Cascadia Tsunami Casualty Estimates

Prepared for

Healthcare Preparedness Program of the

Oregon Health Authority's

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Sustainable Living Solutions LLC

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Tsunami monument at Unosumai-chou near Kamaishi (Iwate Prefecture) commemorating the Great East Japan Earthquake and Tsunami of 11 March 2011. The inscription at the bottom of the monument reads: "Memorial Stone of the Tsunami! Just run. Run Uphill! Don't worry about the others. Save yourself first. And tell the future generations that a Tsunami once reached this point. And that those who survived were those who ran. Uphill. So run! Run uphill!". (Source: UNESCO, 2012)

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Executive Summary

The Cascadia Tsunami Casualty Estimates Report provides expected ***tsunami casualty estimates*** from a magnitude 9 Cascadia earthquake for the entire Oregon coast. The report includes information on the possible ***uses of the casualty estimates***. The work, which was funded by the Healthcare Preparedness Program of the Oregon Health Authority's Health Security, Preparedness and Response, was conducted to complement efforts of the Coastal Hospital Resilience Project to inform planning efforts by the eleven coastal hospitals, the counties, State of Oregon and others (Wang, 2017; Wang, 2018; Wang and Norse, 2019; Wang and others, 2019; and Wang and Franczyk, 2020).

Tsunami survivors that experience near drowning may end up with "tsunami lung".

Direct health effects of tsunamis are described. Injuries and drowning have accounted for the vast majority of mortality experienced in countries affected by tsunamis. Injury related conditions will account for many of the health care needs among those requiring medical attention in the immediate aftermath of a tsunami. Whether resulting from the earthquake or the tsunami, falling structures, and waters full of swirling debris have inflicted crush injuries, fractures, and a variety of open and closed wounds (accessed on February 15, 2021, World Health Organization website: https://www.who.int/violence_injury_prevention/other_injury/tsunami/en/). Many survivors of tsunamis, including from the 2011 Great East Japan Earthquake, contracted a systemic disorder called "*tsunami lung*," a series of severe systemic infections following aspiration pneumonia caused by near-drowning (Kawakami and others, 2012).

Results indicate that expected tsunami casualties in Oregon are approaching 20,000, with the vast majority being fatalities accompanied by fewer than 1,000 injuries. Importantly, it has been assumed that all persons are quick to evacuate by foot using the most optimal tsunami evacuation route. Table ES1 shows county summaries starting from North to South.

Table ES1: Tsunami Casualty Estimates by County*

County	Injuries	Fatalities	Total
Clatsop	334	12,090	12,424
Tillamook	341	4,786	5,127
Lincoln	100	1,015	1,115
Lane	2	43	45
****Douglas**	0	0	0
Coos	19	352	370
Curry	24	382	406
Total	**819**	**18,667**	**19,486**

* Estimates were developed assuming that *all* persons quickly evacuate by foot for a DOGAMI Large tsunami scenario. Does not include earthquake casualties
** See text for comments on Douglas County and the likely under-reporting of estimates

The majority of people who cannot escape the tsunami will die rather than suffer injuries. Due to the extensive low-lying coastal plains on the north Oregon coast and the development patterns that exposes many people to tsunami hazards, the expected casualties (both in number and loss ratios) in Clatsop and Tillamook Counties are the highest. These estimates include permanent and visitor populations for a summer "night" (i.e., 2 AM) when populations are high. Casualties from the earthquake are *not* included in Table ES1. References used to develop the tsunami casualty estimates provided herein are from: Allan and others, 2020a; Allan and others, 2020b; Allan and O'Brien, 2021; Bauer and others, 2020; and, Wood and others, 2015. Supporting documentation and sources used, including assumptions, data, methods, are documented or referenced.

The tsunami casualty estimates may be used for disaster planning to address expected post-disaster high patient demands at hospitals at the same time that hospitals will experience a reduced capacity due to damage.

Introduction

After a Cascadia earthquake and tsunami, a surge of emergency care needs (i.e., demand) will occur at the same time there are reduced services available (i.e., capacity). As a consequence, many with life-threatening injuries lose their lives due to the delay in the provision of care. This report provides critically important information that can be used by Oregon's coastal hospitals for disaster planning to address the expected surge of patients.

