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# EARTHQUAKE AND TSUNAMI IMPACT ANALYSIS FOR COASTAL LINCOLN COUNTY, OREGON

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## DISCLAIMER



## WHAT'S IN THIS REPORT?

This report evaluates a Cascadia subduction zone earthquake (Mw 9.0) and tsunami (M1, L1, and XXL1 scenarios) affecting coastal Lincoln County, Oregon, in order to understand the degree of potential destruction, including building losses, debris generated, fatalities and injuries, and estimated numbers of the displaced populations. The goal is to help coastal communities prepare for this inevitable disaster.

*Cover: Photo from Wikimedia commons: https://commons.wikimedia.org/wiki/File:US_Navy_050102-N-9593M-040_A_village_near_the_coast_of_Sumatra_lays_in_ruin_after_the_Tsunami_that_struck_South_East_Asia.jpg. U.S. Navy photo by Photographer's Mate 2nd Class Philip A. McDaniel, January 2, 2005*

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## EXCEL SPREADSHEET

*A Microsoft® Excel® spreadsheet showing data that are the basis for this report's tables and figures is available in the digital file set of this report.*

# EXECUTIVE SUMMARY

This report provides an evaluation of the potential impacts of a Cascadia earthquake and accompanying tsunami in coastal Lincoln County. The analyses presented here include an assessment of the numbers of people, businesses, and critical facilities located in three Cascadia tsunami inundation zones (M1, L1, and XXL1). XXL1 represents the maximum considered inundation scenario given our knowledge of the Cascadia subduction zone (CSZ). Large (L1) and Medium (M1) inundation zones reflect earthquake and tsunami scenarios that are more likely to occur than XXL1 but are characterized with less slip on the subduction zone (critical for tsunami generation) and thus carry more risk because they are less conservative. L1 captures 95% of the uncertainty in tsunami modeling (there is a ~5% chance that the tsunami could exceed the L1 scenario), while the M1 scenario captures 78% of the uncertainty (there is a ~22% chance that the tsunami could exceed the M1 inundation zone).

A major focus of this study has been to provide improved evaluations of local 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 CSZ earthquake and 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 Lincoln County.

We used previously developed physical models of a CSZ earthquake and tsunami, "Beat the Wave" tsunami evacuation modeling, and the recently published FEMA Hazus Tsunami Model to develop standardized loss estimates for each community, including injuries, fatalities, and building damage. From the latter we estimated the amount of debris generated from the building damage. Our 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 vary widely throughout the calendar year. The tsunami injury and fatality modeling evaluates a nighttime (2 AM) evacuation scenario (maximizing visitor occupancy), quantifying impacts to permanent and temporary residents.

- The total permanent resident population present on the Lincoln County coastline within a tsunami zone ranges from ~4,220 (M1) to ~11,470 (XXL1). If the temporary population is included, the local population could increase to ~16,700 (M1) to ~42,000 (XXL1) assuming 100% occupancy;
- The fraction of the total permanent resident population within the three tsunami zones varies widely between communities.
    - The communities of Gleneden Beach, Bayshore, Yachats, and to a lesser extent Waldport each have relatively large numbers of people located in the XXL1 tsunami zone; respectively 75%, 74%, 77%, and 53%;
    - Within the L1 zone, Yachats has 60% of its population in the tsunami zone, Bayshore (58%), and Waldport (44%);
    - For the M1 scenario, communities with the largest number of people in the tsunami zone include Bayshore (44%), Waldport (37%), and Yachats (27%);
    - The communities of Newport, Depoe Bay, and especially Otter Rock have relatively few people in the various tsunami zones due to all three communities being largely perched on marine terraces; and,
    - These findings reflect contrasting patterns in the general shape and elevation of the Lincoln County coastline, whether it is open coast versus up an estuary; tsunami travel;

dispersion (loss of energy) and inundation extents between the communities; and the distribution of permanent residents within the communities;

- Beachside State Recreation Area and Beverly Beach State Park are mostly (>88%) located in the M1 tsunami zone, and 100% within the L1 and XXL1 tsunami zones; South Beach State Park and Tillicum campground are also 100% within the L1 and XXL1 tsunami zones;
- All major Lincoln County coastal communities can experience significant influxes of visitors, well exceeding their local resident populations. Of note, the community of Gleneden Beach can swell by ~760% to 600% (M1 to XXL1), Lincoln City by ~400% (M1 to XXL1), Yachats by ~660% to 420% (M1 to XXL1), and Newport by ~300% (M1 to XXL1). These results demonstrate the importance of these communities as major tourist destinations with potentially large numbers of visitors located in the tsunami zones. The popularity of these communities as centers of tourism presents challenges associated with preparing such a large transient population for a CSZ earthquake and tsunami;
- Analyses of Lincoln County population demographics indicate that the countywide resident population of ≥65 years of age is ~29-30% of the total population for all three tsunami zones; this reflects about 1,280, 1,930, and 3,620 residents in the M1, L1, and XXL1 zones who are ≥65 years of age. Nevertheless, two communities have significantly more people ≥65 years of age: Gleneden Beach (52%), followed by Lincoln Beach (~40%); Seal Rock has 45% of people ≥65 in the L1 and XXL1 tsunami zones. Variations in demographics will likely impact ability to evacuate from the tsunami zone;
- The number of buildings located in a tsunami zone are greatest in Lincoln City, Gleneden Beach, Newport, and to a lesser degree Waldport. Nevertheless, the largest number of buildings across the entire county falls within the “other” category (~3,570). The bulk of this latter group reflect residential buildings established along the open coast outside of community boundaries, as well as along the shores of each of the estuaries. Exposure to the tsunami hazard is highest in Waldport and at Bayshore. This is because both communities are significantly exposed to all three tsunami inundation scenarios;
- Building damage caused by earthquake shaking is estimated to range from $621 million in Newport to a low of tens of thousands in the various campgrounds. The large losses estimated for Newport can be attributed to the effects of liquefaction (and lateral spreading) along the Newport bayfront and building engineering. Earthquake damage losses in Lincoln City are also substantial and are estimated to reach $396 million. Countywide damage losses caused by the earthquake alone are expected to exceed $2.1 billion;
- Incorporating damage caused by the tsunami results in destruction levels for an M1 event that range from ~20% (Lincoln Beach) to ~75% damage at Depoe Bay and 91% damage in Waldport; for an XXL1 event our analyses indicate >70% destruction in most communities, including Lincoln City, Gleneden Beach, Newport, Seal Rock, Bayshore, Waldport, and Yachats; complete destruction will occur at all four campgrounds. These findings can be attributed to the powerful hydraulic forces associated with the tsunami and the prevalence of light-frame construction material (i.e., wood frame) on the Oregon coast;
- Combined earthquake and tsunami damage for each tsunami zone indicates losses that range from ~$2.4 billion for an M1 size event, $2.8 billion for an L1 size event, and $3.5 billion for an XXL1 size event. These estimates reflect community-wide losses associated with the earthquake,

combined with destruction caused by the tsunami. Note that these estimates exclude building content losses, such that the numbers may be viewed as minimal estimates;

- The destruction of buildings in coastal Lincoln county is expected to generate ~239,000 tons (M1) to ~705,000 tons (XXL1) of debris. This equates to ~23,900 dump trucks for M1 to as much as 70,500 dump trucks for an XXL1 event (assuming dump truck capacity of ~10 $yd^3$). These estimates are almost certainly on the low end, as they do not include debris associated with content from buildings (personal items, business equipment, etc.), road rip-ups, vehicles, and vegetation;
- Modeled tsunami casualties (injuries and fatalities) vary widely between communities. This is due to many factors, but most important is the relative distance to high ground.
    - For the M1 scenario, estimated fatalities are confined mainly to the communities of Lincoln City (~80 resident/110 visitor), and Gleneden Beach (~25 resident/180 visitor) with few fatalities in the remaining communities. Low casualties associated with the M1 scenario in the majority of the communities is indicative of the fact that high ground is located close to the population centers, allowing for quick access to high ground, or the tsunami simply does not reach them;
    - For the maximum-considered XXL1 tsunami scenario, the number of fatalities increases and ranges from very few (e.g., Lincoln Beach, Depoe Bay, Otter Rock, Siletz, Toledo, Seal Rock and Yachats) to ~620 at South Beach State Park in Newport, followed by Gleneden Beach (~480), Bayshore (~450), and Beverly Beach State Park (~390). Overall, the bulk of the fatalities (79%) are likely to be from the temporary visitor population;
    - High casualties associated with the temporary visitor population is predicated on the assumption that these facilities are at 100% occupancy.
    - The large number of potential fatalities at South Beach State Park and Gleneden Beach is entirely due to the significant travel distances required to reach high ground.
    - These results demonstrate a need to evaluate alternative forms of high ground (e.g., vertical evacuation structures), and/or retrofitting bridges to withstand the earthquake shaking, thereby allowing for faster evacuation;
- Following the effects of the earthquake and accompanying tsunami, communities can expect to have to deal with many hundreds to potentially thousands of displaced people requiring immediate short-term shelter and care (~days to a few weeks), after which many people are likely to be evacuated from the coast. Hazus modeling indicates that the numbers of displaced increase significantly as one progresses from M1 (~16,260) to XXL1 (~38,580). We expect these challenges to be especially difficult in the following communities: Lincoln City, Newport, Gleneden Beach and Yachats. Furthermore, an estimated 7,770 people outside of UGB and community boundaries will require shelter and care; and
- Compared with fatalities, injuries from the earthquake and XXL1 tsunami were found to be relatively low. Overall, our combined earthquake and tsunami Hazus modeling indicates ~350 critically injured (Levels 2 and 3 in Table 2-2) for the M1 scenario, ~400 for L1, and ~530 for XXL1 in Lincoln County.

Although each community in coastal Lincoln County has unique circumstances and challenges, as supported by the results of this study, our results unequivocally demonstrate that in every community, ***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 15,899 killed and another 2,529 missing (as of September 10, 2020; National Police Agency of Japan, 2020); most of the people killed were due to drowning (Mori and Takahashi, 2012). The earthquake and tsunami destroyed 121,992 buildings (282,920 buildings experienced partial collapse), 730,359 buildings were partially damaged, 4,198 roads were damaged, along with 116 bridges (National Police Agency of Japan, 2020).

The Oregon coast is similarly exposed to large megathrust subduction zone earthquakes, capable of generating catastrophic tsunamis (Witter and others, 2011). 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 (Goldfinger and others, 2017, 2012; Priest and others, 2009; Satake and others, 2003; Witter and others, 2012). The most recent tsunami generated by a large subduction zone earthquake on the Oregon coast occurred on January 26, 1700 (Atwater and others, 2005). Goldfinger and others (2017) estimated the conditional probability of an earthquake on the Cascadia subduction zone (CSZ) at ~16–22% in the next 50 years; a partial rupture of the CSZ impacting the southern Oregon coast has a conditional probability of ~37–43% (Goldfinger and others, 2012). Because many communities on the Oregon coast have large numbers of people, residences, and businesses located in the tsunami zone, there is a high potential that the next great earthquake and tsunami will result in many fatalities, catastrophic destruction of local infrastructure, and lasting damage to Oregon's economy. The objective of this report is to perform an analysis of community exposure to tsunami inundation, providing estimates of infrastructure damage and casualty estimates for Lincoln County on the central Oregon coast. In providing such information, we address a specific need expressed in the 2013 Oregon Resilience Plan, to document the "who," "what," and "where" in terms of population exposure, building damage and socioeconomic impacts (OSSPAC, 2013). The overall approach presented here follows comparable efforts undertaken for Clatsop and Tillamook Counties (Allan and others, 2020a,b).

Following the 2011 Tōhoku, Japan tsunami, the Federal Emergency Management Agency (FEMA) commissioned an effort to standardize quantification of tsunami impacts (FEMA, 2013), later refined and incorporated into FEMA's Hazus framework (FEMA, 2017). 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 inputs needed by Hazus includes a wide variety of tsunami modeling, engineering, and societal information, including earthquake ground motion and ground deformation, tsunami inundation, flow velocities and flow depths, building inventories, and population demographics.

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 in order to model five scenarios for locally (CSZ) generated tsunamis (Priest and others, 2013g; Witter and others, 2011). More recently, DOGAMI pioneered techniques for tsunami evacuation modeling ("Beat the Wave" [BTW]) at Seaside and Gearhart (Priest and others, 2015), Warrenton/Hammond (Gabel and Allan, 2016), Rockaway Beach, (Gabel and Allan, 2017), Pacific City (Gabel and others, 2018a), Reedsport and

Florence (Gabel and others, 2018b), Newport (Gabel and others, 2019a), Lincoln City/unincorporated Lincoln County (Gabel and others, 2019c), the Coos estuary (Gabel and others, 2019b), unincorporated Lincoln County (Gabel and others, 2019d), Port Orford (Gabel and others, 2020a), and Nehalem Bay (Gabel and others, 2020b). These BTW studies graphically demonstrate evacuation challenges and mitigation opportunities but do not quantify potential loss of life. Since 2015, Williams and others (e.g., Williams and others, 2020) developed a Hazus-compatible building inventory for all seven Oregon coastal counties, identifying the location, size, and primary usage (e.g., residential, commercial) of buildings, information fundamental to addressing fatalities and building damage potential.

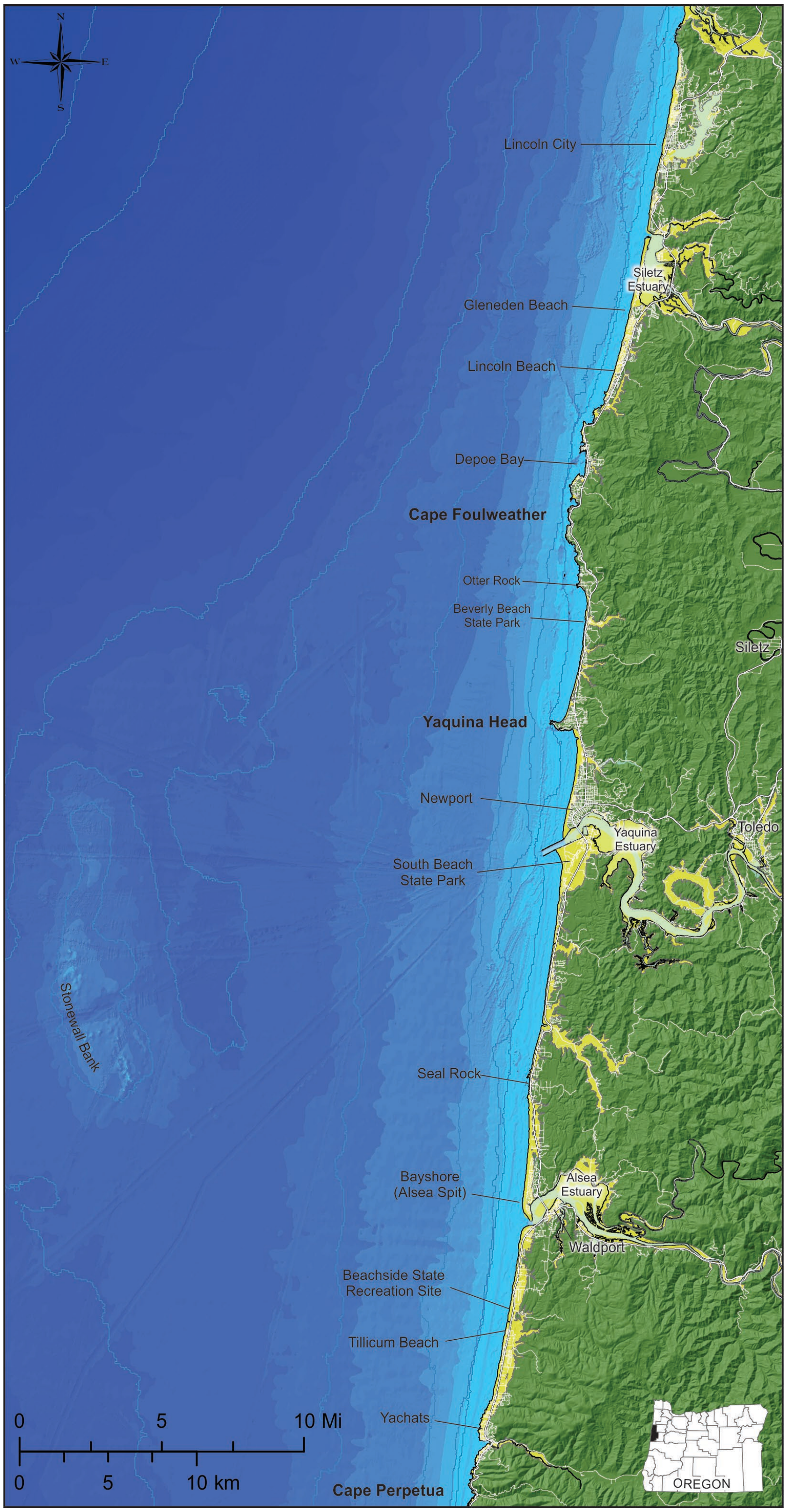
Although most data needed by Hazus to model the effects of earthquake and tsunami impacts are in place, one key missing element is a spatially explicit population model for the Oregon coast. Specifically, how many people are located in the tsunami zone, their demographics, and where they are located relative to safety from the tsunami at the time of the 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 to full-time residents, many homes and condominium units located in the tsunami zone are second homes or vacation rentals (Raskin and Wang, 2017), while numerous coastal parks and campgrounds are also 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. Furthermore, *population estimates should assume the highest seasonal occupancy so that design capacities will be based on the maximum potential evacuation need*, while also identifying vulnerable population groups within the tsunami zone that may present special evacuation challenges (DLCD, 2015).

The purpose of this report is to evaluate the potential effect of a CSZ earthquake and accompanying tsunami in coastal Lincoln County (**Figure 1-1**). Specifically, we evaluate estimates of potential building losses, generated debris, fatalities, and injuries, as well as estimates of numbers of displaced people. The study also provides an assessment of vulnerable population groups, essential facilities, and critical infrastructure that are integral to response and recovery. This study integrates previous earthquake and tsunami modeling with a new population model (comprising permanent and temporary people) for the purpose of

1. evaluating tsunami evacuation challenges and opportunities on the coast; and
2. completing a detailed socioeconomic analysis using several data sources to identify vulnerable communities in the tsunami zone.

This report initially describes and documents our overall Hazus approach, especially the development of the population model. Results from the countywide assessments are provided in Section 3, with broad conclusions in Section 4. With the exception of the community of Siletz, summary information specific to each community and tsunami inundation zone is provided in Appendix A. We do not provide community profile information for Siletz since it is not directly affected by a Cascadia tsunami. However, damage and casualty data caused by the earthquake may be found in the accompanying spreadsheet file.

