DMV records we compared the permanent residential population (adjusting for minors) with the 2010 decennial census estimates on a per census-block-group basis, limited to the 27 census block groups that intersect the communities in this study. **Figure 9-1** shows a reasonable correlation between the U.S. Census 2010 population count and the DMV-based estimate.

Figure 9-1. Census block group permanent population estimates using geocoded Oregon DMV records (adjusted for minors) compared to U.S. Census 2010 population count, for the 27 census block groups covering the five communities in this study. For reference, a 1:1 line is shown in grey. Linear regression analysis with a forced zero-intercept yields r^2 = 0.77.



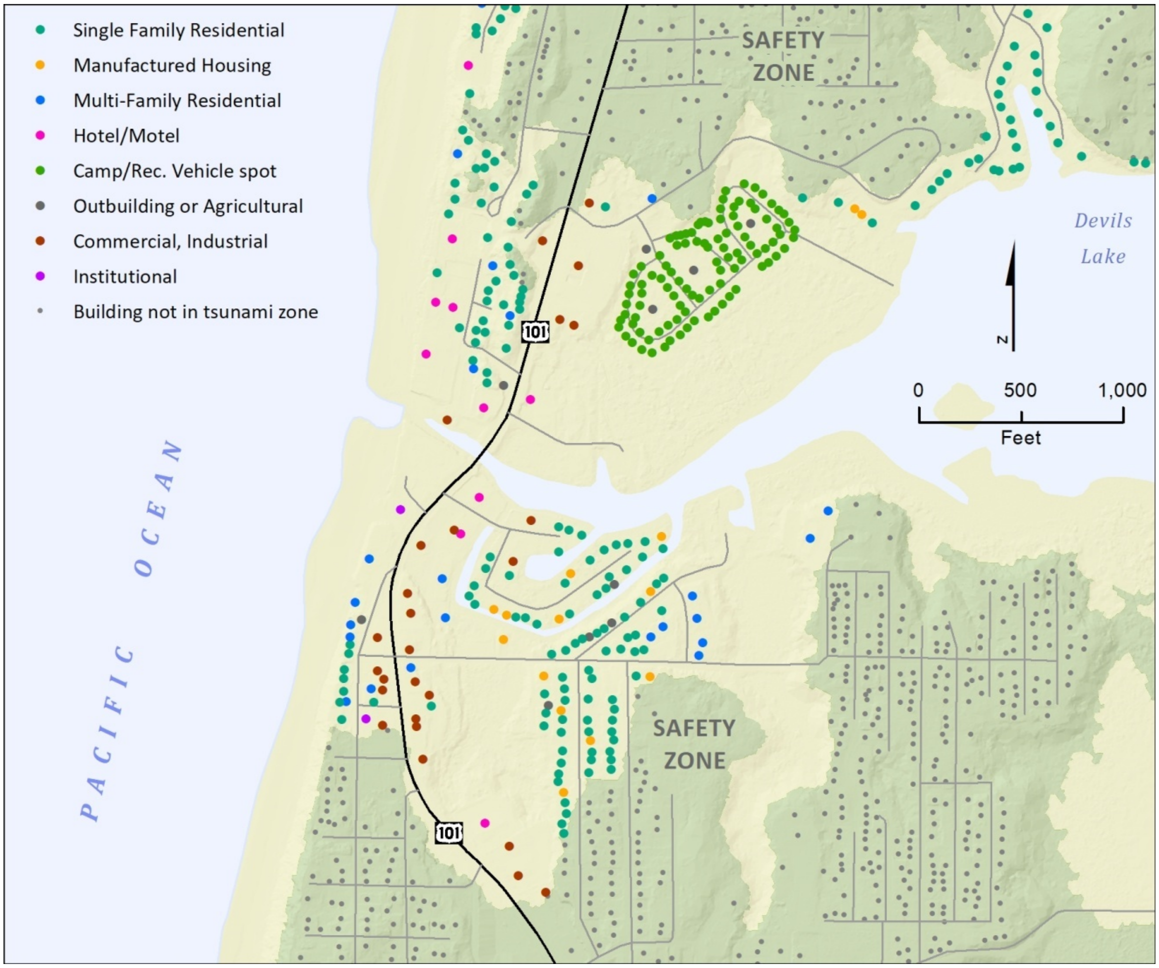
9.2 Temporary Residents at 2 AM, Summer Weekend

The User-Defined Facilities (UDF) datasets obtained from Williams and others (M. Williams, written communication, 2019) identified all buildings that can be considered a residential facility, including traditional single-family residences, manufactured housing, multi-family residential buildings including condominiums, motels and hotels, dormitories, assisted living facilities, and bed and breakfast establishments. The datasets contain information on building primary usage (Hazus “occupancy class”), square footage, number of stories, year built, and building type (e.g., wood frame, steel frame).