This report provides tsunami-related casualty estimates from a hypothetical tsunami generated from a Cascadia magnitude 9 earthquake. Estimates are by counties, cities and unincorporated areas for the entire Oregon coast. Information is provided on the uses of the tsunami casualty estimates. The work was completed to complement the Coastal Hospital Resilience Project, which is described in the Background section of this report. Health effects of tsunamis is discussed. The methods used for the development of the estimates are reviewed. Published papers and supporting documentation used are discussed or referenced, including assumptions, data, methods.

The Cascadia Tsunami Casualty Estimates Report was prepared for the Oregon Health Authority (OHA) Health Security, Preparedness and Response (HSPR) Healthcare Preparedness Program (HPP) by the Sustainable Living Solutions LLC (SLS LLC) under contract number 167761-0 dated December 21, 2020.

Background

Cascadia Earthquakes and Tsunamis

A magnitude 9 Cascadia earthquake will induce strong ground shaking that lasts about 3 to 5 minutes. The offshore subduction zone earthquake rupture will create a powerful tsunami, which will arrive at the Oregon coastline as soon as 10 minutes after the initiation of the earthquake. The tsunami will be a series of waves, where the first wave will likely not be the largest wave. The earthquake will induce regional subsidence of coastal areas; trigger ground failures (also known as permanent ground displacement) including landslides, liquefaction, and lateral spreading; and seiches where inland bodies of water experience sloshing.

Widespread damage in coastal communities is inevitable. Ground shaking and ground failures will damage building structures and lifeline infrastructure systems, such as road networks and water distribution systems. Communities hit by the tsunami will experience significant damage. Anyone caught by the tsunami will likely suffer injuries or die. Casualties along the Oregon coast would be at their highest if the earthquake were to occur during a summer night, as temporary populations in the tsunami zone are high at that time. This is in contrast with the cities along the Interstate 5 corridor where casualties would be highest if the earthquake were to occur during a winter day. In this case, higher populations concentrated in older vulnerable commercial and industrial buildings coupled with extensive landslides and liquefaction due to wet ground would be heavily impacted.

Oregon Coastal Hospital Resilience Project

To prepare for Cascadia earthquakes and tsunamis, the OHA HSPR HPP has supported the Oregon Coastal Hospital Resilience Project. Partners for this project involve the HPP regional liaisons, the eleven hospitals along the Oregon coast, a wide range of community stakeholders, the Oregon Department of Geology and Mineral Industries (DOGAMI) and the Oregon Association of Hospitals and Healthcare Systems (OAHHS). The primary goal of the project is to help the coastal hospitals better prepare their communities for a magnitude 9 Cascadia subduction zone earthquake and tsunami.

Five Oregon Coastal Hospital Resilience Project reports are available for free download from the DOGAMI publication website. Each of the reports are briefly described and listed below in the order in which they were published. Resilience planning maps were created for each of the eleven hospitals.

1. An initial pilot study that involves hospitals and lifelines substantiates that the coast will be isolated and normal practices of transporting patients from the coast to inland hospitals will not be possible after a Cascadia earthquake. Citation: Wang, Y., 2017, Oregon hospital and

water system earthquake risk evaluation pilot study: Oregon Department of Geology and Mineral Industries, Open-File Report O-17-01, 144 p., https://www.oregongeology.org/pubs/ofr/p-O-17-01.htm

2. This study establishes that the coastal hospitals are not prepared for a Cascadia earthquake. Citation: Wang, Y., 2018, Oregon coastal hospitals preparing for Cascadia: Oregon Department of Geology and Mineral Industries Open-File Report O-18-03, 97 p., https://www.oregongeology.org/pubs/ofr/p-O-18-03.htm

3. These are some Cascadia earthquake guidelines for the coastal hospitals including recommendations for hospitals to prepare for a 3-week duration (as the standard 96 hours is not sufficient). Citation: Wang, Y., and Norse, K. L., 2019, Resilience guidance for Oregon hospitals: Oregon Department of Geology and Mineral Industries, Open-File Report O-19-02, 6 p. plus 3 CREW guidance documents, https://www.oregongeology.org/pubs/ofr/p-O-19-02.htm