**Figure 1-1. Location map showing coastal Lincoln County communities. Yellow zone depicts the XXL1 tsunami zone.**



# 2.0 METHODS

## 2.1 Overview

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 (Madin and Burns, 2013; OSSPAC, 2013) and a corresponding "T-shirt" sized tsunami. For the purposes of this study, we provide Hazus modeling results for three tsunami inundation zones (Priest and others, 2013g; Witter and others, 2011), including Medium (M1), Large (L1), and Extra Extra Large (XXL1). Model results presented here reflect earthquake related damage (including the amount of debris) and casualties simulated for the entire community, while damage and casualties caused by the tsunami are specified for each of the three tsunami inundation scenarios. For injury and fatality estimation we analyzed a "2 AM" scenario for all communities, distinguishing between permanent residents and temporary residents. We did not evaluate a 2 PM scenario because the 2 AM scenario defined for summer occupancy conditions assumes maximum occupancy and we believe is sufficiently conservative to account for uncertainty associated with day trippers.

## 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 [2015a], 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. 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 (i.e., 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).

### 2.2.2 Tsunami

The earthquake scenarios and corresponding surface deformation used to simulate tsunami inundation for the Oregon coast reflect a full-length rupture of the Cascadia megathrust (Witter and others, 2011, 2013). Four representative earthquake 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. Recurrence information was defined from a suite of scientific studies including work undertaken in coastal estuaries (Nelson and others, 1996, 2006; Peterson and others, 1995; Witter and others, 2003) and on the continental shelf (Goldfinger and others, 2012). Inter-event time intervals that separate the 19 full-length tsunamis range from as little as 110 to ~1,150 years (Witter and others, 2011, Table 1). Each tsunami scenario was then weighted using a logic tree, to account for the different models, convergence rates, and recurrence. 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 (XXL1), which simulated a maximum-considered tsunami, was eventually used to guide evacuation planning (Witter and others, 2011). 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, 1/2,000 yr; M, 1/1,000 yr; L, 1/3,333 yr; and XL, <1/10,000 yr. Recurrence for the XXL1 event is not known.

Maximum flow depths were obtained from Priest and others (2013a,b,c,d,e,f), while the maximum momentum flux was derived from Priest and others (2014a,b,c,d,e,f). 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 maximum depth and momentum flux values (FEMA, 2017, 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 for use in Hazus.

Wave arrival times at the tsunami runup limit were obtained from data originally developed by Priest and others (2013a,b,c,d,e,f). As documented by Bauer and others (2020), an independent spreadsheet that implements the Hazus tsunami casualty model was developed to facilitate analysis and reporting of injuries and fatalities resulting from a tsunami (see Section 2.6). The original approach relied on an average wave arrival time unique to the five communities studied. For this project, however, we modified the spreadsheet to support per-record maximum wave arrival times at the tsunami runup limit (in minutes). This was necessary due to the large variation in maximum wave arrival times observed along the Oregon coast and especially up the various estuaries (e.g., the Columbia or Yaquina estuary). For example, in Yaquina Bay, Lincoln County, the wave arrival time ranges from 28 minutes for a tsunami wave arriving at the Nye Beach turnaround, compared with 33 minutes for a tsunami wave traveling up the Yaquina River and arriving at an exit point at Running Springs Road. Although only a 5-minute difference, it is sufficient to influence the calculation of casualties. To resolve this limitation, we used the evacuation flow zone polygons defined in our various "Beat the Wave" studies to associate a group of buildings with a particular tsunami safety point, or exit point. We then determined the maximum wave arrival time at a particular watershed's exit point and assigned that value (in minutes) to the polygon. All buildings within that watershed were then associated, via a spatial overlay, with that wave arrival time. In some open coast communities, such as Gleneden Beach, the maximum wave arrival time varies only slightly, and a single value was assigned to all buildings. Wave arrival times for areas located outside our detailed "Beat the Wave" investigations were defined based on average wave arrival times for that particular area of coast.

## 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 2-1**). 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 (e.g., Lewis, 2007). We followed the methods established by Bauer and others (2018), starting with the incorporation of building records previously developed (e.g., Williams and others, 2020) and modifying or amending records where better information was available.

**Table 2-1. 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.

The User-Defined Facilities (UDF) datasets developed by DOGAMI attempted to identify 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 and assisted living facilities. 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 construction, etc.). While the UDF dataset was a good starting point, it did not always correctly classify residential structures. Therefore, it required a thorough review during which many records were manually updated to correct existing attributes.

We augmented the UDF dataset as follows. We added a "*number of units"* field, identifying the number of rooms, where available, for motels, multi-family residential, and dormitory building types (Hazus occupancy types "RES4," "RES3," "RES5," respectively). 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 damage to temporarily occupied structures such as tents, recreational vehicles, and boats.

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

$$\text{RSMeans} = \text{building square footage} \times \text{standard cost per foot}^2 \quad (1)$$

Per-square-foot replacements costs are derived from the Hazus 4.2 database[1] 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.

An abnormal shortage of skilled labor or materials can occur following 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.

Williams and others (2020) used street-level imagery to determine the building type of all non–single-family residential buildings, using the guidance provided by FEMA (2015b); selected records were updated with information from Lewis (2007) and other ancillary data sources. Williams and others (2020) were unable to locate additional building information that might have helped further refine the building type assignment, or any seismic retrofitting datasets that could be used to update an individual building's seismic design level. Finally, our observations from numerous field visits and analysis of street-level imagery suggested that the statistical distributions for building types identified by FEMA (2011, Tables 3.A1–3.A.10) are not applicable to the Oregon coast. This is because most commercial and industrial buildings built on the Oregon coast use 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.

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

## 2.4 Population Modeling

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, 2017). 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).

Such divisions, however, are inadequate to meet the needs of this project (Bauer and others, 2020). This is because Oregon coastal communities experience significant temporal (daily, seasonal, and annual) population fluctuations, with large visitor influxes occurring on weekends and in the summer months (Dean Runyan Associates, 2018). Community planners have expressed strong interest that our population model accounts 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.

At night, temporary residents occupy residential facilities such as second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds; permanent residents typically occupy residential structures. 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 type.

Development of a detailed temporary population model was therefore motivated by several important factors (Bauer and others, 2020):

1. Computing an overall injury/fatality ratio[2] for the permanent population and assuming that the ratio could be applied to the temporary population could lead to significantly underestimating the numbers of fatalities and injuries. For example, analysis of U.S. Census data and observation of real estate dynamics on the Oregon coast indicate a strong spatial correlation between the temporary population’s preference to be close to the ocean, and thus farther away from tsunami

[2] Total number of tsunami injuries and fatalities divided by the total exposed permanent population.

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

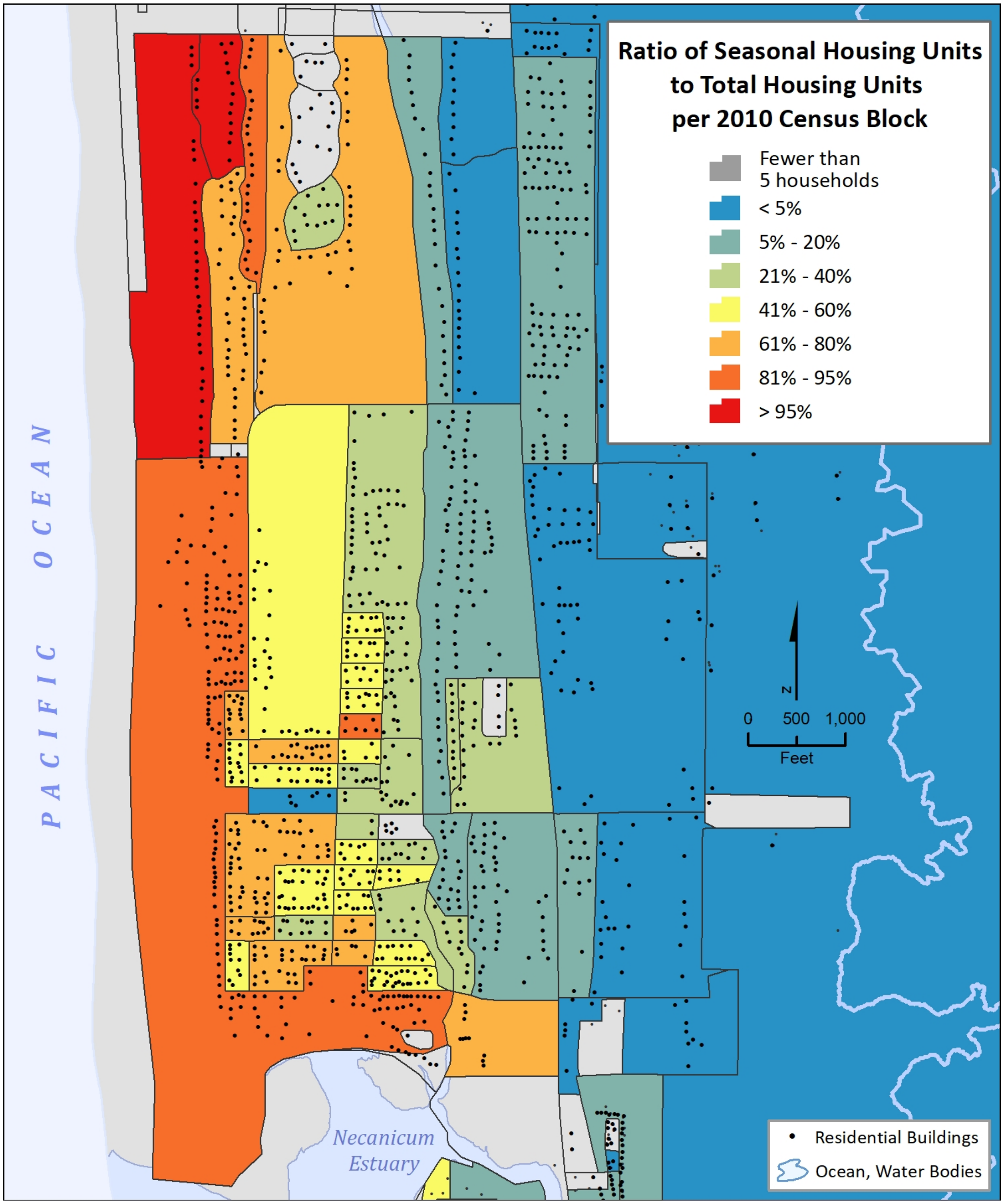
2. It is reasonable to assume that the temporary population may be less aware of tsunami risk, locations of tsunami safe zones, signage, temporal urgency (e.g., if you feel strong ground shaking, evacuate immediately), and local evacuation routes when compared with permanent residents; and
3. Community planners expressed a need for detailed estimates of tsunami injuries and fatalities, as well as estimates of the number of displaced people following a Cascadia event. These data are essential for effective mass care planning. Thus, our modeling of tsunami-caused injuries and fatalities is undertaken assuming 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 then 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. 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, may be considered a conservative estimate (i.e., upper bound), as the population model assumes maximum occupancy. Conversely, planners can use the permanent resident casualty estimates as a baseline (i.e., lower bound). FEMA guidelines (FEMA, 2012a, 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 […] to do this in a meaningful way." Such extensive modeling for all communities was beyond the scope of this project. Within this range, 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.

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 2010 U.S. Census data. Bauer and others (2020) used geocoded Oregon Department of Motor Vehicle (DMV) driver license registration records as of September 2017 to perform similar analyses for five coastal communities, as DMV records are typically associated with a single-family residential home. Although such an approach is more accurate for defining the permanent population, the time required to process DMV records on a countywide basis was beyond the scope of this investigation.

**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: [https://www.census.gov/data.html](https://www.census.gov/data.html).**



U.S. Census population data are organized into hierarchical spatial units of varying sizes, the smallest of which is the census block. Census blocks are typically "bounded by visible features such as roads, streams, and railroad tracks, and by nonvisible boundaries such as property lines, city, township, school district, county limits and short line-of-sight extensions of roads" (U.S. Census Bureau, n.d.). One level above that is the census block group, which is how the U.S. population is defined and distributed. In Lincoln County, census block groups average ~1,200 people (ρ = ± 500) and vary in area from 86 acres (35 hectares) to 157,160 acres (63,600 hectares), while the mean area is ~19,000 acres (~7,700 hectares). In urban areas, census blocks are usually defined at the city block level, while in rural areas census blocks may cover a few hundred square miles. Within each census block group the population may range from negligible to several thousand people. However, unlike DMV records that associate a person with a specific address, census block groups provide a single aggregated population count. For our purposes, we used updated population statistics obtained from the American Community Survey (ACS) data products (2014–2018 census data downloaded from the U.S. Census Bureau, https://www.census.gov/programs-surveys/acs, data accessed 2020) at the census block group level. To estimate the size and distribution of the permanent population in our study area, we distributed the population per census block group among the residential buildings and pro-rated based on square footage. The specific steps associated with this process are summarized in **Figure 2-2A** for the permanent population.

After populating the buildings, or in the case of multi-family residential structures, units, with permanent residents, we then assumed the proportion of 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 (units) to determine temporary occupancy (**Figure 2-2B**). 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 (**Figure 2-2B**). To accomplish these steps, we used the 2010 census data to identify the residential household vacancy rate[3] at the census block level. For each UDF, we then multiplied the corresponding vacancy rate by the number of units, establishing the number of units occupied by temporary residents. This latter value is then multiplied by the people per unit value to derive a temporary population per household unit (**Figure 2-2B**).

Finally, researchers have recognized that demographic factors can be an important factor in tsunami casualties (summarized by González-Riancho Calzada 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, 2017) incorporated population demographics into the FEMA Hazus casualty model. This is accomplished by differentiating those people < 65 years with those ≥ 65 years in the Hazus tsunami casualty model (FEMA, 2017), with the latter group assumed to evacuate at slower walking speeds; a 0.8 walking speed reduction factor was used to account for travel speeds used by persons ≥65 (see Section 2.6.2.4). Hence, for our tsunami casualty modeling purposes, an individual is identified as:

1) either permanent or temporary; and,
2) either < 65 years of age or ≥ 65 years (**Figure 2-2**).

[3] H005006, "Total for seasonal, recreational, or occasional use" in the Total Vacancy data per census block, 2010 U.S. Census divided by total number of households in the census block, obtained from Table S1101.

**Figure 2-2. Summary parameters and explanation used to define the process for distributing the permanent resident and visitor populations across U.S. census block groups.**

| | Occupancy Type | Number of Units | People Per Unit | People per UDF: Explanation | People per UDF: Math | Age < 65 Ratio |
|---|---|---|---|---|---|---|
| A) Permanent Population | Single-family Residential | 1 unit | The ACS 2014–2018 census data reports the number of permanent residents at the census block group (CBG) level. For each CBG in the study area, divide the permanent population number by the total number of units within the CBG. This established a People per unit number. | The People Per Unit value is then multiplied by the total number of units belonging to each UDF to assign the total number of permanent residents. | [Number of Units] × ([Number of permanent people in CBG] / [Number of units in CBG]) | 0.7 |
| | Multi-family Residential | 1 unit per 800 $ft^2$ | | | | 0.7 |
| | Dormitories | 1 unit per 400 $ft^2$ | | | | 0.9 |
| | Assisted Living | 1 unit per 600 $ft^2$ | | | | 0.05 |

| | Occupancy Type | Number of Units | People Per Unit | People per UDF: Explanation | People per UDF: Math | Age < 65 Ratio |
|---|---|---|---|---|---|---|
| B) Temporary Population | Single-family Residential | 2 units < 1,500 $ft^2$ | 2.0 | The 2010 census data reports the residential vacancy rate at the census block (CB) level. For each residential UDF, the corresponding vacancy rate was multiplied by the number of units, establishing the number of units occupied by temporary residents. This was then multiplied by the People Per Unit value. | [People Per Unit] × [number of units] × [CB vacancy rate] | 0.7 |
| | | 3 units < 2,700 $ft^2$ | | | | |
| | | 4 units < 4,000 $ft^2$ | | | | |
| | | 5 units < 5,500 $ft^2$ | | | | |
| | | 6 units ≥ 5,500 $ft^2$ | | | | |
| | Multi-family Residential | 1 unit per 800 $ft^2$ | 2.2 | | | 0.7 |
| | Hotel/Motel | 1 unit per 455 $ft^2$ | 1.7 | | | 0.7 |
| | Dormitories | 1 unit per 400 $ft^2$ | 1.0 | | | 0.9 |
| | Recreational Vehicle | 1 unit | 3.22 | For mapping simplicity, some UDF points are assigned multiple units, such as docks in boat marinas. | [Number of Units] × [People per Unit] | 0.3 |
| | Tent, Yurt | 1 unit | 3.22 | | | 0.9 |
| | Boat | 1 unit | 0.1 | | | 0.9 |

Notes:

Permanent population numbers are taken from ACS 2014–2018 census data at the census block group level.

Temporary vacancy rates are taken from 2010 census data at the census block level.

No permanent residents are assigned to Hotel/Motel, Recreation Vehicle, Tent, Yurt or Boat.

No temporary residents are assigned to Assisted Living.

Average number of people staying in a recreational vehicle (includes camper trailers), tent, or yurt. Mean value derived from T. Bergerson (Visitor survey of day use and overnight use at Oregon State Park coastal region parks, unpublished Oregon State Parks report, 2012, 151 p.), who evaluated the numbers of recreational visitors camping in coastal state parks.

Estimates of those residing on a boat were derived from consultation with local ports and marinas in both Clatsop and Lincoln County.

## 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 to first model earthquake damage using the Hazus User-Defined Facilities (UDF) earthquake model (FEMA, 2011, 2017). In the Hazus earthquake simulation we used Hazus 4.2 Service Pack 1 to model 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.

As noted previously, we model the effects of three discrete tsunami inundation scenarios described by Witter and others (2011) and Priest and others (2013e): M1, L1, and XXL1. These reflect the following CSZ earthquake moment magnitudes ($M_w$): 8.9 (M1), 9.0 (L1), and 9.1 (XXL1); each event is characterized by a unique deformation model to account for the coseismic response. These scenarios contrast with the terrestrial ground motion data from Madin and Burns (2013), which assume a moment magnitude ($M_w$) 9.0 CSZ earthquake. For Hazus loss estimation purposes we determined that the ±0.1 difference in moment magnitude is 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 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.

### 2.5.2 Tsunami

The M1, L1, and XXL1 median depth and momentum flux grids were input data to the Hazus tsunami tool as "Level 3" tsunami data (FEMA, 2017), which reflect advanced level user-provided tsunami model scenarios. We summarized building repair costs for the M1, L1, and XXL1 tsunami events by community[5].

### 2.5.3 Combined earthquake and tsunami

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

Building recovery times are provided in the FEMA Hazus methods (FEMA, 2017, Table 7.10), but we chose not to report them, as Bauer and others (2020) argued that the assumptions behind the tabular

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

[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.

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 (ODOE, 2017; ODOT, 2014; OSSPAC, 2013).

### 2.5.4 Building debris

The Hazus version 4.2 model (FEMA, 2017, 2018) 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 for the three tsunami scenarios.