We augmented the UDF dataset as follows. We added a “*number of units”* field, identifying the number of rooms, where available, for the motels, multi-family residential, and dormitories building types (Hazus occupancy type, “RES4,” “RES3,” “RES5,” respectively). A “*number of bedrooms”* field was added and populated with information, where available, from county assessor records for single-family residential structures.

We further augmented the UDF dataset by adding records to capture the locations of individual tent and yurt sites, recreational vehicle spots, and boat slips in marinas that permit overnight docking. Such locations were digitized as points using orthoimagery and other ancillary data sources, such as Oregon State Park campground maps. We note that the Hazus earthquake and tsunami building damage model is limited to traditional buildings, and thus our building loss estimates exclude damages to temporarily occupied structures such as tents, recreational vehicles, and boats. An example of the mixture of overnight lodging locations and facility types is shown in **Figure 9-2**.

Figure 9-2. Example of building occupancy type variation including temporary non-building residential locations for Lincoln City, Oregon. Classified buildings and sites are limited to locations in the XXL1 tsunami zone and are represented as points. Devil's Lake State Recreation Area campground shown in center right. Tsunami zone shown in yellow.



Single-family residential homes including manufactured housing that have at least one associated permanent resident (Section **9.1**) were assumed to be occupied on a permanent basis, and thus no temporary residents were assigned to such buildings. The absence of any permanent resident designates a single-family residential house as a temporarily occupied building.

Single-family residential homes including manufactured housing that are temporarily occupied may be second homes or vacation rentals. We obtained spatially explicit vacation rental information for two communities (Lincoln City and Newport); however, we did not have sufficient justification for specifying a different temporary occupancy level for a vacation rental versus a second home. Per strong community encouragement, we used city ordinances, where available, that specify *maximum* vacation rental occupancy to assign total number of temporary residents for a given house. For Lincoln City we used three people per bedroom plus one per house (Weston Fritz, written communication, November 2018; Lincoln City Ordinance No. 2016-26). Newport city ordinances limit occupancy to two per bedroom and two per house (Newport Municipal Code 14.25.050). Rockaway Beach currently has no specific ordinances limiting vacation rental occupancy (Terri Michel, written communication, February 2019); we populated homes in Rockaway Beach with two per bedroom plus one person per house. For Gearhart, we populated homes at two per bedroom (City of Gearhart Zoning Ordinance #684s, Section 7.030). For Port Orford we populated homes with two per bedroom plus one person per house.

Number of bedrooms for single-family residential homes was available from Clatsop and Lincoln County tax assessor records. For the communities of Rockaway Beach and Port Orford we used a square footage to number of bedrooms estimate. **Table 9-1** was developed by examining the number of bedrooms versus square footage of the single-family residential homes in Gearhart.

Table 9-1. Square footage to number of bedrooms conversion for single-family residential buildings. Used where number of bedrooms not available from tax assessor records.

Building Square Footage	Number of Bedrooms
< 1,500	2
1,500–2,700	3
2,700–4,000	4
4,001–5,500	5
> 5,500	6

For multi-family residential properties, motels and hotels, dormitories, and assisted living facilities, we first established a number of units value per building. Total number of units per multi-family residential property was obtained from tax assessor records. For multi-family residential buildings we determined number of temporarily occupied units by first determining the number of units taken by permanent residents (assuming 1.7 permanent residents per unit) and subtracting that from the building's total unit quantity. Temporary population was then based on the quantity of remaining units times 1.7 (**Table 9-2**).

Detailed information on number of rentable units (or rooms) per motel/hotel was available for only one community — Lincoln City (S. Gruber, written communication, February 2019). For motels/hotels in other communities we estimated number of rooms by either counting doors from street level imagery or by dividing the building total square footage by 455 square feet per room — a conversion factor that was based on a regression analysis of the available Lincoln City motel data.