4. Information shared with executives from the eleven coastal hospitals at a special leadership event was compiled. It includes presentations as well as resilience planning maps for the three North coast hospitals. Citation: Wang, Y., Franczyk, J. J., Richer, K., Lamb, S., DePew, B., and Saito, A., 2019, Summary report on the Oregon Coastal Hospital Special Leadership Event: Oregon Department of Geology and Mineral Industries, Open-File Report O-19-01, 110 p., https://www.oregongeology.org/pubs/ofr/p-O-19-01.htm

5. This report includes resilience planning maps for the remaining eight (of eleven) hospitals. It also provides disaster resilience guidance and new planning information, such as the “coastal island” map. Citation: Wang, Y., and Franczyk, J. J., 2020, Oregon Coastal Hospital Resilience Project: Oregon Department of Geology and Mineral Industries, Open-File Report O-20-02, https://www.oregongeology.org/pubs/ofr/p-O-20-02.htm

Health Effects of Tsunamis

Among natural hazards, earthquakes are known to cause particularly high number of injuries. This is because of the unpredictable nature of when they occur (e.g., season and time of day) and because of the prevalence of vulnerable infrastructure that experiences damage. Typically, there is a wide geographic distribution of casualties due to regional ground shaking and the spatial distribution of damaged buildings. Casualties range in severity from immediate death to minor injuries. People may be trapped, for example in building rubble, and may experience crush injuries. Circumstances vary where victims may be trapped for days and may become unconscious. Following significant earthquakes, extensive search and rescue operations and transport of victims to emergency care facilities take place. This report does not further address earthquake-related casualties, as the focus is on tsunami-related casualties.

Due to the nature of Cascadia earthquakes, a tsunami will also be triggered. Recent subduction zone events, including in Indonesia (2004) and Japan (2011), have shown that the majority of people who cannot escape the tsunami will perish. Some people injured by the tsunami (or earthquake) will be unable to escape and drown. The majority of tsunami survivors are expected to be closer to the inland margins of the tsunami where the tsunami is less powerful (i.e., the tsunami depths and velocities are lower thereby less destructive). Casualties will be the highest if the earthquake occurs during the summer, which is when the coastal population is at its highest.

According to the World Health Organization (WHO), “Injuries and drowning have accounted for the vast majority of mortality experienced so far in countries affected by the tsunami. Injury related conditions will also account for many of the health care needs among those requiring medical attention in the immediate aftermath of the event. Whether resulting from the earthquake or the tsunami, falling structures, and waters full of swirling debris will have inflicted crush injuries, fractures, and a variety of open and closed wounds” (accessed on February 15, 2021, WHO website: www.who.int/violence_injury_prevention/other_injury/tsunami/en/).

Following the 2004 Indian Ocean tsunami where about 220,000 people perished, researchers who studied the tsunami health effects in Tamil Nadu, India found that injury patterns were concentrated in the first few weeks following the tsunami. This included severe trauma, extensive soft tissue and internal injuries. "Common injuries included contusions, open wounds, fractures and head injuries as a result of people being swept away in the water and thrown again stationary objects or hit by floating debris. In some cases, compression barotraumas of the tympanic membranes were detected as a result of pressure from turbulent water" (CRED, 2006).

Tsunami related health risks also include near-drowning incidents, which involves survival after suffocation caused by submersion in tsunami waters. Aspiration pneumonia, which is a bacterial infection of the lungs, can be caused by inhalation of seawater contaminated with mud and bacteria. A type of necrotizing aspiration pneumonia, referred to as "*tsunami lung*", was observed after the 2004 event (CRED, 2006). If left untreated, the resulting infection often spread into the bloodstream and brain, resulting in abscesses and serious neurological problems, including paralysis (CRED, 2006).

Similarly, Japanese researchers reported, "Many survivors of the tsunami that occurred following the Great East Japan Earthquake on March 11, 2011, contracted a systemic disorder called "*tsunami lung*," a series of severe systemic infections following aspiration pneumonia caused by near drowning in the tsunami. Generally, the cause of aspiration pneumonia is polymicrobial, including fungi and aerobic and anaerobic bacteria" (Kawakami and others, 2012).