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 guidelines provided by FEMA (2013, Chapter 7, and 2011, Chapter 12). 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 by FEMA (2011, Table 12.1). 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, 2017). Unlike 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. 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) 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 2-2**).

**Table 2-2. 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.<br>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.<br>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. |

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).

### 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, 2017). Although human behavior in an emergency situation is likely to be 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. The following sections define in more detail the overall approach and assumptions used to define injuries and fatalities from a CSZ tsunami.

#### 2.6.2.1 Model implementation

Bauer and others (2020) integrated the Hazus tsunami casualty model into a standalone Excel spreadsheet in order to estimate the likelihood of a casualty for every person, incorporating the person's particular distance to the nearest tsunami safety destination, assumptions on group median departure time, and median travel (walking) speed. A travel dispersion coefficient ($C_{STD}$) was also incorporated in the spreadsheet to account for variations (uncertainty) within the group's departure time and evacuation travel speeds. Motivations for developing the spreadsheet versus using the dedicated Hazus tsunami tool are:

1. Our existing tsunami evacuation modeling already provides 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 provided by Bauer and others (2020, Appendix C). There the functional equivalence of the spreadsheet with the FEMA Hazus tsunami Level 2 casualty tool is demonstrated. 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. Thus, the warning time ($T_W$) discussed by FEMA (2017) is assumed to be zero for a CSZ tsunami. Furthermore, tsunami modeling by Witter and others (2011) indicates that the maximum tsunami runup from a CSZ earthquake is typically 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 for multiple coastal communities (Gabel and Allan, 2016, 2017; Gabel and others, 2018a,b, 2019a,b,c,d, 2020a; Priest and others, 2015) 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*) is adjusted to account for the slope of the ground (steep versus flat) and terrain type (e.g., sand versus pavement) that may slow down a person's ability to evacuate. Given that tsunami evacuation nearly always requires the evacuee to move

[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 maximum tsunami runup (tsunami safety) in time ($T_{MAX}$). Complex decision points, such as early wave arrivals or bridge failures that are likely to preclude or impact evacuation along certain routes are not evaluated.

up in elevation, this adjusted distance to tsunami safety is always greater than the straight-line distance measured on a 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 by 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. We did not implement the method 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. Moreover, the time to evacuate a building may be accounted for as simply an evacuation delay, described further below.

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. Each scenario has a unique distance to safety GIS dataset, which can be captured separately, when needed. Such scenarios have been evaluated previously for multiple communities (e.g., Newport [Gabel and others, 2019a] and unincorporated Lincoln County [Gabel and others, 2019c]). For the purposes of this countywide Hazus assessment, we used the most conservative bridge-out scenario, to account for the likely failure of non-retrofitted bridges; bridges that have been retrofitted or rebuilt to current engineering standards are designed to withstand the intense ground motion caused by the earthquake.

#### 2.6.2.3 Departure time

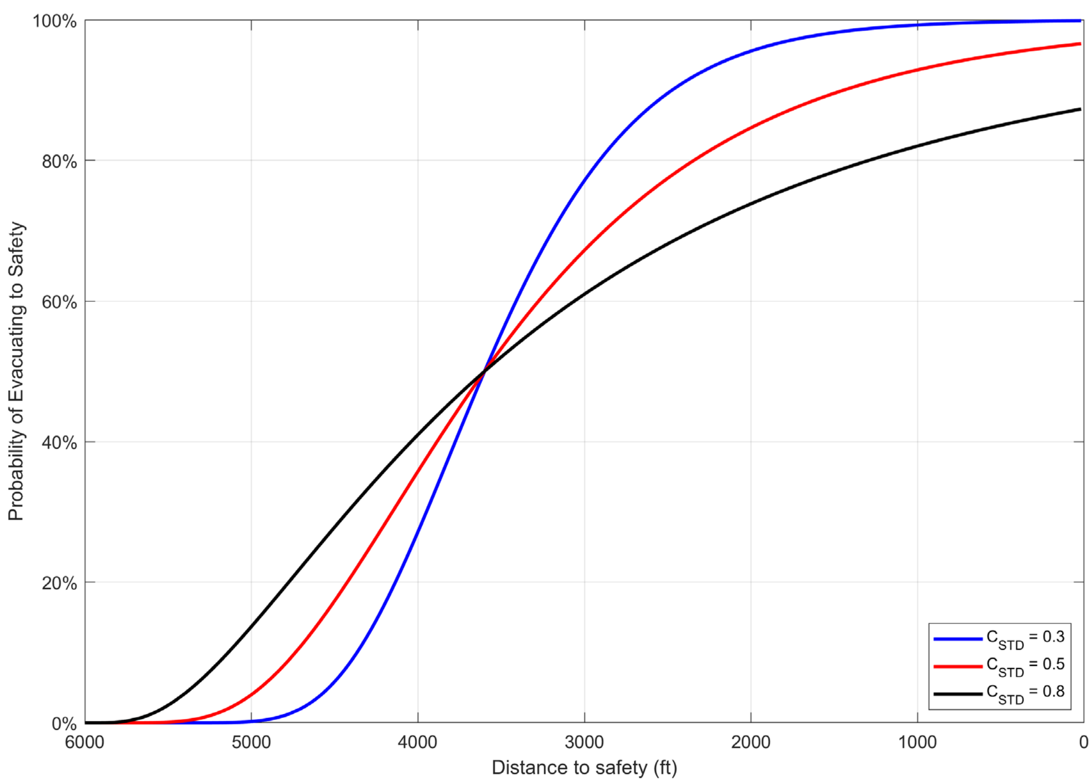
The Hazus tsunami casualty model uses the term *Community Preparedness Level*, which reflects the time required between the tsunami warning (i.e., earthquake shaking) and actual evacuation of the community (FEMA, 2017). The degree of preparedness is classified according to three categories: *Good*, *Fair*, or *Poor*, and is dependent on a suite of factors including tsunami awareness (education/knowledge), preparation of evacuation routes and signage, a community's risk management level, and, where available, emergency loudspeakers and tsunami sirens (FEMA, 2017). According to FEMA, a community with a "good" rating could be one that is designated "Tsunami Ready" by the 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, we focused 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 (Buylova, 2018; Mostafizi and others, 2017; Wood and others, 2016; Wood and Schmidtlein, 2013). In this study we provide injury and fatality estimates assuming a 10- (*good*) and 15-minute (*fair*) group departure (delay) times; we did not model a *poor* preparedness level as the casualty numbers associated with this specific category are very large and probably unrealistic.

The 10-minute (*good*) departure delay is the default value used in all our BTW tsunami evacuation modeling and refers to the time elapsed since the start of the earthquake. It accounts for up to 5 minutes in which earthquake shaking takes place in which people will drop, cover and hold on, followed by an additional 5 minutes of individual preparation — donning shoes and outdoor clothing, gathering immediate family, collecting a go-bag — before leaving the building. We also model a 15-minute (*fair* level of preparedness) departure time to demonstrate how additional milling time (evacuation delay) causes community fatalities to increase significantly.

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 [2017]). For the purposes of our study, we used the Hazus tsunami casualty model defaults of 0.3 and 0.5 for the 10- and 15-minute departure times, respectively, corresponding to the *good*/*fair* community preparedness levels noted above; theses values are the default standard deviation ($C_{STD}$) recommendations provided by FEMA (2017, Table 6.3). **Figure 2-3** 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 given 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 2-3. 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 ($C_{STD}$).**



We are unable to quantify how earthquake-induced building damage 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 (EERI, 2014; Maison and Cobeen, 2016; OBCD, 2010; SPA Risk LLC, 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 (2012b, 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

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 are incorporated into the $C_{STD}$ standard deviation value discussed previously.

The Hazus tsunami casualty model incorporates a travel (walking) speed reduction factor for persons aged 65 and over (FEMA, 2017). This assumption is based on analyses of fatalities in recent tsunamis (González-Riancho Calzada and others, 2015; Koyama and others, 2012; Suppasri and others, 2016). Accordingly, we used a 0.8 walking speed reduction factor to account for travel speeds used by persons ≥65, which equates to an evacuation speed of 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.

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

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

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 by using a range of evacuation speeds and wave arrival times (**Table 2-3**). As noted previously (Section **2.6.2.3**), although the group average (median) departure time may be 10 minutes, the Hazus tsunami casualty model accounts for individual variations from the group average by using the cumulative lognormal distribution and dispersion factor.

#### 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, 2017]). Conversely, where the tsunami wave depth is less than 1.8 m (6 ft) the model assumes a likelihood of 50% fatality/50% injury for individuals caught by the tsunami. 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 must travel. Analyses by Bauer and others (2020) indicated that these distances range from ~30 to 90 m (100 to 300 feet, **Figure 2-4**). In the DOGAMI implementation of the Hazus tsunami casualty model, we defaulted to a 60 m (200 ft) buffer distance as determined by Bauer and others (2020). 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.

**Table 2-3. 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.

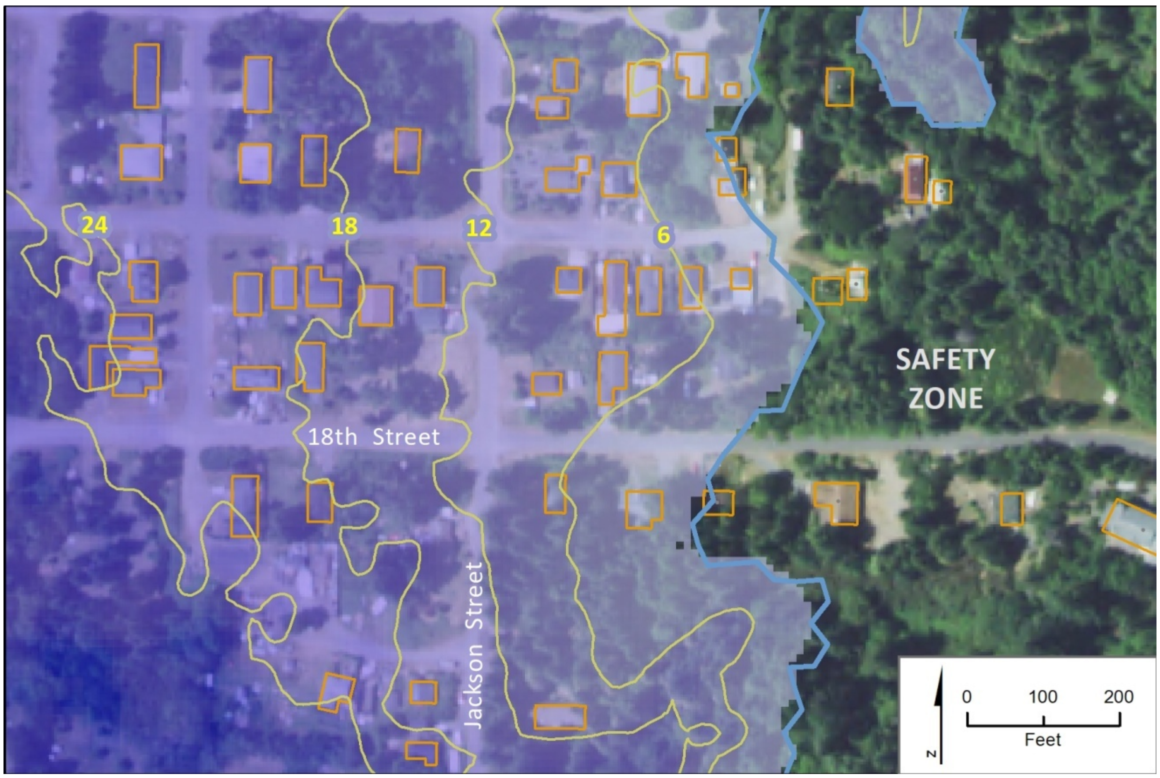
#### 2.6.2.6 Sensitivity testing

We varied evacuation speeds (2 to 10 fps in 1-fps increments) and departure times (5 minutes to 20 minutes in 1-minute increments) consistent with 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- and 15-minute departure times.

### 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 (earthquake and tsunami) to provide planners with a more complete accounting of the potential situation. 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.

**Figure 2-4. 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 2.6.2.5) for an XXL1 tsunami. Building outlines in orange. Imagery: National Agricultural Imagery Program (2016).**




## 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 have shelter needs that may be on the order of days to a few weeks, as arrangements for transportation out of the disaster zone and, ultimately, home may be delayed.

## 2.7 Essential Facilities and Key Infrastructure

We provide the names of essential facilities, special facilities, and key infrastructure 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;
(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. Geocoded Quarterly Census of Employment and Wages (QCEW) data obtained from the Oregon Employment Division in September 2018 was another dataset used to evaluate other potential 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 (OMB, 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.

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 list from visual inspections of orthoimagery and other ancillary geospatial data sources such as Homeland Infrastructure Foundation-Level Data (https://gii.dhs.gov/hifld/). As with the essential facilities and special facilities list, every effort was taken to develop as complete a list as possible.

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

## 2.8 Social Characteristics

DLCD (2015) recommended that a tsunami risk and vulnerability assessment include analyses of the characteristics and locations of populations that may have additional needs or requirements for evacuation. Our modeling allowed us to provide demographic information classified into two broad age groups: <65 years of age, and ≥65 years, for each tsunami zone. In addition to basic demographic information, we further queried the American Community Survey (ACS) data products (U.S. Census Bureau, 2018, Table 1.1), in order to extrapolate additional information that may be useful for informing community tsunami education and evacuation planning. These included:

- 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 2014–2018 ACS 5-year estimates were based on data collected between January 1, 2014 and December 31, 2018. 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.

## 2.9 Model and Data Limitations

### 2.9.1 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 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.

### 2.9.2 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 by 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.

Commercial movers provide guidelines for estimating the weight of a typical household content (e.g., https://www.isapa.org/estimate-weight-household-goods-moving/). 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 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.

### *2.9.3* 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 occurs following large disasters and results in higher costs to repair building damage compared with comparable damage observed in smaller disasters (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.

### 2.9.4 Population models

Estimates of the permanent population in the tsunami zone are derived from U.S. Census data collected in 2010 and ACS data maintained by the U.S. Census Bureau. This approach differs from the approach of Bauer and others (2020), which used Oregon Department of Motor Vehicle records to identify the number of permanent people in the tsunami zone.

**Table 2-4** presents results for four communities where we can compare the approach of Bauer and others (2020) and the approach developed here, which incorporated both ACS data and U.S. 2010 census data. With respect to defining the population, **Table 2-4** highlights two differences. First, both approaches yield comparable permanent population numbers in the communities of Gearhart and Rockaway Beach. This is due entirely to the fact that both these communities are virtually completely inundated under the XXL1 scenario, the extent of which is comparable to the boundaries of the CBG. Hence the values reported are similar. In contrast, **Table 2-4** indicates that the CBG results for the permanent population in Lincoln City and Newport are significantly (~20% to 40%) higher when compared with the DMV approach. There are three possible explanations for this: first, it may be a function of both communities having narrow inundation zones (having been built on high ground) with large portions of the communities outside of the tsunami zone. Thus, the CBGs in these areas account for people located outside of the tsunami zone. Hence, the process of distributing the permanent population across the UDFs based on those buildings in the tsunami zone may be overestimating the number of people actually residing in the tsunami zone. Second, it may be a function of the ACS data having more up-to-date population statistics, though this seems less likely given that DMV records should provide a good representation of numbers of people residing in both communities. Third, it is possible that Bauer and other (2020) may have undercounted the number of people residing in Lincoln City and Newport.

Estimates of the number of temporary population in each of the four communities (**Table 2-4**) and defined for this study are generally lower, when compared with the Bauer and others (2020) approach. The Lincoln City visitor population was substantially lower, a 45% decrease. The reason for this change is primarily due to the number of people assigned to each room/unit. Bauer and others (2020) used a value of three people per room for Lincoln City; this was the preferred choice by community planners. However, for the purposes of this study, we chose to use a standard value of two people per room. Despite the lower numbers of temporary visitors observed in our latest population modeling and given the large uncertainty in the numbers of visitors in any given community on any given day, we remain confident in our overall estimates of potential visitor numbers in coastal Lincoln County.

**Table 2-4. Comparison of the Bauer and others (2020) population model approach with the approach used in this study.**

| Community | Bauer and others (2020) (DMV Records) | | This Study (Census Block Group [CBG] Approach) | | Population Difference | | Building Count | | |
|---|---|---|---|---|---|---|---|---|---|
| | Permanent | Temporary[1] | Permanent | Temporary | Permanent | Temporary | XXL | Entire CBG[2] | Difference[3] |
| Gearhart | 1,495 | 5,459 | 1,447 | 4,532 | −3 % | −20 % | 1,651 | 1,961 | 310 |
| Rockaway Beach | 1,440 | 7,592 | 1,503 | 6,642 | 4 % | −14 % | 2,372 | 4,056 | 1,684 |
| Lincoln City | 2,154 | 11,844 | 2,692 | 8,167 | 20 % | −45 % | 2,523 | 8,499 | 5,976 |
| Newport | 1,161 | 7,171 | 2,002 | 6,161 | 42 % | −16 % | 1,642 | 8,394 | 6,752 |

Notes:

[1] The temporary population modeling script used by Bauer and others (2020) differed slightly from the present study. In Bauer and others, Lincoln City was assigned three people/bedroom when estimating the temporary population. In the present study we assign two people/bedroom for all communities.

[2] This is the total building count within all CBGs that intersected the community boundary.

[3] Difference in both building counts.

The potential for inaccurate population data in a census block group, including undercounting by Bauer and others (2020), is probably the most likely explanation for differences observed in **Table 2-4**. Inaccurate data may be a function of building UDFs not having been fully evaluated for attribute accuracy, leading to over- or under-counting of the local population. In the approach developed here, great care was taken to evaluate building attributes within the XXL inundation zone. The specific steps followed are:

1. Is the building a residential occupancy type? If it is, then it contains residents;
2. What type of residential building is it? For example, if it is a multi-family building such as an apartment it likely contains both permanent and temporary residents, but if it is a hotel then it only contains temporary residents; and,
3. What is the square footage of the building? Depending on the occupancy type, the square footage determines the number of units/rooms, which then influences the number of residents estimated to live there.

Manually checking the many thousands of buildings outside of the tsunami zone is challenging. An example of how the population statistics may be skewed is described here. Consider an apartment building housing 200 permanent residents that is located fractionally outside the tsunami zone but within a census block group; the latter includes an area both within and outside the tsunami zone. Because the apartment building is located outside of the tsunami zone it may have been skipped for further evaluation. However, because the apartment is included in the census block group, those 200 people are inadvertently counted as residing in the tsunami zone.

Continuing with this example, let us say that the apartment building was categorized as a hotel and no permanent residents were assigned to it. Now those 200 permanent residents, which are part of the CBG total, are distributed elsewhere in the CBG, skewing the results in other locations.

Other possible ways in which inaccurate population modeling may occur include:

1. A building is not categorized as a residential building – that means no residents are assigned to it.
2. The square footage is incorrect – that means that either more people or fewer people will be assigned to the building than is realistic.