For dormitories and assisted living facilities we obtained local data where available or from the information contained on the institutions' web sites. Tent sites, yurts or equivalent, and recreational vehicle spots were explicitly digitized as individual units using orthoimagery and other ancillary data sources, such as Oregon State Park campground maps. Boat slips in Newport were digitized as a single point per dock with a multiplier factor associated with it. We distinguished between the three types of temporary lodging in our database, designating them as *TENT*, *RV*, or *BOAT*. We note that motels and recreational vehicle parks sometimes have permanent residents associated with them; these quantities were subtracted from the temporary population estimate for the facility.

Once number of units or rooms was established per building or entity we used the people per unit values and age ratio in **Table 9-2** to populate each record with temporary residents. The age ratio is our estimate of the percentage of people in that unit that are under 65 years of age.

Table 9-2. People per unit and age ratio default assumptions for temporary lodging.

Occupancy Type	People Per Unit	Age Ratio[#]
Single-family Residential	(Bedroom Count)[+]	0.80
Multi-family Residential	1.7	0.80
Hotel/Motel	1.7	0.80
Assisted Living	1.0	0.90
Dormitories	(manual)[^]	(manual)[^]
Recreational Vehicle	2.0	0.30
Tent, Yurt	2.3	0.90
Boat	1.7	0.70

[#] Age ratio is the number of people under 65 years of age divided by the total population for the unit.

[+] Obtained from tax assessor records, or where not available, from square footage (**Table 9-1**).

[^] Manually assigned quantities and age groups.

We maintained two additional fields, ones in which we stored locally obtained information on temporary occupancy (<65 years, ≥65 years). For such records, the assumptions in **Table 9-2** were disregarded and the manual assignments were used. Examples include Oregon Coastal Aquarium and Camp Gray in Newport.

We developed an in-house tool that updated temporary population assumptions based on values in **Table 9-2**. We did not perform any extensive sensitivity analysis. We reviewed the temporary population assumptions with community members, who after the initial strong urging of not underestimating the vacation/second home population, agreed with our assumptions as reasonable for proceeding with tsunami evacuation modeling. We recognize the values listed in **Table 9-2** could benefit from further demographic research.

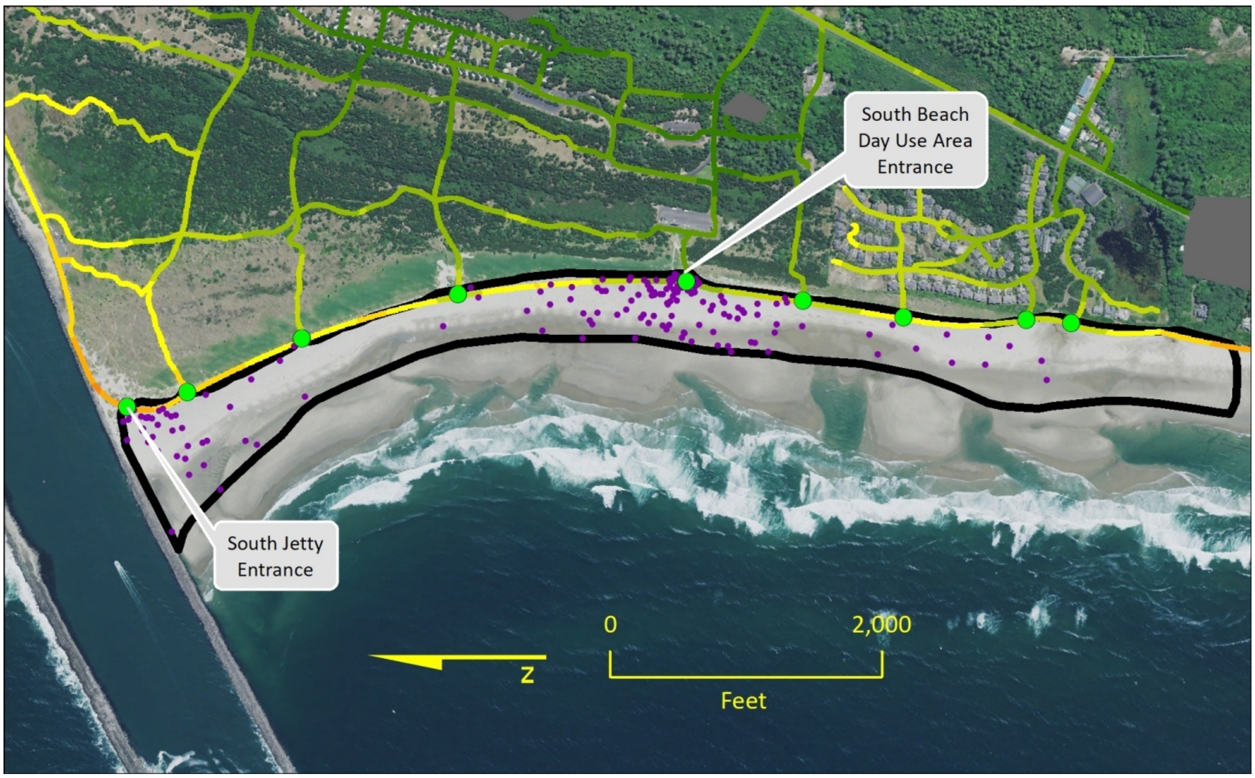
9.3 Daytime Model: South Beach State Park