Many survivors who experienced near-drowning events had "remained in unclean and traumatic conditions without receiving any immediate medical care for several hours." Being immersed in stagnant water, open wounds ad fractures resulted in the spread of bacteria, fungi and amoebae. Other unhygienic conditions increased the vulnerability of open wounds to infection. Health effects also include tsunami-related fires (CRED, 2006).

In the aftermath of a tsunami, health risks may involve increased stress, environmental hazards, water borne diseases, communicable diseases and the loss of shelter. Myocardial infarctions or cardiac arrest can be triggered by stress and overexertion both during and after the tsunami. People often become more exposed to heat and cold, contaminated water, insect bites, and infections. Food and medical supplies may be disrupted that harm people's health. Mental health often declines, such as due to heightened fear and anxiety of aftershocks and additional tsunamis, post-traumatic symptoms, and depression and alcoholism (CRED, 2006).

Health Effects of Tsunamis by the CDC

The Centers for Disease Control and Prevention (CDC) summarizes immediate health concerns, secondary effects and long-lasting effects for tsunamis, which is repeated below (accessed on February 22, 2021, CDC webpage: http://www.cdc.gov/disasters/tsunamis/healtheff.html). The CDC also has information on diseases and health concerns and information for clinicians.

Immediate health concerns

- After the rescue of survivors, the primary public health concerns are clean drinking water, food, shelter, and medical care for injuries.
- Flood waters can pose health risks such as contaminated water and food supplies.
- Loss of shelter leaves people vulnerable to insect exposure, heat, and other environmental hazards.
- The majority of deaths associated with tsunamis are related to drownings, but traumatic injuries are also a primary concern. Injuries such as broken limbs and head injuries are caused by the physical impact of people being washed into debris such as houses, trees, and other stationary items. As the water recedes, the strong suction of debris being pulled into large populated areas can further cause injuries and undermine buildings and services.
- Medical care is critical in areas where little medical care exists.

Secondary effects

- Natural disasters do not necessarily cause an increase in infectious disease outbreaks. However, contaminated water and food supplies as well as the lack of shelter and medical care may have a secondary effect of worsening illnesses that already exist in the affected region.
- Decaying bodies create very little risk of major disease outbreaks.
    - The people most at risk are those who handle the bodies or prepare them for burial.

Long-lasting effects

The effects of a disaster last a long time. The greater need for financial and material assistance is in the months after a disaster, including

- Surveying and monitoring for infectious and water- or insect-transmitted diseases;
- Diverting medical supplies from nonaffected areas to meet the needs of the affected regions;
- Restoring normal primary health services, water systems, housing, and employment; and
- Assisting the community to recover mentally and socially when the crisis has subsided.

Method for Developing Tsunami Casualty Estimates

Information on the best available Cascadia tsunami-related casualty estimates was researched, collected and evaluated from publicly available scientific references. Tsunami casualty estimates provided herein cover the entire Oregon coast and were derived from five references for the listed counties and city as follows:

1. Clatsop County, DOGAMI Open-File Report O-20-10 (Allan and others, 2020)
2. Tillamook County, DOGAMI Open-File Report O-20-14 (Allan and others, 2020)
3. Lincoln County, DOGAMI Open-File Report O-21-02 (Allan and O'Brien, 2021)
4. Lane, Douglas, Coos and Curry Counties, Wood and others (2015)

5. Port Orford, DOGAMI Open-File Report O-20-03 (Bauer and others, 2020)

The methods used for developing tsunami casualty estimates in the above references differ depending on data, analyses and assumptions incorporated in their development. Thus, one of the limitations of the casualty estimates provided herein relates to the inconsistencies of the available data owing to the non-uniform approaches used by the various researchers. Tsunami casualty data used are discussed below. For detailed information on the development of the original tsunami casualty estimates, refer directly to the references listed above.