In summary, although great care was taken to evaluate building UDF attributes, especially those adjacent to the tsunami zone boundary that could potentially skew the population statistics (e.g., multi-family residential), it is possible some of these buildings were misattributed.

Our assignment of 0.318 children for every adult between 18 and 64 years of age (described by Bauer and others [2020, Appendix B]) may either overestimate or underestimate actual numbers. Temporary resident estimates and age demographics were based on several key assumptions as described by Bauer and others (2020) and are without doubt the largest challenges when specifying the visitor population on any given day. Finally, our population model does not account for people living in the tsunami zone who are experiencing homelessness. Homeless encampments are likely present within the tsunami zone of many Oregon coastal communities.

### 2.9.5 Hazus tsunami casualty model

The Hazus evacuation modeling assumes the following responses:

1. Everyone in the tsunami zone will evacuate on foot at some time after the ground stops shaking;
2. Their exit from the building is unimpeded;
3. They take the most optimal route to safety; and,
4. Their evacuation speed is not limited by congestion from fellow evacuees or vehicles or the presence of obstacles on roads and trails.

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 (Johnston 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 roads and trails is likely to be affected by building debris produced by the ground shaking strewn onto roadways and sidewalks, deformed roads, and trails due to lateral spreading due to liquefaction, the presence of liquefaction sand boils, and downed power lines. 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 intact docks and dock ramps. Neither seiching within enclosed marinas nor potential damage to the dock or its walkway to dry land is modeled.

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 evacuation of damaged buildings 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.

Although one can identify shortcomings with the FEMA Hazus tsunami modeling, 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 starting points and not an end point for tsunami risk-reduction discussions" (Wood and Schmidtlein, 2013, p. 1,625).

# 3.0 RESULTS

This section presents results of the Hazus analysis used to quantify earthquake and tsunami related impacts (i.e., building damage, debris, injuries, fatalities, etc.) for communities along the Lincoln County coastline. Each community is characterized by diverse population demographics, historical and contemporary development patterns, socioeconomic characteristics, tsunami risk, and bathymetric, topographic, and geologic circumstances that influence evacuation potential and building damage. These factors in turn influence community preparation, response, and, ultimately, recovery following a CSZ earthquake and tsunami.

## 3.1 Population Demographics

Summary population and demographic information for coastal Lincoln County is presented in **Table 3-1** and **Figure 3-1**. Both present the permanent population within each community's tsunami zone and include a conservative estimate of the temporary population that may also be present. As a reminder, the temporary population is derived from a summer 2 AM weekend scenario that maximizes visitor occupancy (i.e., assumes 100% occupancy in all hotel/motels, vacation homes and camping spots). Examination of **Table 3-1** indicates the following results:

1. The total permanent resident population present on the Lincoln County coastline within a tsunami zone ranges from ~4,220 (M1) to ~11,470 (XXL1) (**Table 3-1**). Including the temporary population suggests that the coastal population could increase to ~16,700 (M1) to ~42,000 (XXL1) assuming 100% occupancy. Such a dramatic increase in the local population is indicative of the large number of vacation homes, hotel/motels, and campgrounds distributed along coastal Lincoln County;
2. As expected, the numbers of permanent and temporary residents within each tsunami zone increase as the tsunami inundation zone increases (i.e., from M1 to XXL1, **Figure 3-1**);
3. The fraction of the total permanent resident population within the three tsunami zones varies widely between communities and parks (**Figure 3-1**). For example, Beverly Beach State Park, Beachside park, and Tillicum campground are mostly located in the M1 tsunami zone, and 100% within the L1 and XXL1 tsunami zones (**Table 3-1**). The communities of Gleneden Beach, Bayshore, Yachats, and to a lesser extent Waldport each have relatively large numbers of people located in the XXL1 tsunami zone; respectively 75%, 74%, 77% and 53%. Within the L1 zone, Yachats has 60% of its population in the tsunami zone, Bayshore (58%), and Waldport (44%). For the M1 scenario, communities with the largest number of people in the tsunami zone include Bayshore (44%), Waldport (37%), and Yachats (27%). Thus, the communities of Bayshore and Waldport are especially vulnerable since they have a relatively large proportion of their permanent (and visitor) population in all three tsunami zones.

4. The communities of Newport, Depoe Bay, and especially Otter Rock have relatively few people in the various tsunami zones (**Figure 3-1**, *center* plot). These findings are due to all three communities being largely perched on marine terraces and therefore are elevated relative to the tsunami inundation zone as well as the distribution of permanent residents within the communities. Similarly, Toledo has few people in the tsunami zones (M1 = 1%, L1= 2%, XXL1 = 5%), due to the community being located well up the Yaquina estuary such that the tsunami has lost much of its energy as it travels up the estuary and river; and,
5. Each of the Lincoln County communities can experience very large influxes of visitors, well exceeding their local resident populations (**Table 3-1** and **Figure 3-1**, *right* plot). Of note, the community of Gleneden Beach can swell by ~760% to 600% (M1 to XXL1), Lincoln City can increase by ~400% (M1 to XXL1), and Yachats by ~660% to 420% (M1 to XXL1). Accordingly, **Figure 3-1** demonstrates the importance each of these communities as major tourist destinations with potentially large numbers of visitors located in the tsunami zones. Accompanying their popularity as centers of tourism, are challenges associated with preparing such a large transient population for a CSZ earthquake and tsunami.

**Table 3-2** and **Figure 3-2** differentiate the local population by age group (<65 and ≥65 years of age). These results have an important bearing on the ability of people to evacuate quickly, specifically as it relates to the speed at which people may be able to travel to reach safety; recall that the evacuation speed for those ≥65 is reduced by 20% (a 0.8 walking speed reduction factor, see section 2.6.2.4). Thus, communities with larger numbers of people ≥65 years of age may want to consider evaluating 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 countywide resident population ≥65 is ~27% of the total population in the M1 tsunami zone, increasing to 30% for XXL1; this equates to ~1,280, 1,930, and 3,620 Lincoln County residents in the M1, L1, and XXL1 zones who are ≥65 years of age. However, the actual number of people age ≥65 and older varies from one community to another, with the community of Gleneden Beach having the largest number (52%) of people ≥65 in the various tsunami inundation zones (**Table 3-2**), followed by Lincoln Beach (~40%); Seal Rock has 45% of people ≥65 in the L1 and XXL1 tsunami zones.

## 3.2 Building Damage and Debris

The number of residents (permanent and temporary) per building occupancy type and within the XXL1 tsunami zone is provided for each community in **Table 3-3** and summarized graphically in **Figure 3-3**. Apparent from both the table and figure are notable differences in where people live or visit among the communities. Permanent residents overwhelmingly reside in single-family dwellings, especially in the communities of Bayshore (95%), Gleneden Beach (87%), and Seal Rock (84%). Multi-family residential buildings in the XXL tsunami zone are more common in Otter Rock (100%), Newport (50%) and Depoe Bay (39%), and to a lesser extent at Waldport (26%). Countywide averages reflect the following: single-family residential (72%), manufactured housing (11%), multi-family residential (16%), and other (dorms, retirement homes, and summer camps) make up the remainder (1%).

There are notable differences between the communities with respect to temporary residents. For example, hotel/motel availability is highest in Depoe Bay (46%), followed by Lincoln City and Newport (35%), and Toledo (21%, **Table 3-3**, **Figure 3-3**). However, what is most notable from **Figure 3-3** are the large numbers of single-family residential rental units or vacation homes (e.g., VRBO or Airbnb) available throughout coastal Lincoln County. For example, large numbers (>70%) of second homes dominate Bayshore, Gleneden Beach, and Lincoln Beach and are used for vacation purposes. Similarly, Lincoln City (48%), Seal Rock (64%), and Yachats (68%) also stand out with respect to having large numbers of vacation homes. Excluding Beverly Beach State Park, South Beach State Park, Beachside, and Tillicum campgrounds, RV and tent sites are most abundant in Seal Rock (31%), Newport (19%), and Waldport (19%).

An evaluation of the number of permanent and temporary residents residing in single-family residential buildings in coastal Lincoln County communities is further explored in the final two columns of **Table 3-3**. We focus on single-family residential buildings because they are the dominant housing type on the Oregon coast (Bauer and others, 2020) and account for a potentially large group of vacationers that may not be directly exposed to tsunami awareness material or evacuation guidance that is at least occasionally found in hotels, motels, and campgrounds. As can be seen in **Table 3-3**, the countywide ratio of permanent residents to single-family homes averages ~1.2, while the ratios for several individual communities (e.g., Gleneden Beach, Lincoln Beach, and Yachats) fall below the 1.2 threshold. This suggests that for these communities, there is a surplus of single-family residential homes relative to the actual permanent population in those communities. Thus, in these communities the surplus single-family dwellings are likely to be either second homes or vacation homes. In contrast, at Otter Rock, Bayshore, Seal Rock, and Newport the ratio of permanent and temporary visitors increases to ≥3.4, indicating that the local population in each of these communities may grow significantly as visitors (predominantly vacationers) stay in those destinations. Thus, larger ratios suggest more beds thereby highlighting those communities that are more likely to be major recreation destinations. In addition, the results demonstrate the importance of vacation homes, especially during a summer weekend when visits to the coast tend to be maximized compared with the baseline that considers just the permanent residents; compare last two columns of **Table 3-3**. The highest permanent and temporary population relative to the number of single-family residential homes observed occurs at Otter Rock (4.95) and Bayshore (4.1). Hence, the local community may at times have an extremely large visitor population that may not be aware of the Cascadia tsunami hazard, let alone be prepared to deal with such an event.

Integral to pre- and post-disaster planning is knowledge of what will happen to buildings in the various communities as a result of earthquake ground motion and subsequent tsunami forces. These data are presented in **Table 3-4**; note **Table 3-4** also includes estimates of the broader community-wide earthquake related damage expected to occur both inside and outside the tsunami zone. **Figure 3-4** summarizes graphically the results of **Table 3-4**.

The number of buildings located in each of the three tsunami zones is provided in the second through fourth columns of **Table 3-4** and plotted as bar graphs in **Figure 3-4** *(upper left*). Not surprisingly, the communities of Lincoln City, Gleneden Beach, Newport, and to a lesser degree Waldport have the largest numbers of buildings located in a tsunami zone. Nevertheless, the largest number of buildings across the entire county falls within the "other" category (~3,570). The bulk of this latter group are residential buildings established along the open coast outside of community boundaries, as well as along the shores of each of the estuaries. At Waldport, Bayshore, and to a lesser extent Yachats, the relatively small change between M1 and XXL1 is indicative of the fact that virtually the entire community is inundated by tsunami in all three scenarios, such that the exposure risk at these sites is especially high.

Building replacement costs (assuming complete destruction) are shown in **Figure 3-4** (*upper right*) for each of the tsunami zones. Lincoln City ($690 million), along with Newport ($637 million) and "other" ($460 million) indicate significant building value in the XXL1 tsunami zone. Countywide building replacement costs for each tsunami zone total $1.1 billion (M1), $1.6 billion (L1), and $2.7 billion (XXL1) (**Table 3-4**).

Damage caused by earthquake shaking is presented in **Figure 3-4C** for each tsunami zone, along with the community-wide earthquake-related damage (cyan bars); the latter data thus reflect earthquake damage across the entire community urban growth boundary. As can be seen in **Table 3-4**, the costs associated with earthquake damage are estimated to range from ~$360 million (M1) to ~$730 million (XXL1), across the three tsunami zones. **Table 3-4** and **Figure 3-4** show discrete community damage losses range from a high of $235 million in Newport to ~$7 million in Seal Rock, with the state parks and recreation areas showing damage levels that are in the tens of thousands; earthquake damage losses in areas beyond the specified communities (other category) are estimated to reach $124 million.

The countywide earthquake damage losses outside the tsunami zones are the difference between losses inside a tsunami zone and the countywide totals (may be determined from **Table 3-4**); this equates to ~$1.7 billion (M1), $1.57 billion (L1), and $1.33 billion (XXL1) in losses outside of the tsunami zones. These data become important when considering the total damage losses caused by the combined tsunami and earthquake damage losses. The decrease in damage losses outside the tsunami zones is indicative of the increasing inundation (and tsunami caused damage) as one moves from M1 to XXL1.

Combined earthquake and tsunami damage for each tsunami zone is included in **Table 3-4** and **Figure 3-4D**. These results indicate losses that range from ~$690 million (M1) to ~$2.2 billion (XXL1) across the county. Factoring in the additional earthquake losses outside the tsunami zones and described above, our analyses indicate that Lincoln County could experience ~$2.4 billion in damage for an M1 scenario, $2.8 billion for L1, and $3.5 billion for an XXL1 size event. Note that these estimates exclude building content losses and damage to roads such that these totals may be viewed as minimal estimates. At the community level, Newport experiences the largest combined losses (i.e., inside and outside the tsunami zone), which reaches ~$940 million, followed by Lincoln City at ~ $810 million.

As can be seen from the earthquake building loss ratio (**Table 3-4**), earthquake damage accounts for about two thirds of the total building damage in Lincoln County. Significant building damage due to earthquake shaking is observed in Toledo, Newport, and Seal Rock—probably a function of a combination of factors including ground failure through liquefaction and lateral spreading, and the presence of older building structures.

Incorporating damage caused by the tsunami results in destruction levels for an M1 event that range from ~18% (Tillicum Campground) to 91% at Waldport (**Figure 3-4E**; destruction levels for an M1 event are especially high in Lincoln City (~63%), Depoe Bay (75%), Newport (63%), and Bayshore (64%). For a maximum considered XXL1 size event, **Table 3-4** indicates > 84% destruction in several areas, including Yachats, Waldport, Newport and Gleneden Beach. Lowest destruction levels are generally observed in a few remote areas (e.g., Toledo, ~42% destruction) and in those communities perched high on marine terraces (e.g., Lincoln Beach and Depoe Bay) where many buildings are located outside of the tsunami zone. Significant destruction at Yachats, Waldport, Newport, and Gleneden Beach is indicative of the large hydraulic forces associated with the tsunami and the prevalence of light-frame construction material (i.e., wood frame) on the Oregon coast. Combined earthquake and tsunami damage in Lincoln County averages ~50% destroyed in the M1 event, 64% in the L1 event, and 82% in the XXL1 event. Although not included in **Table 3-4**, our Hazus analyses indicate that of the total number of buildings assessed here for coastal Lincoln County, 18% will be completely destroyed, 16% will experience extensive damage, and 23% of the buildings are expected to suffer moderate damage. Thirty-one per cent of the remaining buildings will experience slight damage, while ~11% are expected to experience no damage.

Finally, **Table 3-4** and **Figure 3-4F** indicate that the weight of debris generated countywide could range from ~239,000 tons (M1) to ~705,000 tons (XXL1). This equates to ~24,000 dump trucks for M1 to as much as 70,000 dump trucks for an XXL1 event. These estimates are almost certainly on the low end, as they do not include debris associated with content from buildings (personal items, business equipment, etc.), road rip-ups, vehicles, and vegetation. If we assume an additional 5 tons of personal items as debris per residential building (typical for most residential buildings), this adds ~6% additional weight to the building debris estimates provided in **Table 3-4**.

**Table 3-1. The number of residents in the tsunami-hazard zone for coastal communities in Lincoln County, Oregon, based on census block and tsunami-hazard data.**

| Community | Total Permanent Resident Population | Combined Population (Permanent + Temporary[1]) | Number of Permanent Residents | | | Permanent Residents (%)[2] | | | Number of Temporary Residents[1] | | | Permanent + Temporary Percent (%) Increase | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Medium | Large | XX-Large | Medium | Large | XX-Large | Medium | Large | XX-Large | Medium | Large | XX-Large |
| Lincoln City | 9,322 | 26,550 | 1,119 | 1,520 | 2,693 | 12 | 16 | 29 | 3,587 | 5,184 | 8,167 | 18 | 25 | 41 |
| Gleneden Beach | 1,015 | 5,225 | 96 | 192 | 648 | 10 | 19 | 64 | 641 | 1,255 | 3,295 | 14 | 28 | 75 |
| Lincoln Beach | 662 | 2,310 | 49 | 82 | 287 | 7 | 12 | 43 | 118 | 230 | 807 | 7 | 13 | 47 |
| Depoe Bay | 1,725 | 3,965 | 11 | 32 | 470 | 1 | 2 | 27 | 8 | 58 | 955 | 0 | 2 | 36 |
| Otter Rock | 299 | 1,403 | 0 | 2 | 5 | 0 | 1 | 2 | 0 | 3 | 10 | 0 | 0 | 1 |
| Beverly Beach State Park | 0 | 873 | 0 | 0 | 0 | — | — | — | 766 | 873 | 873 | 88 | 100 | 100 |
| Newport | 10,960 | 21,592 | 796 | 986 | 1,945 | 7 | 9 | 18 | 1,952 | 2,428 | 4,304 | 13 | 16 | 29 |
| South Beach State Park | 0 | 1040 | 0 | 0 | 0 | — | — | — | 242 | 1040 | 1040 | 23 | 100 | 100 |
| Siletz | 1,283 | 1,451 | 0 | 0 | 0 | — | — | — | 0 | 0 | 0 | — | — | — |
| Toledo | 3,453 | 4,446 | 19 | 73 | 168 | 1 | 2 | 5 | 3 | 15 | 40 | 1 | 2 | 5 |
| Seal Rock | 381 | 1,044 | 0 | 17 | 84 | 0 | 4 | 22 | 0 | 78 | 350 | 0 | 9 | 42 |
| Bayshore | 1,171 | 3,683 | 497 | 653 | 823 | 42 | 56 | 70 | 1,127 | 1,492 | 1,891 | 44 | 58 | 74 |
| Waldport | 2,146 | 3,610 | 677 | 768 | 936 | 32 | 36 | 44 | 655 | 806 | 982 | 37 | 44 | 53 |
| Beachside State Recreation Site | 0 | 238 | 0 | 0 | 0 | — | — | — | 238 | 238 | 238 | 100 | 100 | 100 |
| Tillicum Beach Campground | 0 | 196 | 0 | 0 | 0 | — | — | — | 90 | 196 | 196 | 46 | 100 | 100 |
| Yachats | 847 | 3,285 | 135 | 407 | 611 | 16 | 48 | 72 | 754 | 1,571 | 1,934 | 27 | 60 | 77 |
| Other[3] | 14,617 | 26,365 | 823 | 1,475 | 2,797 | 6 | 10 | 19 | 2,333 | 3,597 | 5,461 | 12 | 19 | 31 |
| Lincoln County Total | 47,881 | 107,277 | 4,223 | 6,206 | 11,468 | 11 | 18 | 35 | 12,512 | 19,066 | 30,543 | 27 | 39 | 54 |