Estimates of the number of vehicles parked at the South Jetty (40) and Jetty and South Beach State Park Day Use Area (128), were determined from a combination of field visits and from inspection of orthoimagery. These data were assumed to be representative of peak summer weekend usage. Once on the beach, all members of an individual party associated with the vehicle are assumed to be in spatial proximity while on the beach; we did not model individual dispersion. We used the occupant and age group estimates per vehicle summarized by Bergerson and Rushing (2017) to establish demographics per party: 3.3 people per vehicle, with 1.23 people per party being 65 and over years of age. We did not include any beach visitors walking from the South Beach State Park campground.

We are aware of the population distribution model of Mostafizi and others (2017), in which people were normally distributed around the centroid of a polygon, including beach segments. We determined that such a model was not applicable for South Beach State Park, where access to the beach is constrained to a limited number of points. We were not aware of any other population distribution model in the literature that would be applicable for remote beaches with limited, automobile-oriented access. From personal observation and interpretation of limited orthoimagery we chose an exponential decay model that dispersed the 168 parties (554 individuals) as random points on the beach from the two main entry points, following an exponential decay function. Once placed, each point was assigned a distance to safety based on its linear distance to the nearest exit point using the Esri® Spatial Analyst Near function, with a "loose sand" speed adjustment factor of 0.56 (Priest and others, 2015, Table 2-1). While the model assumed two entry/dispersal points, evacuees were assumed to evacuate the beach via the closest exit point, which may not be the most optimal exit point for tsunami safety and may not be their original entry point. We modeled a total of 10 individual distributions, noting the observations of Mostafizi and others (2017) where more than 10 repetitions did not significantly change group mortality rate estimation. With each repetition we captured the distance to safety for all parties, then calculated an overall group injury and fatality rate for each repetition.

We repeated the exercise using a random distribution model, with 168 points randomly placed within the bounding polygon in **Figure 9-3**. Distance-to-safety metrics were computed, and injury and fatality estimates were summarized and compared to the exponential decay model.

Figure 9-3. Example distribution of 168 parties at South Beach State Park, summer weekend. Bounding polygon shown in black outline; parties shown as purple dots; beach entry points shown with leader lines; beach exit points shown as green circles. Evacuation network shown in shades of green, yellow, and orange representing increasing distances to safety. Imagery: National Agricultural Program, 2016.



10.0 APPENDIX C: HAZUS TSUNAMI CASUALTY MODEL: SPREADSHEET DEVELOPMENT

10.1 Background

We were motivated to develop a standalone Excel spreadsheet that implements the Hazus tsunami casualty model (FEMA 2013, FEMA 2017a) for several reasons:

1. Our "Beat the Wave" methods (Priest and others, 2015) already produce path distance to safety data in a manner identical to the USGS Pedestrian Evacuation Analyst Tool (PEAT) (Jones and others, 2014), and thus re-creating the path distance for use in Hazus would be redundant;
2. We had a project need for considerable flexibility in terms of rapid evaluation of alternative population and evacuation scenarios, including distinguishing temporary and permanent residents, along with rapid evaluation of population assumptions and model parameter settings; and,
3. Of particular importance, the Hazus tsunami model currently estimates casualties at the census block level, not at the building level, and uses a worst-case assumption of time-to-safety for all occupants within a census block (D. Bausch, personal communication, July 2018).