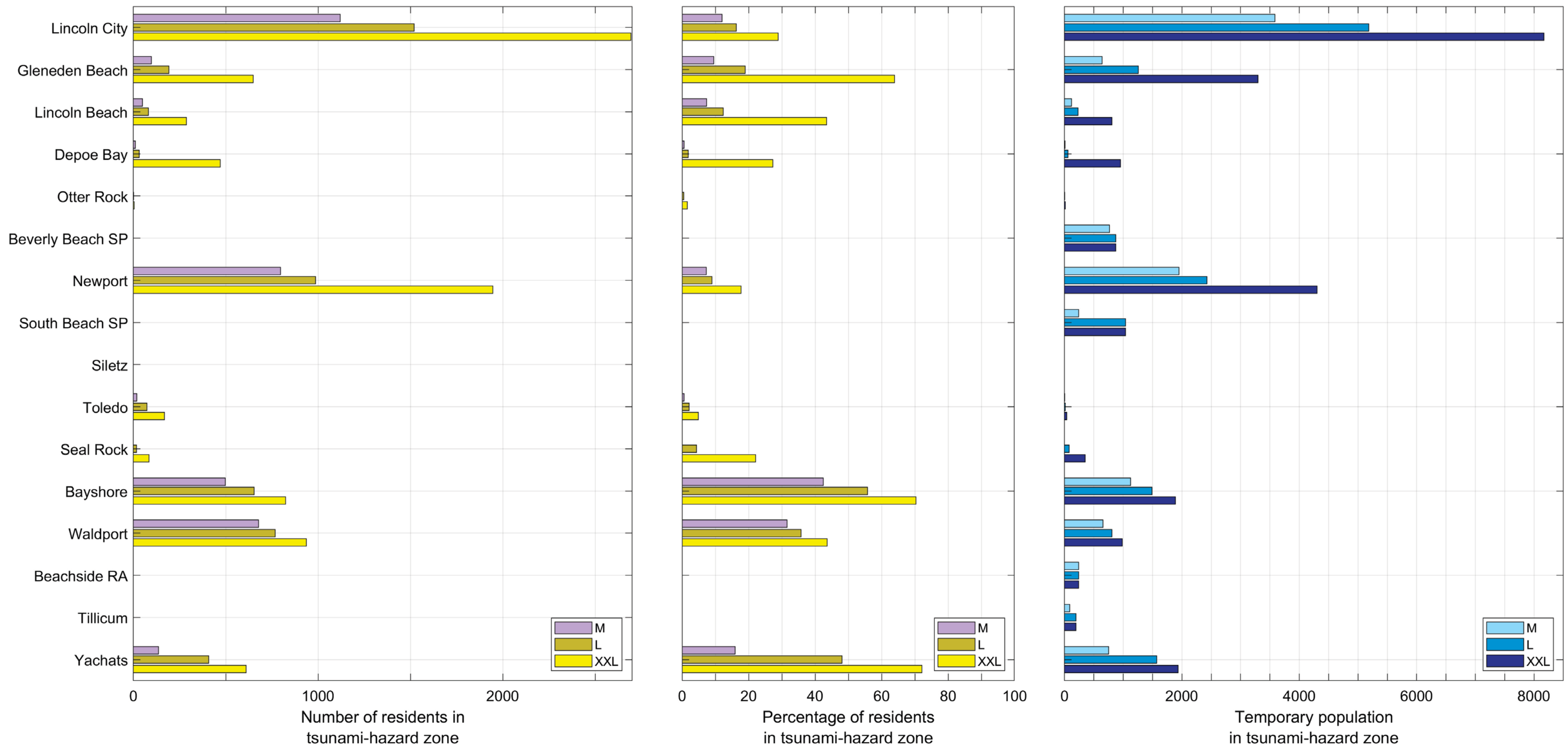
Notes:

[1] Assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

[2] Expressed as a proportion of the total resident population.

[3] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Figure 3-1. (left) The number and (center) percentage of permanent residents (right) and temporary (visitor) populations by community in the tsunami-hazard zones.**




Notes:

Percentage of residents expressed as a proportion of the total resident population.

Temporary population estimate assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

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

| Community | Medium | | | Large | | | XX-Large | | |
|---|---|---|---|---|---|---|---|---|---|
| | <65 | ≥65 | Older Age Ratio[1] | <65 | ≥65 | Older Age Ratio[1] | <65 | ≥65 | Older Age Ratio[1] |
| Lincoln City | 871 | 248 | 22% | 1,153 | 367 | 24% | 1,980 | 713 | 26% |
| Gleneden Beach | 47 | 50 | 52% | 93 | 100 | 52% | 313 | 335 | 52% |
| Lincoln Beach | 30 | 19 | 39% | 50 | 32 | 39% | 173 | 114 | 40% |
| Depoe Bay | 7 | 4 | 35% | 20 | 11 | 35% | 304 | 166 | 35% |
| Otter Rock | 0 | 0 | 0% | 1 | 0 | 24% | 4 | 1 | 24% |
| Beverly Beach State Park | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Newport | 539 | 257 | 32% | 673 | 313 | 32% | 1,397 | 549 | 28% |
| South Beach State Park | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Siletz | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 0 | 0% |
| Toledo | 16 | 3 | 16% | 61 | 11 | 16% | 141 | 27 | 16% |
| Seal Rock | 0 | 0 | 0% | 9 | 7 | 45% | 47 | 38 | 45% |
| Bayshore | 324 | 173 | 35% | 425 | 227 | 35% | 537 | 287 | 35% |
| Waldport | 453 | 224 | 33% | 515 | 253 | 33% | 631 | 305 | 33% |
| Beachside State Recreation Site | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Tillicum Beach Campground | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Yachats | 97 | 38 | 28% | 291 | 116 | 28% | 437 | 173 | 28% |
| Other[2] | 557 | 266 | 32% | 989 | 487 | 33% | 1,882 | 915 | 33% |
| Lincoln County Total | 2,939 | 1,284 | 27% | 4,281 | 1,925 | 30% | 7,845 | 3,623 | 30% |

Notes:

[1] Ratio of ≥65 relative to total resident population.

[2] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Figure 3-2. Local resident population demographics. Example provided is for the XXL1 tsunami zone.**

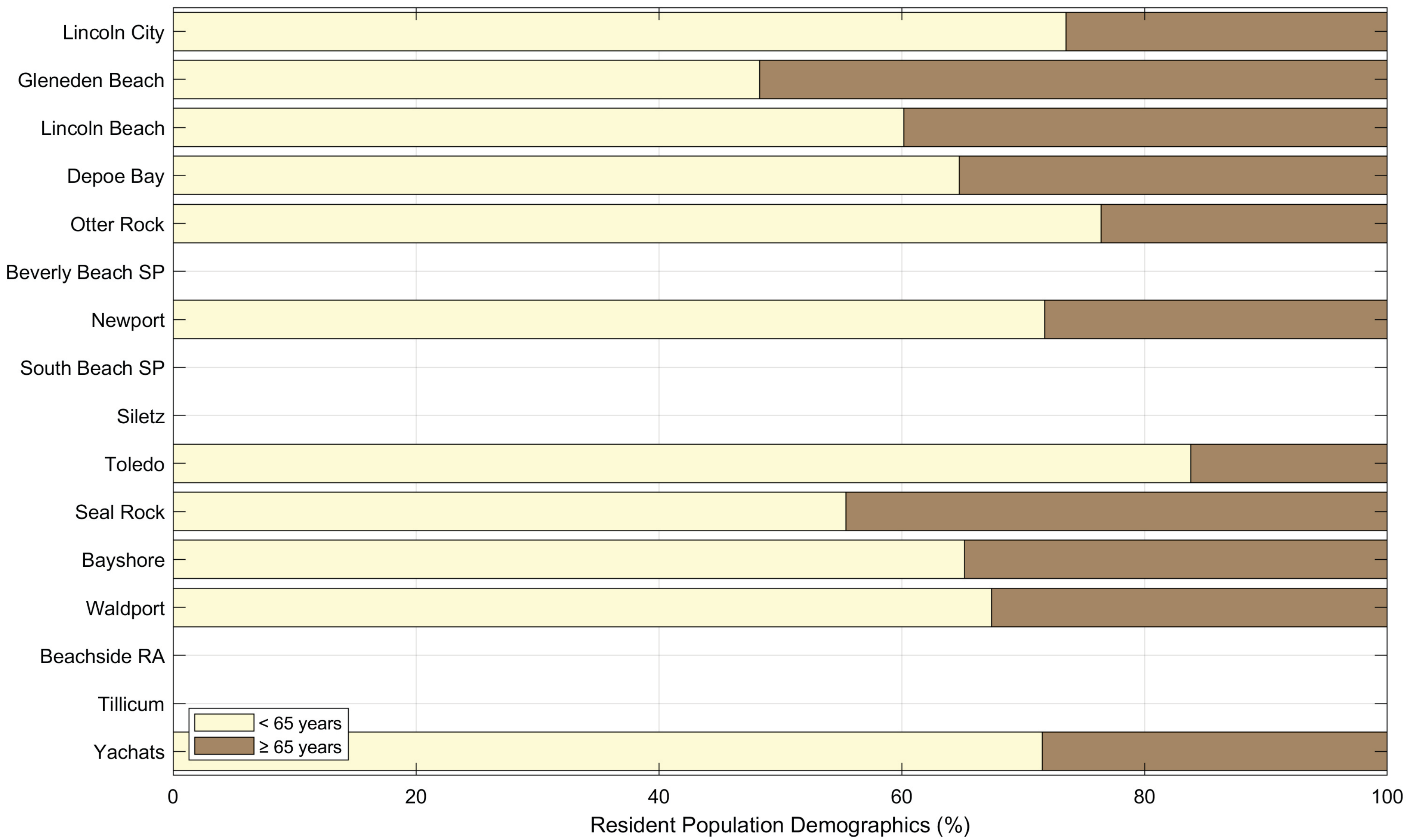


**Table 3-3. Number of residents (permanent and temporary) per building occupancy type per community in the XXL1 tsunami zone. P is permanent and T is temporary population.**

| Community | Total Number of Single-Family Residential Homes | Number of Residents | | | | | | | | | | | | | | Ratio of Permanent Residents Relative to Number of Single-Family Residential Homes | Ratio of Permanent and Temporary Residents Relative to Number of Single-Family Residential Homes, Summer Weekend |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Single-Family Residential | | Manufactured Housing | | Multi-family Residential | | Hotel/ Motel | | Mobile[1] | | Other[2] | | Total[3] | | | |
| | | P | T | P | T | P | T | P | T | P | T | P | T | P | T | | |
| Lincoln City | 1,947 | 1,874 | 3,890 | 251 | 105 | 567 | 660 | 0 | 2,839 | 0 | 673 | 0 | 0 | 2,693 | 8,167 | 1.09 | 3.14 |
| Gleneden Beach | 1,082 | 563 | 2,820 | 59 | 109 | 27 | 117 | 0 | 78 | 0 | 171 | 0 | 0 | 648 | 3,295 | 0.57 | 3.28 |
| Lincoln Beach | 298 | 171 | 554 | 59 | 76 | 58 | 126 | 0 | 51 | 0 | 0 | 0 | 0 | 287 | 807 | 0.77 | 2.88 |
| Depoe Bay | 192 | 266 | 336 | 23 | 11 | 182 | 166 | 0 | 442 | 0 | 0 | 0 | 0 | 470 | 955 | 1.50 | 3.31 |
| Otter Rock | 3 | 5 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 10 | 1.55 | 4.95 |
| Beverly Beach State Park | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 873 | 0 | 0 | 0 | 873 | NA | NA |
| Newport | 589 | 788 | 1,075 | 101 | 38 | 956 | 718 | 0 | 1,442 | 0 | 781 | 50 | 90 | 1,896 | 4,144 | 1.51 | 3.40 |
| South Beach State Park | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,040 | 0 | 0 | 0 | 1,040 | NA | NA |
| Siletz | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NA | NA |
| Toledo | 68 | 1,120 | 28 | 33 | 3 | 23 | 0 | 0 | 9 | 0 | 0 | 0 | 0 | 168 | 40 | 2.13 | 2.59 |
| Seal Rock | 84 | 71 | 225 | 12 | 9 | 2 | 7 | 0 | 0 | 0 | 109 | 0 | 0 | 84 | 350 | 0.98 | 3.76 |
| Bayshore | 647 | 783 | 1,841 | 29 | 27 | 11 | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 823 | 1,891 | 1.26 | 4.14 |
| Waldport | 463 | 467 | 496 | 223 | 50 | 246 | 64 | 0 | 182 | 0 | 190 | 0 | 0 | 936 | 982 | 1.49 | 2.67 |
| Beachside State RA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 238 | 0 | 0 | 0 | 238 | NA | NA |
| Tillicum Beach Campground | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 196 | 0 | 0 | 0 | 196 | NA | NA |
| Yachats | 549 | 469 | 1,318 | 32 | 35 | 66 | 77 | 0 | 503 | 0 | 0 | 44 | 0 | 611 | 1,934 | 0.91 | 3.38 |
| Other[4] | 2,345 | 2,125 | 3,700 | 484 | 284 | 42 | 48 | 0 | 181 | 0 | 1,088 | 0 | 0 | 2,651 | 5,301 | 1.11 | 2.81 |
| Lincoln County Total | 8,267 | 7,693 | 16,295 | 1,306 | 747 | 2,179 | 2,005 | 0 | 5,726 | 0 | 5,360 | 93 | 90 | 11,272 | 30,223 | 1.24 | 3.36 |

Notes:

[1] Mobile includes tents, boats, and recreational vehicles.

[2] Other includes dormitories, retirement villages and private camps.

[3] Aggregate of all permanent and temporary building occupancy types.

[4] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Figure 3-3. Community overview showing building occupancy type for (left) permanent and (right) temporary residents in the XXL1 tsunami zone.** ***(continued on next page)***

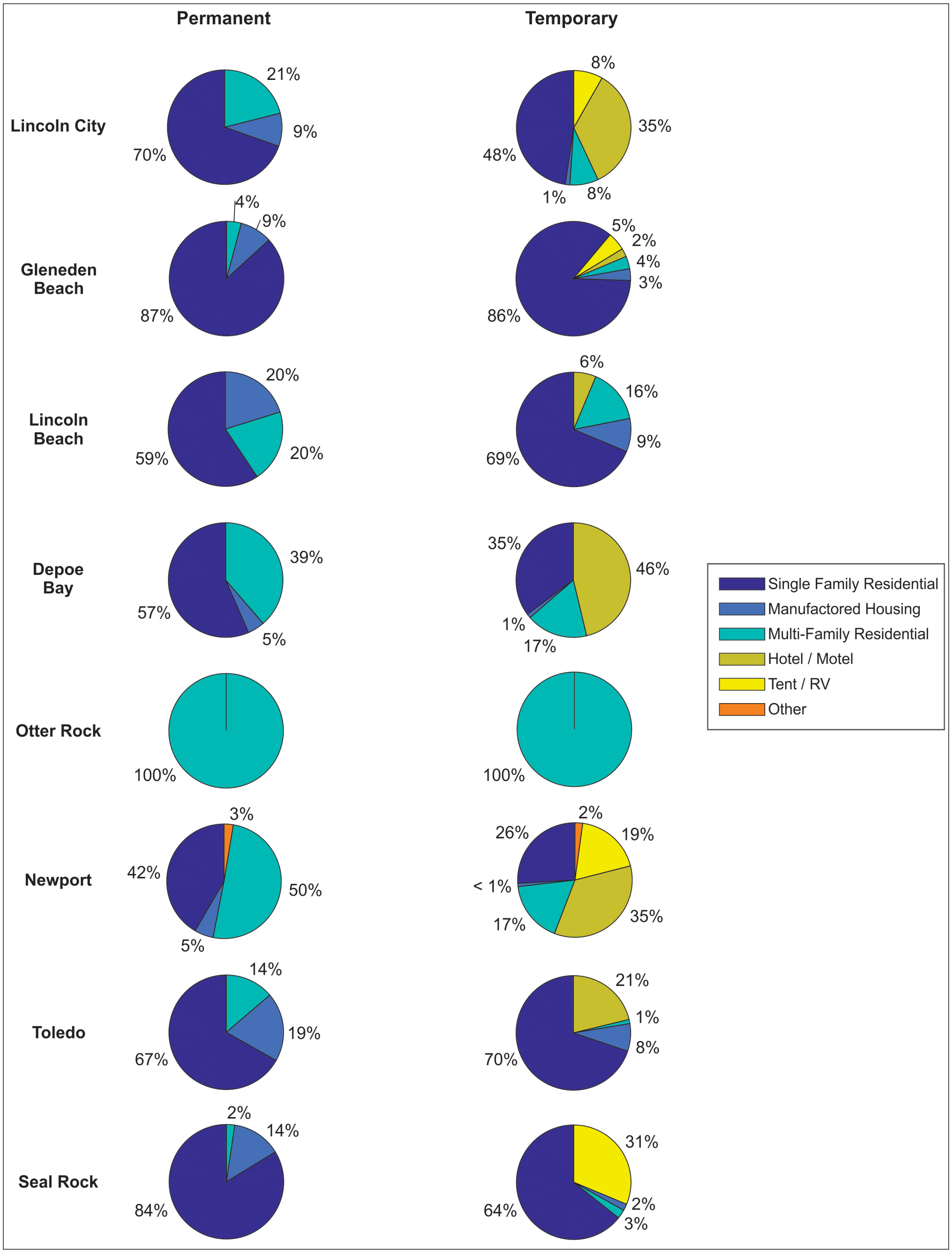


**Figure 3-3.** ***(continued)*** **Community overview showing building occupancy type for (left) permanent and (right) temporary residents in the XXL1 tsunami zone.**

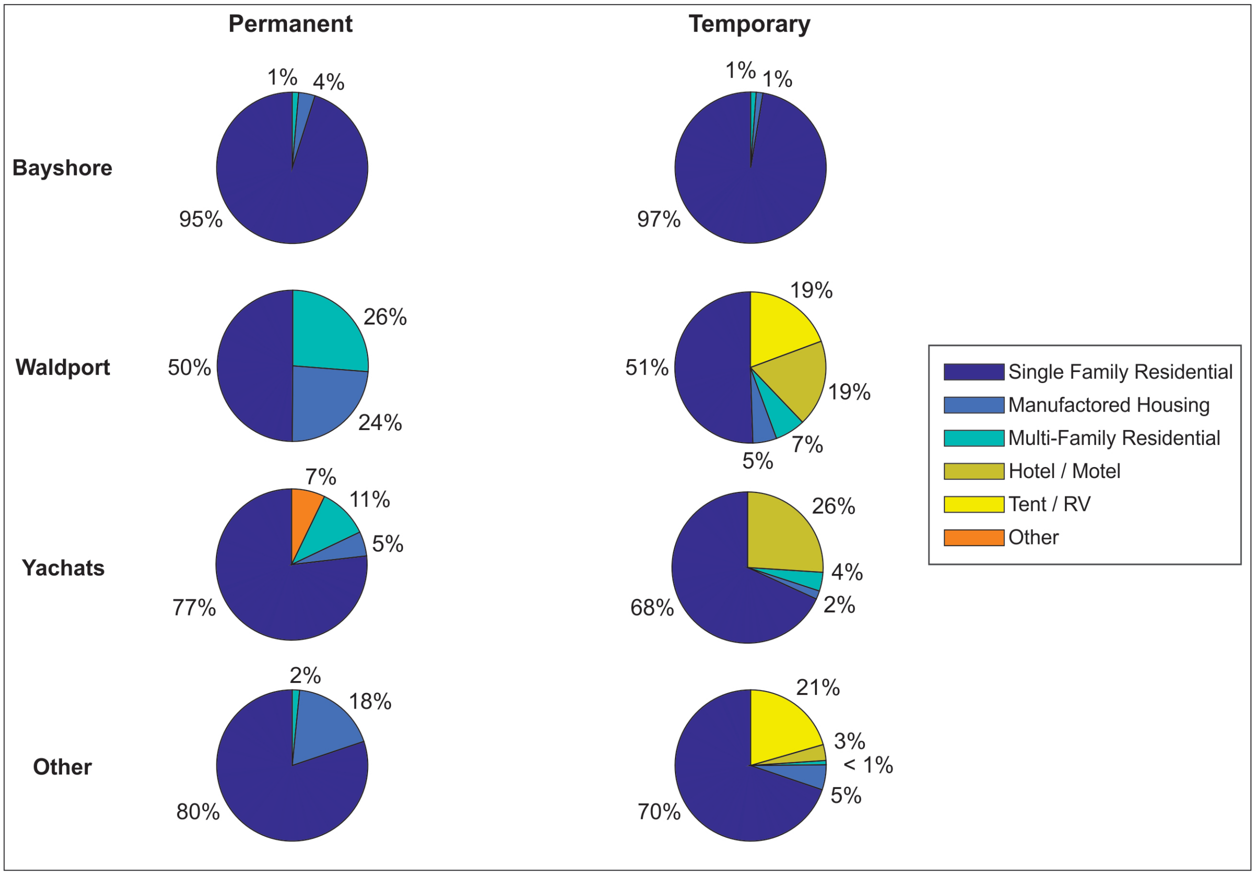


**Table 3-4. Earthquake- and tsunami-induced building damage and debris estimates by community.**

| | Number of Buildings by Tsunami Zone | | | Building Replacement Cost by Tsunami Zone[1] ($ Million) | | | Earthquake Building Loss by Tsunami Zone[2] ($ Million) | | | Earthquake Building Loss by Community[3] | | Combined Earthquake and Tsunami Building Loss by Tsunami Zone ($ Million) | | | Combined Earthquake and Tsunami Building Loss by Tsunami Zone (%) | | | Combined Earthquake and Tsunami Building Debris by Tsunami Zone (Tons) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Community** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **($ Million)** | **Building Loss Ratio** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** |
| Lincoln City | 902 | 1,290 | 2,314 | 281 | 406 | 690 | 61 | 91 | 127 | 396 | 57% | 176 | 307 | 542 | 63% | 75% | 79% | 45,565 | 80,791 | 142,766 |
| Gleneden Beach | 190 | 372 | 1,330 | 41 | 88 | 229 | 7 | 13 | 37 | 50 | 22% | 22 | 52 | 193 | 53% | 58% | 84% | 7,478 | 16,682 | 59,993 |
| Lincoln Beach | 27 | 81 | 340 | 10 | 17 | 53 | 1 | 3 | 9 | 31 | 59% | 2 | 5 | 25 | 20% | 27% | 48% | 287 | 1,210 | 9,209 |
| Depoe Bay | 12 | 29 | 342 | 3 | 7 | 123 | 2 | 2 | 27 | 60 | 49% | 3 | 4 | 61 | 75% | 53% | 49% | 1,108 | 1,756 | 18,778 |
| Otter Rock | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 24 | NA | 0 | 0 | 0 | 0% | 36% | 100% | 0 | 13 | 126 |
| Beverly Beach State Park | 13 | 15 | 15 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 88% | 2 | 3 | 3 | 88% | 100% | 100% | 749 | 929 | 930 |
| Newport | 489 | 644 | 1,059 | 381 | 442 | 637 | 161 | 187 | 235 | 621 | 97% | 240 | 393 | 554 | 63% | 89% | 87% | 87,255 | 128,240 | 174,021 |
| South Beach State Park | 1 | 10 | 10 | 0 | 2 | 2 | 0 | 2 | 2 | 2 | 97% | 0 | 2 | 2 | 0% | 100% | 100% | 0 | 726 | 721 |
| Siletz | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 34 | NA | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 |
| Toledo | 65 | 126 | 215 | 20 | 43 | 101 | 7 | 14 | 38 | 178 | 177% | 8 | 16 | 43 | 40% | 37% | 42% | 3,721 | 7,049 | 19,078 |
| Seal Rock | 0 | 22 | 136 | 0 | 3 | 20 | 0 | 0 | 7 | 15 | 76% | 0 | 1 | 16 | 0% | 28% | 79% | 0 | 190 | 6,131 |
| Bayshore | 416 | 551 | 692 | 61 | 81 | 102 | 8 | 10 | 13 | 19 | 19% | 39 | 70 | 99 | 64% | 86% | 96% | 11,882 | 20,830 | 29,343 |
| Waldport | 494 | 597 | 800 | 113 | 128 | 160 | 54 | 58 | 70 | 101 | 63% | 103 | 121 | 151 | 91% | 95% | 94% | 43,178 | 50,587 | 62,567 |
| Beachside RA | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | NA | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 |
| Tillicum Beach Campground | 1 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15% | 0 | 0 | 0 | 18% | 52% | 100% | 3 | 36 | 79 |
| Yachats | 168 | 542 | 748 | 50 | 108 | 152 | 10 | 26 | 42 | 50 | 33% | 15 | 64 | 139 | 29% | 59% | 92% | 4,494 | 19,891 | 43,039 |
| Other[4] | 1,223 | 2,060 | 3,567 | 165 | 272 | 460 | 48 | 82 | 124 | 475 | 103% | 82 | 175 | 377 | 50% | 65% | 82% | 33,020 | 67,084 | 137,830 |
| Lincoln County Total | 4,001 | 6,343 | 11,574 | 1,128 | 1,600 | 2,732 | 361 | 491 | 732 | 2,059 | 68% | 691 | 1,211 | 2,204 | 50% | 64% | 82% | 238,740 | 396,015 | 704,610 |

Notes:

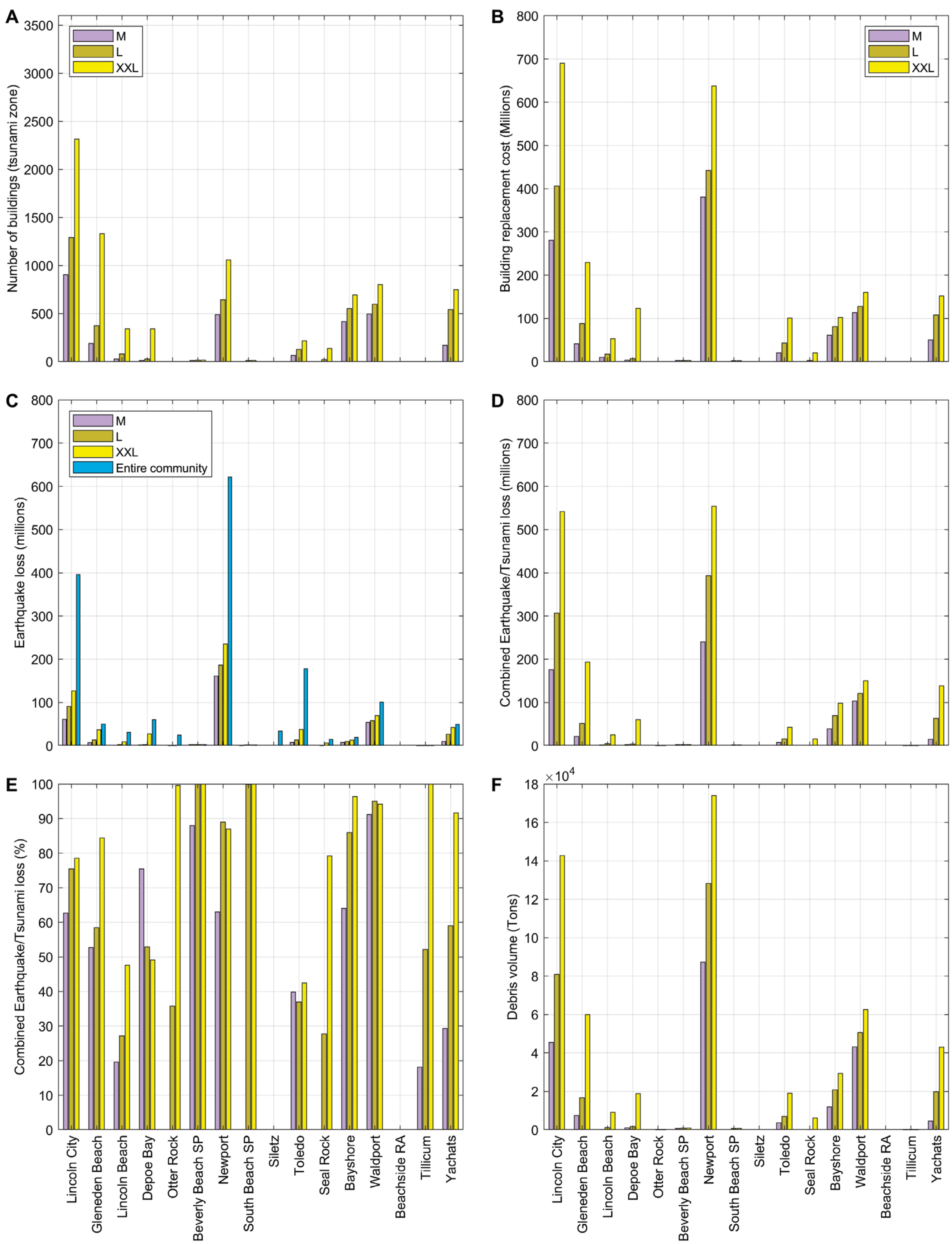
[1] Total cost to replace buildings in each tsunami zone;

[2] Earthquake building losses defined for each tsunami zone;

[3] Earthquake building losses defined for the entire community (inside and outside the tsunami zone);

[4] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Figure 3-4. Community overview showing (A) number of buildings per tsunami zone, (B) total replacement costs (millions), (C) earthquake losses (millions), (D) combined tsunami and earthquake losses (millions), also expressed as a (E) ratio, and (F) debris generated (weight).**



## 3.3 Earthquake-Caused Injuries and Fatalities

Our Hazus analyses indicate that injuries from a CSZ earthquake greatly outnumber fatalities (**Table 3-5**). Modeled injuries experienced by residents and visitors are expected to be highest in Newport and Lincoln City, followed by the "other" category. The latter numbers are of concern as these will be spread out over a very broad area. This will make it extremely challenging and time consuming to medivac the injured to appropriate field hospitals. Of the total number of injuries identified (~1,400), Hazus estimates ~300 people are likely to require hospitalization. The low fatalities (~50 combined) and injury estimates associated with the earthquake are likely due to the prevalence of wood frame construction. However, we note that even if injuries are minor, impacted persons may delay evacuation from a tsunami zone while they tend to injuries.

**Table 3-5. Earthquake-induced injuries and fatalities determined for each community and expressed as a total for the county.**

| | | Permanent Residents | | | | Temporary Residents | | | |
|---|---|---|---|---|---|---|---|---|---|
| Community Zone | Total Population[2] | Level 1 | Level 2 | Level 3 | Level 4 | Level 1 | Level 2 | Level 3 | Level 4 |
| Lincoln City | 26,550 | 83 | 19 | 2 | 3 | 154 | 38 | 5 | 9 |
| Gleneden Beach | 5,225 | 14 | 3 | 0 | 0 | 25 | 5 | 0 | 1 |
| Lincoln Beach | 2,310 | 14 | 4 | 0 | 0 | 24 | 6 | 1 | 1 |
| Depoe Bay | 3,965 | 24 | 6 | 0 | 1 | 23 | 6 | 1 | 1 |
| Otter Rock | 1,403 | 3 | 1 | 0 | 0 | 28 | 9 | 1 | 3 |
| Beverly Beach State Park | 873 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Newport | 21,592 | 122 | 29 | 3 | 5 | 119 | 31 | 4 | 8 |
| South Beach State Park | 1040 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Siletz | 1,451 | 22 | 5 | 0 | 1 | 2 | 0 | 0 | 0 |
| Toledo | 4,446 | 40 | 9 | 1 | 1 | 23 | 8 | 1 | 3 |
| Seal Rock | 1,044 | 5 | 1 | 0 | 0 | 4 | 1 | 0 | 0 |
| Bayshore | 3,683 | 6 | 1 | 0 | 0 | 14 | 3 | 0 | 0 |
| Waldport | 3,610 | 36 | 9 | 1 | 1 | 13 | 3 | 0 | 1 |
| Beachside RA | 238 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tillicum Beach Campground | 196 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Yachats | 3,285 | 9 | 2 | 0 | 0 | 27 | 7 | 1 | 2 |
| Other[1] | 26,365 | 194 | 45 | 3 | 5 | 88 | 21 | 2 | 4 |
| Total | 107,277 | 574 | 134 | 10 | 18 | 545 | 138 | 17 | 32 |

Notes:

See **Table 2-2** for a more complete description of Hazus defined injury levels. Level 1 denotes minor injuries, level 2 denotes injuries requiring hospitalization, level 3 denotes life threatening injuries, level 4 denotes fatalities.

[1] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

[2] Assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

## 3.4 Tsunami-Caused Injuries and Fatalities

Casualty numbers (injuries plus fatalities) attributed to a Cascadia tsunami are presented in **Table 3-6** and graphically in **Figure 3-5**. Overall, our Hazus modeling indicates that tsunami related casualties will greatly exceed earthquake related casualties, especially when accounting for the combined permanent resident and visitor populations. Of particular note, injuries caused by the tsunami average about 11% (±6%) of the total number of casualties, indicating that tsunami related deaths account for the bulk of the total number of casualties (**Table 3-7**). This is because the Hazus tsunami casualty model estimates that people who do not escape from the tsunami zone are much more likely to die than to be injured and survive. Those who are injured are largely confined to a small narrow band where the tsunami flow depth falls below 6 feet (see Section 2.6.2.5).

As can be seen in **Table 3-6** and **Figure 3-5**, modeled tsunami casualties vary widely between the communities. This is due to many factors, but most important is the relative distance to high ground. For the M1 scenario, estimated casualties are confined mainly to three communities: Lincoln City (~90 resident/120 visitor), Gleneden Beach (~30 resident/190 visitor), and Bayshore (~20 resident/40 visitor). Hence, for the M1 tsunami scenario, our Hazus modeling suggest either few or no casualties in the remaining Lincoln County communities; note that these latter estimates fall within the margin of error in the Hazus modeling. Aside from the previously mentioned communities located at the open coast, low casualty numbers determined for the M1 scenario is indicative of the fact that most of the communities are:

1) built on high ground (e.g., marine terraces at Newport); or
2) high ground is located close to the population centers allowing for quick access out of the inundation zone; or,
3) are located well up the estuaries (e.g., Toledo and Siletz) such that the M1 event does not reach them.

The number of casualties associated with the maximum-considered XXL1 tsunami scenario increase dramatically, ranging from no expected casualties (e.g., Depoe Bay, Otter Rock, and Toledo) to as many as ~660 at South Beach State Park in Newport and ~500 in Gleneden Beach (**Table 3-6**). In both areas the bulk of those expected to be killed (>87%) are likely to be visitors. Overall, we find the average number of fatalities observed in the permanent population is ~4% (standard deviation, $\rho$=5%). The large number of potential fatalities at South Beach State Park and Gleneden Beach is attributed to the significant travel distances required to reach high ground. Evacuation modeling of Newport and the rest of Lincoln County by Gabel and others (2019a,c) identified a few key mitigation options that could be implemented to reduce fatalities, including reinforcing core evacuation routes and building vertical evacuation structures.

We estimate that, combined, countywide fatalities could range from ~540 (M1) to as high as 3,680 (XXL1), with the bulk of the fatalities (~79%) likely coming from the temporary visitor population. Given that these casualty estimates are for 12 Lincoln County communities and three major parks, total deaths caused by even an M1 CSZ tsunami when accounting for all 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 and did not consider the temporary visitor population. From our analyses, we find ~140 fatalities within the resident population for the M1 scenario, along with an additional ~400 fatalities within the visitor population. Combining these results with recently published data for Clatsop County (~3,700 resident and ~7,700 visitor fatalities [Allan and others, 2020a]) and Tillamook County (~260 resident and ~1,970 visitor fatalities [Allan and others, 2020b]) suggests that estimates by OSSPAC (2013) are low.

**Figure 3-5** presents a graphical summary of the estimated fatalities and displaced population for all three tsunami scenarios. Casualties are presented on the left of **Figure 3-5**, while estimates of the displaced population are on the right. The permanent resident population reflects the following color scheme: purple (M1), gold (L1), and yellow (XXL1). We provide contrasting cool colors to characterize different visitor occupancy levels (we assume 10% [dark blue], 50% [cyan], and 100% [pale blue] scenarios). Because the permanent resident population is easiest to define in our population model, we argue that this likely reflects a low-end estimate of casualty numbers associated with each of the three tsunami events. This is shown in **Figure 3-5** by the left edge of the dark blue bars. Conversely, the resident plus visitor population (assuming 100% occupancy), is characterized by the length of the entire bar (right edge of the pale blue 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. One could speculate on visitor occupancy by developing scenarios that vary from 10% (e.g., winter occupancy conditions, dark blue shading) or 50% (an average visitor occupancy, cyan shading) to better define the potential number of casualties and displaced people. Refining such estimates, guided by local input, would help clarify a range of possible scenarios leading to more informed evaluations. As noted previously, the large number of fatalities estimated for South Beach State Park in southern Newport for the XXL1 scenario (**Figure 3-5**, *left*) is indicative of the fact that high ground, and hence safety from the tsunami, is some distance away. Conversely, the much lower casualty numbers in the majority of Lincoln communities are due entirely to the fact that high ground is close by, enabling more people to reach safety in time. Regardless of differences in local geography, it is evident from **Figure 3-5** that the number of casualties associated with even an M1 size event (especially when factoring in the temporary visitor population) has the potential to be large when scaled up for the rest of the Oregon coast.

For the displaced population (**Figure 3-5**, *right* and **Table 3-8**), 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, Gleneden Beach, Bayshore, and the Other category (not shown in Figure 3-5), each of which might potentially have to deal with several thousand people, many of whom would be nonresidents. The extremely large number of displaced people in the Other category after an XXL1 event will be especially challenging as many of these people will be disbursed widely across the county, making it extremely challenging for post-disaster evacuation. Identifying these groups early on and providing or encouraging pre-disaster preparation (e.g., two-week ready) will be key to their survival.