In this section, our use of the casualty term refers to injuries and fatalities.

10.2 Spreadsheet Development

The DOGAMI spreadsheet implements the casualty estimates as described by FEMA (2017a, Equations 6.1–6.7) with several exceptions and enhancements:

- Our focus was on quantifying casualties from a near-source tsunami that provides no warning time. The T_W (warning time) is provided as a placeholder in the DOGAMI spreadsheet but is not currently implemented.
- For a near-source tsunami, such as one generated from a CSZ earthquake, the time from the earthquake commencement to maximum wave runup is assumed to be the first wave (Witter and others, 2011); thus we did not implement the T_0 term used by FEMA (2017a, Table 6.3). The user supplies a wave arrival time, and the DOGAMI spreadsheet assumes this is the maximum wave arrival time at the runup line.
- Users of the DOGAMI spreadsheet found the meaning of the FEMA Hazus tsunami model Community Preparedness Level (C_{PREP}) parameter ambiguous. The term may be more meaningful within a distant-source tsunami context. To overcome the usage hurdle, the spreadsheet instead has the user supply a median departure time for the group, in minutes. C_{PREP} is then simply calculated as Departure Time divided by the user-supplied Maximum Wave Arrival time (T_{ARRIVE}) and is provided in the spreadsheet for reference. Note that C_{PREP} is used in the DOGAMI spreadsheet formulae.
- The DOGAMI spreadsheet has the user supply a *distance to safety*, rather than a *time to safety*, value for each record. We chose this because the distance to tsunami safety from a particular point is fixed for a given tsunami scenario, and it is much more straightforward to compute casualty estimates for varying departure times and evacuation walking speeds when using distance instead of time.
- A record, which commonly is a house, may contain one or more individuals, which can be further distinguished by their permanent or temporary residence status and by their age group. Individuals in a record may be fractional — for example, 3.68 permanent residents, which can be

divided between 1 person who is age 65 and above, and 2.68 people who are less than 65 years of age.

- The beta term for the departure distribution, referred to as C_{STD}, is directly supplied by the user and is equivalent to the FEMA Hazus tsunami casualty tool term.
- The age-65-and-over speed adjustment factor in the spreadsheet is equivalent to the FEMA Hazus tsunami casualty tool. Although this can be changed by the user in the spreadsheet, we used the Hazus default 0.8 speed reduction factor setting for this study.
- In the partial safe zone, the fatality and injury rates are adjustable by the user. We had no motivation to change the suggested 50%/50% Hazus default setting; nonetheless, it can be changed should the user have motivation to do so.
- The DOGAMI spreadsheet makes a simplifying assumption regarding the "partial safe zone," in that the user specifies an average distance between the partial safe boundary and the safe boundary (FEMA, 2017a, Figure 6.5). In practice, the distance between the suggested 2-m (6 ft) depth contour to maximum inundation contour may vary widely across a study area, especially in terrain with broad flat surfaces. However, Oregon coastal cities typically have sharp topographic features wherein the partial safe zone is relatively small (example shown in **Figure 2-3**). For this study we symbolized the tsunami depth raster data relative to the evacuation network and determined that a fixed value was a reasonable approximation for each community. Note that the overall injury and fatality total will remain the same regardless of the parameter value; what will change with a change in the "partial safe zone" parameter is the number of injuries relative to fatalities.

10.3 Validation

To enhance confidence in our spreadsheet's casualty estimates, we compared the results from a Hazus tsunami run and the DOGAMI UDF-based spreadsheet. For comparison, we used our data assembled for Rockaway Beach, one of the communities analyzed in this report. In this section, we make frequent references to the Hazus Structured Query Language (SQL) database that accompanies a Hazus installation.

To ensure the same population numbers were being used by the two tools, we summarized our UDF demographic data at the census block level, and via a backdoor SQL table loading, forced the [dbo].[tsNSIGBS].[Pop2amU65] and [dbo].[tsNSIGBS].[Pop2amO65] values to be equivalent to our UDF <65 / ≥65 population numbers for a given census block. Keeping matters straightforward, we set the Pop2pm values in [dbo].[tsNSIGBS] to zero.