Although the numbers of displaced increase significantly from M1 (~16,200) to XXL1 (~38,600) (**Table 3-8**), our Hazus results demonstrate that even a medium (M1) event would result in the displacement of many thousands of people. These numbers are direct reflection of the fact that many of these communities are major tourist destinations with large numbers of vacation homes, camping spots, and to a lesser extent hotel/motels located in the tsunami zone. The low number of displaced people in places such as Beachside State Recreation Site and Tillicum under the XXL1 scenario (**Figure 3-5**, *right*) is indicative of the fact that most people would be killed, because high ground under this scenario is far away, such that evacuees travelling at a walk pace would not survive. In these areas, required evacuation speeds needed to survive the XXL1 event are faster than a walk (e.g., fast walk to jog).

Finally, the assumptions and observations described previously about tsunami casualties are predicated on the fact that people will evacuate from the tsunami zone within 10 minutes from the start of earthquake shaking. If people respond slowly and take an additional 5-minute delay (i.e., a 15-minute departure time), the casualty numbers will increase significantly (**Table 3-7**). As can be seen from the table, a 5-minute difference in the departure delay could cause the number of casualties to increase by 7,400 people. Thus, efforts directed at reducing human response times are critical for reducing overall casualties.

**Table 3-6. Estimated injuries and fatalities associated with three CSZ tsunami scenarios, based on a 2 AM summer weekend scenario by community. Tsunami injury and fatality estimates assume a departure time of 10 minutes after the start of earthquake shaking. Assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.**

| | Number of Permanent Residents by Tsunami Zone | | | Estimated Number of Temporary Residents by Tsunami Zone[1] | | | Injuries and Fatalities to Permanent Residents by Tsunami Scenario | | | Injuries and Fatalities to Temporary Residents by Tsunami Scenario[1] | | | Injuries and Fatalities to Permanent Residents by Tsunami Scenario, Percent[2] | | | Injuries and Fatalities to Temporary Residents by Tsunami Scenario, Percent[3] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Community Zone** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** | **Medium** | **Large** | **XX-Large** |
| Lincoln City | 1,119 | 1,520 | 2,693 | 3,587 | 5,184 | 8,167 | 90 | 112 | 171 | 123 | 154 | 241 | 8% | 7% | 6% | 3% | 3% | 3% |
| Gleneden Beach | 96 | 192 | 648 | 641 | 1,255 | 3,295 | 26 | 28 | 66 | 193 | 206 | 430 | 27% | 15% | 10% | 30% | 16% | 13% |
| Lincoln Beach | 49 | 82 | 287 | 118 | 230 | 807 | 0 | 0 | 0 | 0 | 0 | 1 | 0% | 0% | 0% | 0% | 0% | 0% |
| Depoe Bay | 11 | 32 | 470 | 8 | 58 | 955 | 0 | 0 | 0 | 0 | 0 | 0 | 0% | 0% | 0% | 0% | 0% | 0% |
| Otter Rock | 0 | 2 | 5 | 0 | 3 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0% | 0% | 0% | 0% | 0% | 0% |
| Beverly Beach State Park | 0 | 0 | 0 | 766 | 873 | 873 | 0 | 0 | 0 | 1 | 163 | 416 | 0% | 0% | 0% | 0% | 19% | 48% |
| Newport | 796 | 986 | 1,945 | 1,952 | 2,428 | 4,304 | 1 | 18 | 87 | 6 | 39 | 178 | 0% | 2% | 4% | 0% | 2% | 4% |
| South Beach State Park | 0 | 0 | 0 | 242 | 1,040 | 1,040 | 0 | 0 | 0 | 0 | 1 | 656 | 0% | 0% | 0% | 0% | 0% | 63% |
| Siletz | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0% | 0% | 0% | 0% | 0% | 0% |
| Toledo | 19 | 73 | 168 | 3 | 15 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0% | 0% | 0% | 0% | 0% | 0% |
| Seal Rock | 0 | 17 | 84 | 0 | 78 | 350 | 0 | 0 | 0 | 0 | 0 | 1 | 0% | 0% | 0% | 0% | 0% | 0% |
| Bayshore | 497 | 653 | 823 | 1,127 | 1,492 | 1,891 | 19 | 98 | 143 | 42 | 225 | 329 | 4% | 15% | 17% | 4% | 15% | 17% |
| Waldport | 677 | 768 | 936 | 655 | 806 | 982 | 6 | 8 | 12 | 3 | 10 | 38 | 1% | 1% | 1% | 0% | 1% | 4% |
| Beachside State Recreation Site | 0 | 0 | 0 | 238 | 238 | 238 | 0 | 0 | 0 | 2 | 23 | 160 | 0% | 0% | 0% | 1% | 10% | 67% |
| Tillicum Beach Campground | 0 | 0 | 0 | 90 | 196 | 196 | 0 | 0 | 0 | 0 | 1 | 193 | 0% | 0% | 0% | 0% | 0% | 98% |
| Yachats | 135 | 407 | 611 | 754 | 1,571 | 1,934 | 0 | 0 | 1 | 0 | 1 | 6 | 0% | 0% | 0% | 0% | 0% | 0% |
| Other[4] | 823 | 1,475 | 2,797 | 2,333 | 3,597 | 5,461 | 2 | 6 | 169 | 8 | 21 | 362 | 0% | 0% | 6% | 0% | 1% | 7% |
| Lincoln County Total | 4,223 | 6,206 | 11,468 | 12,512 | 19,066 | 30,543 | 143 | 271 | 649 | 394 | 859 | 3,012 | 4% | 3% | 4% | 3% | 4% | 20% |

Notes:

[1] Assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

[2] Casualties expressed as percentage of those injured or killed in the tsunami zone relative to the total number of community-wide permanent residents.

[3] Casualties expressed as percentage of those injured or killed in the tsunami zone relative to the total number of community-wide temporary residents, assuming 100% occupancy.

[4] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Table 3-7. Injury and fatality estimates for an XX-Large tsunami for two median departure times.**

| Community Zone | Number of Permanent Residents | Total Number of Residents (Permanent + Temporary[1]) | 10-Minute Departure | | | | 15-Minute Departure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Injuries | Fatalities | Total | Injuries Ratio[2] | Injuries | Fatalities | Total | Injuries Ratio[2] |
| Lincoln City | 9,322 | 26,550 | 43 | 369 | 412 | 10% | 152 | 2,255 | 2,407 | 6% |
| Gleneden Beach | 1,015 | 5,225 | 20 | 476 | 496 | 4% | 54 | 1,099 | 1,153 | 5% |
| Lincoln Beach | 662 | 2,310 | 0 | 1 | 1 | 20% | 9 | 118 | 127 | 7% |
| Depoe Bay | 1,725 | 3,965 | 0 | 1 | 1 | 20% | 12 | 152 | 164 | 7% |
| Otter Rock | 299 | 1,403 | 0 | 0 | 0 | 19% | 0 | 1 | 1 | 7% |
| Beverly Beach State Park | 0 | 873 | 25 | 391 | 416 | 6% | 23 | 597 | 619 | 4% |
| Newport | 10,960 | 21,592 | 23 | 241 | 265 | 9% | 63 | 1,142 | 1,206 | 5% |
| South Beach State Park | 0 | 1,040 | 32 | 624 | 656 | 5% | 23 | 818 | 842 | 3% |
| Siletz | 1,283 | 1,451 | 0 | 0 | 0 | 0% | 0 | 0 | 0 | 0% |
| Toledo | 3,453 | 4,446 | 0 | 0 | 0 | 9% | 1 | 18 | 19 | 3% |
| Seal Rock | 381 | 1,044 | 0 | 1 | 2 | 17% | 5 | 71 | 75 | 6% |
| Bayshore | 1,171 | 3,683 | 26 | 445 | 471 | 6% | 44 | 1,019 | 1,063 | 4% |
| Waldport | 2,146 | 3,610 | 7 | 43 | 50 | 14% | 26 | 473 | 499 | 5% |
| Beachside State Recreation Site | 0 | 238 | 7 | 153 | 160 | 4% | 5 | 190 | 195 | 2% |
| Tillicum Beach Campground | 0 | 196 | 3 | 190 | 193 | 2% | 3 | 192 | 194 | 1% |
| Yachats | 847 | 3,285 | 1 | 6 | 7 | 17% | 25 | 409 | 434 | 6% |
| Other[3] | 14,617 | 26,365 | 41 | 491 | 531 | 8% | 96 | 1,980 | 2,076 | 5% |
| Lincoln County Total | 47,881 | 107,277 | 229 | 3,432 | 3,661 | 11% | 540 | 10,535 | 11,076 | 5% |

Notes:

[1] Assumes 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

[2] Tsunami Injury ratio is the number of tsunami injuries divided by total number of tsunami casualties (injuries plus fatalities).

[3] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

**Figure 3-5. (left) Estimated casualty numbers by community for M1, L1, and XXL1 tsunami events assuming various visitor occupancy levels; (right) Estimates of the displaced population in each community assuming various occupancy levels.**

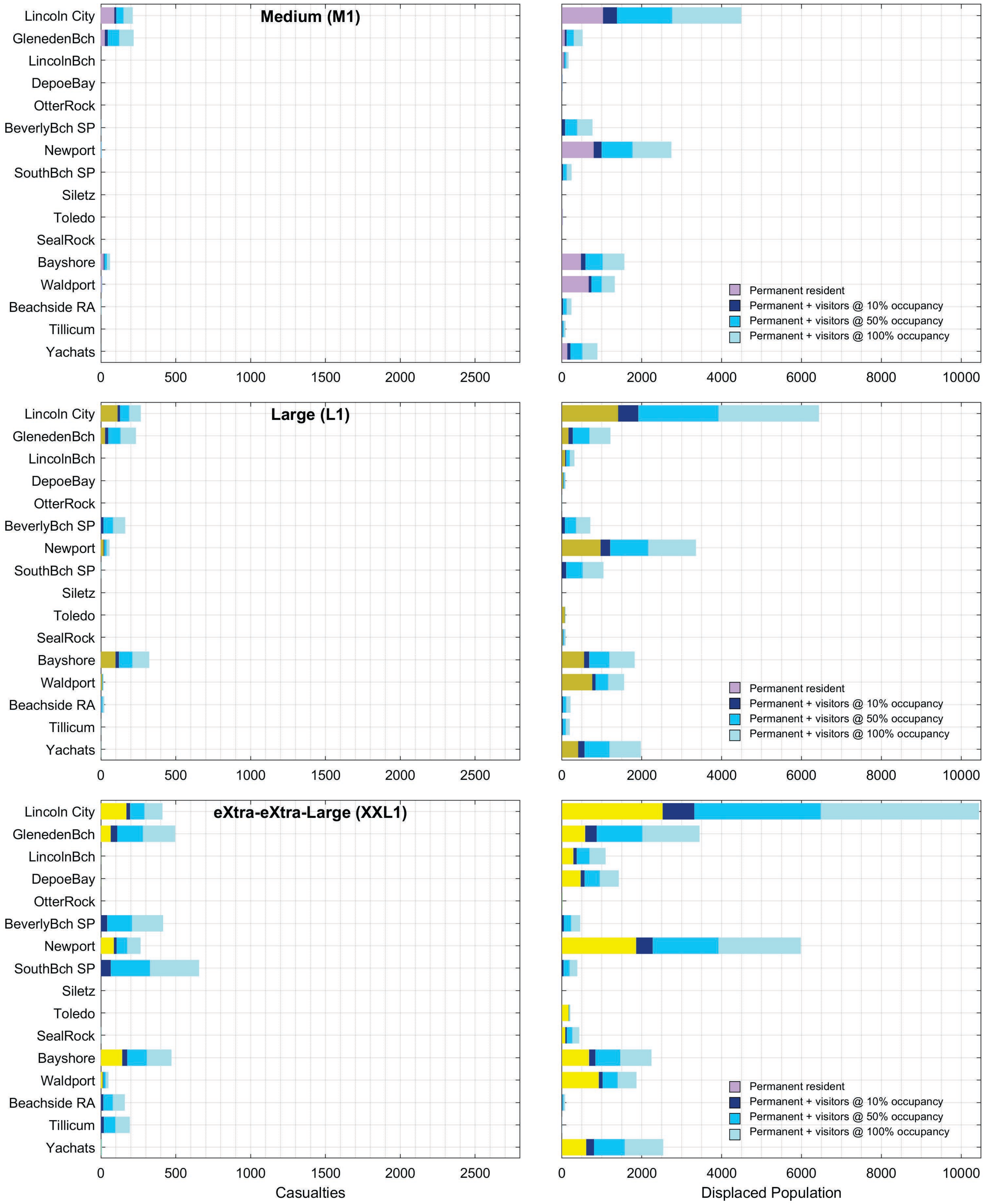


**Table 3-8. Displaced population by tsunami zone.**

| Community Zone | Displaced Population[1] by Tsunami Scenario | | |
|---|---|---|---|
| | Medium | Large | XX-Large |
| Lincoln City | 4,518 | 6,468 | 10,491 |
| Gleneden Beach | 528 | 1,223 | 3,467 |
| Lincoln Beach | 167 | 311 | 1,093 |
| Depoe Bay | 18 | 90 | 1,425 |
| Otter Rock | 0 | 5 | 15 |
| Beverly Beach State Park | 765 | 730 | 481 |
| Newport | 2,743 | 3,365 | 6,008 |
| South Beach State Park | 241 | 1,039 | 416 |
| Siletz | 0 | 0 | 0 |
| Toledo | 22 | 87 | 208 |
| Seal Rock | 0 | 94 | 433 |
| Bayshore | 1,570 | 1,843 | 2,269 |
| Waldport | 1,324 | 1,559 | 1,874 |
| Beachside State Recreation Site | 237 | 219 | 85 |
| Tillicum Beach Campground | 90 | 196 | 6 |
| Yachats | 889 | 1,977 | 2,538 |
| Other[2] | 3,148 | 5,049 | 7,767 |
| Lincoln County Total | 16,248 | 24,244 | 38,565 |

Notes:

[1] Permanent plus temporary population. For the temporary population we assume 100% occupancy of second homes, vacation rentals, condominium units, bed and breakfast facilities, hotels, motels, and campgrounds.

[2] Denotes all other areas impacted by a Cascadia earthquake and tsunami.

## 3.5 Essential Facilities and Key Infrastructure

**Table 3-9** provides a summary list of critical facilities and key infrastructure located in the M1, L1, and XXL1 tsunami hazard zones in each Lincoln County community.

**Table 3-9. Critical facilities and key infrastructure in coastal Lincoln County tsunami inundation zones.**

| Community | Description | Category | Tsunami Zone | | |
|---|---|---|---|---|---|
| | | | M1 | L1 | XXL1 |
| Gleneden Beach | Depoe Bay Fire Station 2200 | city hall | — | — | x |
| Depoe Bay | Samaritan Depoe Bay Clinic | hospital | — | — | x |
| Depoe Bay | U.S. Coast Guard Depoe Bay Station | U.S. Coast Guard Station | x | x | x |
| Newport | Newport Water Treatment Plant | water treatment/water district | — | — | x |
| Newport | Port of Newport | port | x | x | x |
| Toledo | Toledo Police Dept | police department | — | x | x |
| Toledo | Toledo State Airport | airport | x | x | x |
| Seal Rock | Seal Rock Fire Station | fire department | — | — | x |
| Waldport | Central Oregon Coast Fire Station 7200 | fire department | x | x | x |
| Waldport | Yachats Fire Station | fire department | — | x | x |
| Yachats | Yachats Fire Station and South Lincoln Ambulance Service | fire department/ambulance | — | x | x |
| Other | North Lincoln Fire Station 1700 | fire department | — | — | x |
| Other | Wakonda Beach Airport | airport | — | x | x |

The symbology for these categories on DOGAMI tsunami evacuation maps is:

| | | | | | |
|---|---|---|---|---|---|
| city hall | fire department | hospital | National Guard | public works | police department |
| school | wastewater treatment | water treatment/ water district | U.S. Coast Guard Station | | |

## 3.6 Social Characteristics

We used the American Community Survey (ACS) social characteristic data to identify some societal characteristics for each community in Lincoln County. Of specific interest are those households speaking Spanish and individuals with disabilities. Both datasets are important because they have a direct bearing on tsunami outreach and education (e.g., providing material that has been translated) and in terms of identifying those with disabilities who may need additional assistance with developing evacuation plans or actual evacuation. As noted previously, a limitation of these data is that they span the entire community and are not at a resolution that would allow us to better define these statistics by tsunami zone. Additional information relating to the use of ACS data may be found in Appendix A of Bauer and others (2020).

**Table 3-10** identifies the number of Spanish-speaking (and other languages) households in coastal Lincoln County. Overall, Spanish-speaking households are highest in Newport (~11%), Depoe Bay (~10%) and Lincoln City (~7%), while Newport (~2%) has the largest group of Spanish households that speak limited English. Newport also has the largest group of households speaking other languages.

**Table 3-11** presents information on the percentages of people with disabilities in coastal Lincoln County. Overall, these results indicate the proportion of the local population with disabilities ranges from a low of ~15% in Newport to highs of 33% in Waldport and ~25% in Yachats. Of particular concern is the relatively large number of individuals with vision, cognitive, or ambulatory disabilities. These include:

- ~8% of people at Waldport have indicated vision challenges;
- Individuals with cognitive challenges make up ~12% of residents in Waldport and ~10% of residents at Toledo and Yachats; and
- Individuals with ambulatory needs make up sizable portions of Waldport (~23%), Lincoln Beach (16.4%), Depoe Bay (~11.6%), and Yachats (~12%).

These results point to the need to better understand those with disabilities in the tsunami zone, as many of these people will almost certainly need help evacuating. Because the ACS data are not sufficiently detailed, not all of these individuals necessarily reside in the tsunami zone; local emergency managers may wish to assess specific community needs.

**Table 3-10. Household spoken language statistics. Data taken from American Community Survey 2013–2017 5-year estimates.**

| Community | Number of Households Speaking Spanish | Percent of Households Speaking Spanish with MoE | Number of Limited English-Speaking, Spanish Households | Limited English-speaking households, Households Speaking Spanish (%) | Number of Limited English-Speaking, Other Language Households |
|---|---|---|---|---|---|
| Lincoln City | 260 | 6.9% ± 3.1% | 10 | 0.3 | 46 |
| Lincoln Beach | 16 | 1.9% ± 2.0% | — | — | 9 |
| Depoe Bay | 89 | 10.4% ± 6.7% | — | — | — |
| Newport | 500 | 11.1% ± 2.3% | 85 | 1.9 | 94 |
| Toledo | 21 | 1.6% ± 1.6% | — | — | — |
| Waldport | 9 | 0.9% ± 1.0% | — | — | 4 |
| Yachats | 13 | 3.8% ± 5.1% | — | — | — |
| Lincoln County | 1,068 | 5.2% ± 0.7% | 100 | 0.5 | 168 |

Note: MoE denotes margin of error.