A CSZ-generated tsunami provides no warning time; the earthquake shaking is the recognized warning. Maximum wave arrival was set to the same as the first wave arrival: 27 minutes. Evacuation speed was set to 4 feet per second (1.22 meters/second), with a ≥65 age speed adjustment of 0.8. The C_{PREP} for the *Good* and *Fair* was set 0.4 and 0.6, translating to 10.8 and 16.3 minutes median departure time after the earthquake ground motion begins. For C_{STD}, we use the default Hazus values of 0.3 and 0.5 for the *Good* and *Fair* settings of Community Rating.

We converted our Beat the Wave path distance data to integer minutes, dividing by 240 (4 ft/s * 60 s/min). Partial Safe Zone shapefile used the same Safe Zone shapefile, but with a fixed 4-minute difference for a fixed partial safe zone width of 960 feet. The two shapefiles were then provided to Hazus Tsunami Casualty Level 2 as Safe Zone and Partially Safe Zone shapefiles in the Casualty Analysis window interface. In the same interface, we set the Arrival Time and Time to Maximum Runup to 27 minutes and the Warning Time to 0 minutes. After casualty analysis in Hazus, the [dbo].[tsTravelTime], [dbo].[tsCasualtyNightGood], and [dbo].[tsCasualtyNightFair] Hazus SQL tables were then exported and processed.

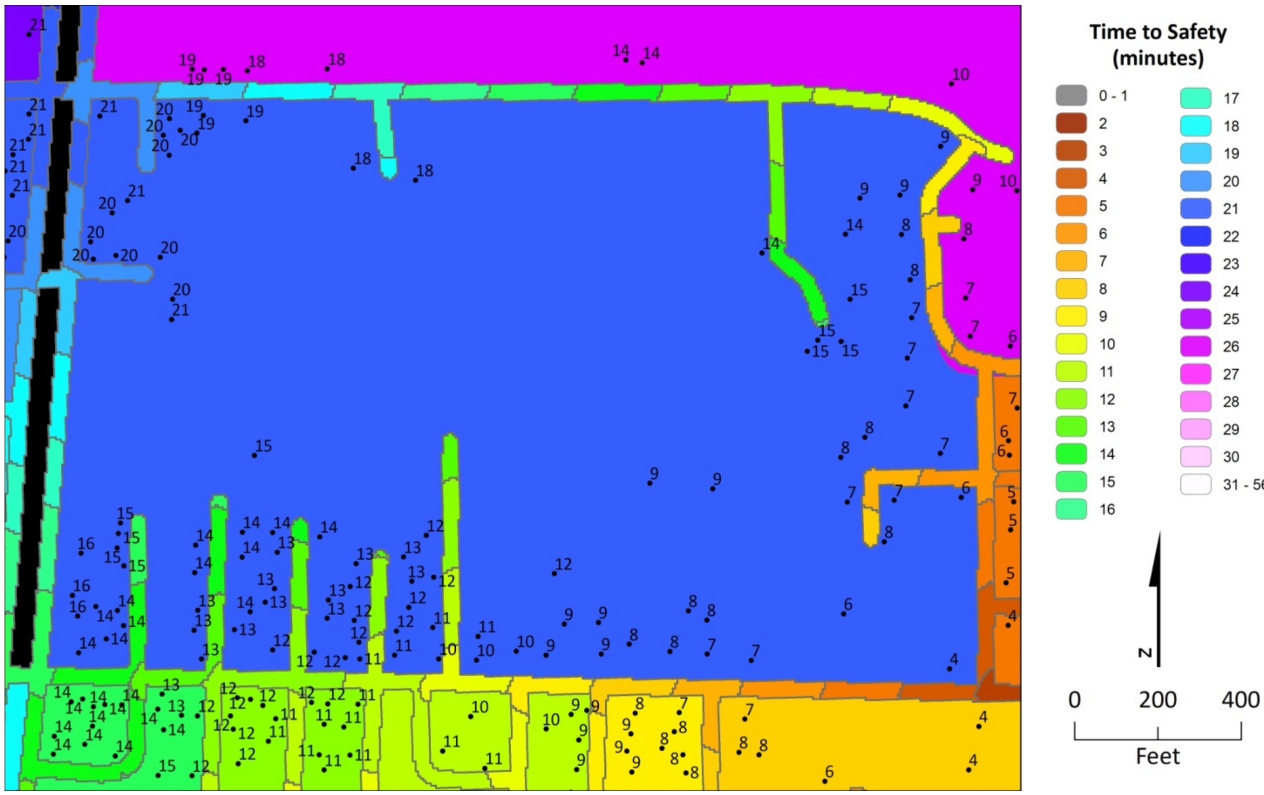
The differences between the casualty estimates from the DOGAMI spreadsheet and the Hazus tsunami casualty level 2 tool were large (**Table 10-1**), with the Hazus tsunami casualty level 2 tool consistently estimating significantly more fatalities.

Table 10-1. Tsunami casualty estimates as determined by DOGAMI spreadsheet and by FEMA Hazus tool.

	Good Preparedness (10-minute Departure)		Fair Preparedness (15-minute Departure)	
Casualty Category	**DOGAMI Spreadsheet**	**Hazus 4.2 SP1 Tool**	**DOGAMI Spreadsheet**	**Hazus 4.2 SP1 Tool**
Fatalities: Under 65	138	260	397	510
Fatalities: 65 and over	116	205	244	316
Injuries: Under 65	60	94	71	76
Injuries: 65 and over	47	60	47	43

The results can be explained by Hazus' current implementation method (Hazus version 4.2 SP2), wherein it typically chooses the *maximum* travel time that intersects with the census block and applies that travel time to safety to *all* residents within the census block (D. Bausch, written communication, July 2018). This conservative implementation introduces a systematic bias that is especially pronounced for irregularly shaped large census blocks where residents have ample time to evacuate, yet due to vagaries in the evacuation network, some portion of that network may have very large time-to-safety values. **Figure 10-1** illustrates the situation. The Hazus tool assigned the blue census block in the center a travel time of 21 minutes, even though the travel time from each building, whose individual travel times to safety in minutes are shown as labels, is typically much less. Note the center census block's intersection in its northwest corner with an evacuation network time of 21 minutes — this is the value that the Hazus tool assigned to *all* occupants of that census block.

Figure 10-1. Travel time to safety for the evacuation network (shown as narrow trapezoids), individual buildings (shown as dots with labels indicating the time to safety [in minutes] for the building's occupants), and Hazus-assigned census block time-to-safety (in minutes).Tsunami safety is to the east of this diagram.



To assure the DOGAMI spreadsheet is correctly implementing the casualty estimates, we assigned all records in the DOGAMI spreadsheet within a given census block a travel time identical to what Hazus determined the travel time should be for that census block, using the time-to-safety assignments from `[dbo].[tsTravelTime]` Hazus SQL table. The casualty results are nearly identical (**Table 10-2**). We attribute the minor differences to rounding errors, as the Hazus tool often stores various data and intermediate results in integer format, and the DOGAMI spreadsheet uses floating point format.

Table 10-2. Tsunami casualty estimates as determined by DOGAMI spreadsheet and by the FEMA Hazus tsunami tool, with DOGAMI spreadsheet records using the Hazus-assigned time-to-safety values for a census block.

	Good Preparedness (10-minute Departure)		Fair Preparedness (15-minute Departure)	
Casualty Category	**DOGAMI Spreadsheet**	**Hazus 4.2 SP1 Tool**	**DOGAMI Spreadsheet**	**Hazus 4.2 SP1 Tool**
Fatalities: Under 65	258	260	509	510
Fatalities: 65 and over	211	205	320	316
Injuries: Under 65	95	94	78	76
Injuries: 65 and over	63	60	45	43

Our objective was to instill confidence in the DOGAMI spreadsheet results, not to systematically examine the implication of the conservative implementation by the Hazus tsunami casualty tool on casualty estimates at a regional level.

Cross-validation has value for all parties. The validation process uncovered one implementation bug within the Hazus 4.2 SP1 tool (fixed in Hazus 4.2 SP3; FEMA, 2019b), and uncovered an implementation bug within the DOGAMI spreadsheet itself, which we addressed.

11.0 APPENDIX D: TSUNAMI CASUALTY MODEL SPREADSHEET USER GUIDE

The accompanying DOGAMI Excel spreadsheet that implements the Hazus tsunami casualty model is intended to be adaptable to a variety of user needs. The spreadsheet uses Hazus terminology (FEMA, 2017b), including the Good, Fair, and Poor community preparedness designations, in order to improve its adoption by others. For injury and casualty calculations, the spreadsheet uses Excel tags where appropriate.