**Table 3-11. Number of individuals with disabilities (by type) for coastal Lincoln County. Data taken from American Community Survey 2013–2017 5-year estimates. Note: An individual with a disability may have more than one difficulty.**

| Community | Total Number of Individuals* | Number of Individuals* with a Disability | Percent of Individuals with a Disability | Hearing | Vision | Cognitive | Ambulatory | Self Care | Independent Living |
|---|---|---|---|---|---|---|---|---|---|
| Lincoln City | 8,476 | 1,784 | 21.0% ± 2.4% | 5.7% ± 1.4% | 4.1% ± 1.3% | 8.7% ± 1.8% | 12.2% ± 2.4% | 3.7% ± 1.3% | 10.3% ± 2.1% |
| Lincoln Beach | 1,571 | 373 | 23.7% ± 7.5% | 6.8% ± 4.9% | 0.6% ± 0.7% | 8.6% ± 4.2% | 16.4% ± 6.4% | 2.4% ± 2.0% | 6.9% ± 3.4% |
| Depoe Bay | 1,760 | 369 | 21.0% ± 6.9% | 8.2% ± 3.8% | 3.4% ± 2.5% | 5.3% ± 3.2% | 11.6% ± 5.0% | 6.2% ± 3.8% | 7.6% ± 4.1% |
| Newport | 10,024 | 1,544 | 15.4% ± 1.8% | 5.1% ± 1.2% | 3.3% ± 1.0% | 6.4% ± 1.4% | 9.8% ± 1.7% | 3.7% ± 1.1% | 8.0% ± 1.9% |
| Toledo | 3,514 | 819 | 23.3% ± 5.1% | 6.9% ± 2.4% | 3.0% ± 1.4% | 9.7% ± 3.7% | 11.2% ± 3.5% | 3.7% ± 1.6% | 11.7% ± 4.7% |
| Waldport | 2,200 | 718 | 32.6% ± 8.2% | 7.0% ± 2.9% | 7.8% ± 3.5% | 11.9% ± 5.5% | 23.1% ± 6.1% | 7.3% ± 3.1% | 11.6% ± 4.1% |
| Yachats | 662 | 162 | 24.5% ± 5.9% | 10.1% ± 3.9% | 4.5% ± 3.0% | 9.5% ± 5.6% | 12.3% ± 5.0% | 6.9% ± 3.4% | 9.1% ± 4.0% |
| Lincoln County | 46,983 | 10,186 | 21.7% ± 1.1% | 6.9% ± 0.7% | 3.5% ± 0.5% | 8.5% ± 0.8% | 12.2% ± 1.0% | 4.0% ± 0.5% | 8.9% ± 0.9% |

# 4.0 DISCUSSION

This study extends the original work undertaken by Bauer and others (2020) and Allan and others (2020a,b) by implementing the 2017 FEMA Hazus methods on a countywide basis in order to estimate building loss and casualties from a catastrophic CSZ earthquake and tsunami. The approach used the best available information on the CSZ earthquake (Mw 9.0, Madin and Burns, 2013) and resultant M1, L1 and XXL1 tsunami (Priest and others, 2013e), together with a detailed building database and a 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 this initial work by evaluating in more detail expected impacts caused by three different tsunami inundation scenarios that could impact coastal Lincoln County. In particular, the present study extends the population model to include new information that evaluates the temporary visitor population, types of housing that permanent and temporary residents occupy and their relative distances to safety outside the 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[9].

**Building damage:** Our analyses reveal that the earthquake alone accounts for significant community-wide building losses that range from a few tens of thousands at Tillicum Beach Campground to $623 million in Newport (**Table 3-4**); an estimated $396 million in damage is expected for Lincoln City. These variations reflect differences in the type and age of building construction among the communities, the size and purpose of the community and density of buildings (e.g., a state park versus a town), and the number of buildings established in terrain that may be subject to landslides or be on liquefiable soils. Countywide losses in coastal Lincoln County caused by a CSZ earthquake are projected to reach ~$2.1 billion, most of which will occur in Newport, Lincoln City, Toledo, and areas outside of community boundaries ("other").

Damage to buildings from the tsunami is expected to be catastrophic — the smallest amount of earthquake/tsunami destruction this analysis predicts is ~18% for the M1 scenario at Tillicum Beach campground increasing to >80% loss in the communities of Yachats, Waldport, Bayshore, Newport, and Gleneden Beach in an XXL1 size event; Beverly Beach State Park, South Beach State Park, Beachside and Tillicum campgrounds are effectively wiped out as well. Much of this destruction can be attributed to the prevalence of light-frame (mainly wood) construction, which is very vulnerable to tsunami damage. In addition, with the exception of Newport, most of these communities and campgrounds are built on low-lying coastal plains or estuary deposits that are completely inundated in an XXL1 event.

Combined earthquake and tsunami damage indicate that Lincoln County could experience ~$2.4 billion in damage for an M1 scenario, ~$2.8 billion for L1, and $3.5 billion for an XXL1 size event. Note that these estimates exclude building content losses, such that these estimates are minimum estimates.

**Building debris:** 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), within ports and harbors and in the navigation channels. Jetties such as those built at the mouth of Yaquina Bay are expected to be severely damaged or completely destroyed. Such effects

[9] https://www.oregon.gov/LCD/Publications/TsunamiLandUseGuide_2015.pdf

are likely to compromise marine traffic access into the Yaquina estuary and thus the port of Newport. Our analyses indicate that the debris produced from building damage could range from ~239,000 tons (M1) to ~705,000 tons (XXL1). This equates to ~24,000 dump trucks for M1 to as much as 70,000 dump trucks for an XXL1 event. These estimates are almost certainly on the low end, as they do not include debris associated with content from buildings (personal items, business equipment, etc.), road rip-ups, vehicles, and vegetation. Nonetheless, the amount of debris listed here provides 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 in coastal Lincoln County varies from ~4,200 (M1), ~6,200 (L1) to ~11,500 (XXL1). Including the temporary (visitor) population visiting the coast increases the overall coastal population substantially. Our Hazus analyses presented in **Table 3-1** suggest that the temporary visitor population could potentially reflect an additional 12,500 (M1) to as many as 30,500 (XXL1) 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. It should be recognized though that these totals assume every lodging facility is fully booked and in use at the time of the event, thereby providing the most conservative estimate of numbers of people on the coast. While 100% occupancy is an unlikely scenario, the point remains that there is a high probability that a significantly large number of displaced temporary visitors, in addition to the displaced permanent residents, will need emergency care and support following a Cascadia event. 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 results estimate the number of people killed in the tsunami zones could reach ~500 people (M1), ~1,000 (L1), and as many as 3,400 in an XXL1 event, exceeding estimates provided in the Oregon Resilience Plan, which ranged from 600 to ~5,000 fatalities for the entire coast (OSSPAC, 2013). Of note, the results from OSSPAC were based on an M1 event that accounts for 79% of the expected inundation scenarios. Thus, the M1 results presented here are more consistent with the same size earthquake event used in the OSSPAC assessment. Combining results for the M1 scenario modeled in Lincoln with those from our Clatsop and Tillamook Counties (Allan and others 2020a,b), we estimate ~4,100 permanent resident casualties, increasing to ~13,800 when factoring in the temporary visitor populations (assumes 100% occupancy). Accordingly, it is apparent that coast-wide tsunami fatality estimates for even an M1 tsunami could be substantial for the Oregon coast, potentially approaching levels observed in the 2011 Tōhoku, Japan event.

To assist the public, considerable hazard related information has been developed over the past decade to enable coastal communities and visitors to make informed decisions. These include detailed evacuation maps for every coastal community that are available in print and online (e.g., http://nvs.nanoos.org/TsunamiEvac). In addition, recent tsunami evacuation modeling undertaken by DOGAMI 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:

***Casualties attributed to a CSZ tsunami can be substantially reduced if people undertake the following simple steps:***

1. ***Practice their evacuation routes;***
2. ***Evacuate as soon as possible after the earthquake; and***
3. ***Travel as fast as possible (e.g., a fast walk, jog, or run) to safety.***

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. Oregon Emergency Management has 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 to pursue this option.

We quantified impacts to both temporary and permanent populations in our injury and fatality estimates for two reasons: First, 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 3-5**), and second, 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, or optimal routes to safety and are more likely to engage in counterproductive milling (delay) behaviors that will lead to greater risk of death. In contrast, we hypothesize that permanent residents are generally better prepared (are aware of the hazard and their evacuation routes) and are less likely to delay their departure 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.

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 for a number of Oregon coastal communities including Seaside and Cannon Beach in Clatsop County, and Rockaway Beach in Tillamook County, 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. Although many hotel/motels in Lincoln County are similarly located next to the ocean, high ground is invariably much closer to these facilities when compared with similar establishments in the northern counties.

However, even with permanent residents, our assumptions of individuals' preparation and awareness may not match actual preparedness. For example, we assume 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 education challenges. 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 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.

**Displaced population:** Given the near-complete destruction of buildings within the tsunami zone (**Table 3-8**), 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 (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. A major concern identified for Lincoln County is the potentially large number of people outside of community boundaries who will also be impacted by the earthquake and tsunami. Given how spread out many of these people are, a major challenge for emergency managers will be figuring out how to get supplies to pockets of people, while also endeavoring to evacuate many of these people to centralized locations where emergency shelters are established. Key to this process is to ensure that these people are well prepared and hence are "two-week" ready to ensure they can survive the aftermath until help arrives.

# 5.0 RECOMMENDATIONS

Utilizing the FEMA Hazus model, this study has evaluated the degree of impact associated with three CSZ tsunami scenarios in order to document potential building losses, debris weight, fatalities and injuries, and estimated numbers of the displaced populations throughout coastal Lincoln County. 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 a tsunami is triggered. Great care has been taken as part of this study to address the needs of local communities. Discussions with local community planners undertaken by Bauer and others (2020) helped frame the overall study approach and assumptions applied in our latest countywide Hazus modeling.

**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 both 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., motels, vacation rentals, second homes, or tents) 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, ~70% of people visiting Yachats are likely to end up in single-family vacation or second homes that are farther from high ground. Similarly, in the communities of Gleneden Beach and Bayshore the bulk (86%

and 97%, respectively) of visitors stay in vacation homes. This contrasts with places like Newport where most visitors camp (e.g., South Beach State Park).

Besides vacation homes, our analyses demonstrate that a number of the coastal communities have significant numbers of hotels/motels located in the tsunami zone (especially XXL1). Those that do include Lincoln City, Depoe Bay, Newport, and Yachats where hotel and motels account for, respectively, 35%, 46%, 35%, and 26% of beds where visitors may stay. Luckily, high ground is relatively close for each of these communities such that investment in appropriate signage, education of lodging staff, and access to high resolution "neighborhood" scale evacuation maps in every hotel/motel room may be sufficient. Thus, tsunami education and outreach targeting each of these lodging groups become essential in order to mitigate against the potentially large loss of life likely to occur without such measures.

Two key approaches are in place to begin to address such needs:

1) 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.
2) To address evacuation information needs, DOGAMI staff in partnership with the Northwest Association of Networked Ocean Observing Systems (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 individuals or businesses to develop their own custom evacuation brochures for any location on the Oregon coast. More recently, DOGAMI has initiated the development of higher-resolution tsunami evacuation neighborhood maps[10] 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.

Finally, building a culture of awareness is needed to survive the next CSZ tsunami. Such an effort could include funds to post and maintain tsunami wayfinding signage of sufficient density along core evacuation routes and 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 needed outreach at the grassroots level.

**Mitigation**

Tsunami evacuation modeling throughout coastal Lincoln County demonstrates 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 (posted and/or on road/path surfaces) that direct people along core routes to areas outside the tsunami zone. Such efforts, guided by our evacuation modeling results, are now being implemented in multiple communities including Seaside, Cannon Beach, Manzanita, and Newport. In each of these communities, a "beach to safety" plan has been developed for core evacuation routes, and signage consisting of posted signs as well as thermoplastic signage on roads and paths is being implemented. Signs of this nature need

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

to be spaced sufficiently close together and illuminated at night so that the signage may 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 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 will be critically important for post-disaster recovery (e.g., the Yaquina bridge in Newport), we did not identify any community in Lincoln County that is dependent on bridges for evacuation purposes. Conversely, construction of vertical evacuation towers in a few key locations could potentially save many lives. Of the communities examined here, the community of Taft is particularly exposed to the tsunami hazard, given that community's susceptibility to all three tsunami inundation scenarios (Gabel and others 2019c). Similarly, South Beach State Park has significant exposure and risk (Gabel and others 2019a; Bauer and others, 2020), particularly because the overwhelming majority of people camping there will not be familiar with the surrounding terrain.

In many communities, people reside in older manufactured housing. Manufactured houses installed prior to 2003 are susceptible to slipping off their foundations during earthquake shaking (OBCD, 2010; SPA Risk LLC, 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 (2012b, 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, whether the scenario is M1 or XXL1. Accordingly, all Oregon coastal communities will need to be prepared to shelter large numbers of people who escape the tsunami. The need for shelter is likely to last many weeks until tsunami evacuees can be relocated out of the disaster area. 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 a few tens (e.g., Otter Rock) to potentially many thousands (e.g., Lincoln City, Gleneden Beach, Newport, Bayshore, and Yachats, in a worst case summer scenario with every vacancy filled).

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 5% to 17% across the coastal communities depending on the scenario. This finding is not unexpected 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 range from ~300 to ~530 people in Lincoln County. Given that there are about 483 licensed beds at the 11 coastal hospitals (OSSPAC, 2013), these facilities can be expected to be quickly overwhelmed. Aside from a capacity issue, 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.

**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 coastal Lincoln County could yield an estimated ~239,000 tons of debris in the M1 scenario, increasing to ~396,000 tons for L1 and 705,000 tons in an XXL1 event. These estimates are almost certainly on the low end, as they exclude the content volume within buildings (e.g., personal and business-related items), vehicles, and other forms of debris. Utilizing the number of household counts throughout Lincoln County (8,267 buildings), we estimate an additional 41,300 tons (assumes 5 tons per household) of debris could be generated from personal effects. This equates to ~6% of the total volume of debris reported in Table 3-4. The estimated building replacement cost for coastal Lincoln County is likely to exceed $2.4 billion in an M1 event, $2.8 billion in L1, increasing to $3.5 billion in an XXL1 earthquake and tsunami.

Wood-frame construction predominates in many Oregon coastal communities, and the majority of such buildings in the tsunami zone will probably be completely destroyed by the tsunami. This means that for Lincoln County there is likely to be a significant 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 subsidence effects caused by the earthquake. For example, the XXL1 earthquake deformation model estimates that the coastline could drop by ~5.8 ft in Lincoln County; an M1 event would yield about 2.5 ft of subsidence (data derived from Witter and others, 2011). Such changes will inevitably lead to accelerated rates of coastal erosion along with increased incidences of coastal flooding in low-lying areas. These changes can be expected to be significant in the weeks to months following the event, with further change progressively decreasing over time as the coastline re-equilibrates to the new sea level regime.

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, 2018), and can aid in community recovery. More information on the National Flood Insurance Program can be obtained from https://www.fema.gov/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 3.6). The ACS estimates are for the entire community, including people outside the tsunami zone, so the total number of individuals identified in this report is likely to be on the high end compared with those actually in the 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[11] that tracks electricity-dependent Medicare populations and the Centers for Disease Control and Prevention's Behavioral Risk Factor Surveillance System (BRFSS)[12], 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.

Finally, 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.

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[11] https://empowermap.hhs.gov/

[12] https://www.cdc.gov/brfss/index.html

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# 8.0 APPENDIX A: COMMUNITY PROFILES

Appendix A includes additional summary information specific to each community. These data include the effects of both the earthquake and accompanying tsunami (M1, L1, and XXL1) that can inform preparation, recovery, and mitigation planning.

A) **Area analyzed:** We summarized data when possible within the community's designated urban growth boundary (UGB). Planners consider 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. For unincorporated communities, we used a geospatial layer of unincorporated communities compiled by the Department of Land Conservation and Development. The summary community profile maps highlight several datasets including the boundary used for analysis (UGB or city limits depending on data availability), building placements and tsunami zone. In addition, the maps include the results of the evacuation modeling (path distances) based on a 4 ft per second (walk) evacuation speed (with 10-minute delay) out of the inundation zone. We distinguish the chance of successful evacuation (green lines) versus increased likelihood of fatality (red lines). In all cases, the likelihood of successful evacuation improves significantly if individuals increase their evacuation speed or leave sooner.

B) **Population demographics:** These data reflect the permanent (resident) population within each respective tsunami zone (M1, L1, and XXL1), expressed as absolute numbers and as a percentage of the total community population. A conservative estimate of the number of temporary visitors is also presented, assuming 100% occupancy of vacation homes, hotel/motels, and camping areas. Additional demographic information of the permanent (resident) population distinguishes those <65 years and those over 65 years of age.

C) **Distance to safety:** Distance to safety plots show the number of permanent and temporary residents as a function of distance to safety. The closer a person is to safety (i.e., right side of the figure) the greater the chance of successful evacuation. The distance to safety figure includes a 4 ft per second (walk) threshold line (vertical dash black line). Left of this line, the model assumes people will not be able to evacuate out of the inundation zone in time, while those to the right have a greater chance of surviving. We also include a 2 standard deviation gray dash line that highlights uncertainty in the 4 fps threshold, which is a function of the wave arrival time. Finally, we include a cumulative percent curve to further define the proportion of people relative to safety in the community.

D) **Distance to safety and building type:** This figure is similar to C), with the exception that it now defines the tendency of people (permanent and temporary) to be in particular building types. Here we distinguish between the following building types: single-family residential, manufactured housing, multi-family residential, hotel/motel, and mobile (e.g., tent, RV, etc.). These data define where people tend to be predominantly located. For example, many coastal hotel/motels tend to be located close to the ocean and are mostly used by visitors.

E) **Building losses:** The effects of a $M_w$ 9.0 Cascadia Subduction Zone earthquake and accompanying tsunami (M1, L1, and XXL1) in terms of economic losses and debris generated are included in this figure. For each tsunami zone, we define the number of buildings in the zone and the building replacement cost. Earthquake losses are defined for the tsunami zone and as a total for the entire community. These data are then combined with the tsunami losses calculated by Hazus. Finally, the weight of debris generated by the tsunami is also presented. As a reminder, these data do not include the weight of content in buildings and therefore reflect a minimum value.

F) **Fatalities and displaced population:** To standardize tsunami injury and fatality estimation across all communities, 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. In all cases, we factor in a 10-minute evacuation delay prior to getting underway that accounts for ~3 minutes of expected earthquake shaking and up to 7 minutes for people to organize themselves, leave the building, and begin to evacuate. For each community, we provide graphical representations of the modeled fatalities, for both permanent and temporary residents. For the temporary population we assume 10%, 50%, and 100% occupancy estimates. The displaced population is defined as the difference between the local (permanent) population and the fatalities (for permanent and temporary). Planners can apply their own judgment as to the occupancy levels associated with the temporary visitors and adjust downward from the 100% occupancy estimate.