11.1 User-Supplied Parameters

Parameters in the orange cells are adjustable by the user, and the naming generally corresponds to the terms provided by FEMA (2017a, Table 6.3), with one exception. Users of the DOGAMI spreadsheet found the meaning of the FEMA Hazus tsunami model Community Preparedness Level (C_{PREP}) parameter ambiguous. The term may be more meaningful within a distant-source tsunami context. To overcome the usage hurdle, the spreadsheet instead has the user supply a median departure time for the group, in minutes. C_{PREP} is then simply calculated as Departure Time divided by the user-supplied Maximum Wave Arrival time (T_{ARRIVE}) and is provided in the spreadsheet for reference. Note that C_{PREP} is used in the DOGAMI spreadsheet formulae.

The DOGAMI spreadsheet applies a constant factor for computing the Partial Safe Zone, for reasons discussed in Section **10.2** .

The DOGAMI spreadsheet has the user supply a per-record, rather than a per-census-block, estimate of number of people at a location (typically a building), and the location's distance to safety (in feet). The spreadsheet uses *distance to safety*, rather than a *time to safety*, value for each record, as the distance to tsunami safety from a particular point is fixed for a given tsunami scenario, and it is much more straightforward to compute casualty estimates for varying departure times and evacuation walking speeds when using distance instead of time. In addition, for each record the user specifies the number of people <65 and ≥65 at that location (typically a building).

11.2 Injury and Fatality Estimates

The spreadsheet provides summary statistics, including the number of permanent, temporary, and combined population < 65 years of age, ≥ 65 years of age, the total number of injuries and fatalities, and a casualty ratio, which is the total number of injuries and fatalities divided by the total population in the tsunami zone.

11.3 Hazus Tsunami Casualty Model Features Currently Not Implemented

Our focus was on quantifying casualties from a near-source tsunami that provides no warning time. The T_W (a.k.a. $T_{warning}$ time) is provided as a placeholder in the DOGAMI spreadsheet but is not currently implemented.

For a near-source tsunami, such as one generated from a CSZ earthquake, the time from the earthquake commencement to maximum wave runup is assumed to be the first wave (Witter and others, 2011). We found the T_0 parameter (arrival time of FEMA [2017a, Table 6.3]) to be potentially confusing to users. The user supplies a wave arrival time (T_{arrive}), and the DOGAMI spreadsheet assumes this is the maximum wave arrival time at the runup line. It is referenced to the onset of start of the earthquake.

11.4 Hazus Tsunami Casualty Model Assumption

The Hazus casualty model is one-dimensional in that it assumes an evacuee simply needs to arrive at tsunami safety by a given time, and that there are no intermediate temporal requirements en route to safety. Depending on the complexities of the local topography and the evacuation routes, an evacuee may need to arrive at a certain point (e.g., a bridge) in time en route to their safety destination, because it may be possible for an evacuation route to be cut off by early wave arrival. Such is the case in Seaside, Oregon (described by Priest and others, 2015). En route time-sensitive inundation information, such as needing to arrive at and traverse a crossing at a low elevation point (such as a bridge) prior to arriving at the final tsunami safety destination, is not included in the Hazus tsunami evacuation model or in the DOGAMI casualty spreadsheet. Other assumptions made with the Hazus tsunami casualty model are discussed in Section 2.10.5.

11.5 Excel Spreadsheet: Sensitivity Testing

The accompanying Excel spreadsheet, DOGAMI Hazus Tsunami Casualty Model Spreadsheet with Sample Data.xlsx, contains Microsoft Visual Basic code that enables rapid tabular graphical representation of the variation in injury and fatality rate, depending on the group departure time and the walking speed. The code changes the cells B3 (Excel tag "Depart_Good"), and B10 (Excel tag "WalkRate"), copying the injury and fatality rate for the combined, permanent, and temporary population (Cells J22, J8, and J15, respectively), and placing them incrementally in the `MacroOutput` worksheet's columns A through C. The code automatically adjusts the C_{STD} value depending on the departure time, as described in section **2.6.2.3** , using the adjustments in worksheet `MacroOutput` columns E2:F25. The `MacroOutput` contains summarization tables and default graphs.

For security reasons we do not distribute an Excel spreadsheet with an enabled macro. The code is embedded as text in the worksheet `MacroText`. The code can be copied and pasted into a Microsoft Visual Basic module and easily modified to fit a user's needs.