The tsunami casualty estimates for Clatsop, Tillamook and Lincoln counties and Port Orford were developed by DOGAMI. DOGAMI's analyses included the DOGAMI Large (L) tsunami, which assumes a magnitude 9.0 (M9.0) Cascadia earthquake with a release of approximately 650 to 800 years of slip accumulation. The DOGAMI Large (L) tsunami line provides the inland extent of tsunami inundation with an associated 95% confidence interval. The Large tsunami line does not extend as far inland as the tsunami evacuation line (i.e., XXL), which, while useful for evacuation planning and life safety purposes, is not likely to occur due to conservative assumptions (Priest and others, 2013a; Priest and others, 2013b).

For hospital planning purposes, the DOGAMI Large tsunami line was selected for use herein to avoid being overly conservative. However, if the XXL tsunami evacuation scenario were to be selected, then the number of casualties could be significantly higher. Similarly, if the DOGAMI Small tsunami were selected, then the number of casualties could be significantly lower.

Additional information on DOGAMI tsunami hazards is available at:

- Tsunami webpage: https://www.oregongeology.org/tsuclearinghouse/
- Local tsunami hazard zones: OFR O-13-19 (https://www.oregongeology.org/pubs/ofr/p-O-13-19.htm)
- DOGAMI "Beat the Wave" evacuation maps are available for free download for Warrenton and Clatsop Spit, Gearhart, Seaside, Nehalem Bay, Rockaway Beach, Pacific

City, some unincorporated areas of Tillamook County, Lincoln City, some unincorporated areas of Lincoln County, Newport, Florence, Reedsport, areas around Coos Bay, and Port Orford

- Tsunami inundation maps: https://www.oregongeology.org/tsuclearinghouse/pubs-inumaps.htm
- Tsunami evacuation maps (including assembly areas): https://www.oregongeology.org/tsuclearinghouse/pubs-evacbro.htm
- Original scientific publication describing development of the tsunami scenarios: DOGAMI Special Paper 43 (2011) (https://www.oregongeology.org/pubs/sp/p-SP-43.htm)
- Tsunami information on the hospital resilience maps in Open-File Report O-19-01 https://www.oregongeology.org/pubs/ofr/p-O-19-01.htm (Wang and others, 2019) and Open-File Report O-20-02 https://www.oregongeology.org/pubs/ofr/p-O-20-02.htm (Wang and Franczyk, 2020)

DOGAMI's method for estimating casualties incorporated FEMA's Hazus software program and was further developed as described in a pilot study of these five coastal communities: Gearhart, Rockaway Beach, Lincoln City, Newport, and Port Orford (Bauer and others, 2020). The Hazus tsunami casualty model estimates are based on a rational actor pedestrian evacuation model in which all persons in the tsunami zone have acute awareness of the impending tsunami, that they possess knowledge of or can quickly determine the most optimal route to a tsunami safety area, and that all individuals seek safety as pedestrians and not by vehicles. The model assumes a group average (median) departure time and travel (walking) speed and accounts for individual variations from the group average using a lognormal distribution (FEMA, 2017a). While human behavior in an emergency situation is highly variable, the results from the Hazus tsunami casualty model provide critically important data for planners that will help assess the status quo, identifying areas where injury and fatality rates will likely be higher, while also providing the ability to quantify the efficacy of proposed mitigation solutions, such as tsunami vertical evacuation structures where needed (Bauer and others, 2020).

DOGAMI's modeling, including assumptions, also involved:

- Accurate wave arrival times after the onset of the Cascadia earthquake, which are based on DOGAMI's tsunami modeling (Priest and others, 2013a and 2013b; Gabel and others, 2020). These wave arrival times were also used in DOGAMI "Beat the Wave" evacuation models in Clatsop, Tillamook and Lincoln counties (DOGAMI Beat the Wave Open File Reports O-15-02, O-17-06, O-18-05, O-18-06, O-19-08, O-19-06, O-19-05, O-20-07 and O-20-05)
- American Community Survey (ACS) data
- A "delay time" of 10 minutes, where there is a 10-minute delay after earthquake shaking starts before people begin their tsunami evacuation towards tsunami-safe ground
- Two sets of evacuation walking speeds:
    - 4 feet per second (fps) and a slower speed of 3.2 fps for individuals 65 years in age and older
    - 6 feet per second (fps) and a slower speed of 4.8 fps for individuals 65 years in age and older
- Expected evacuation routes (or pathways) to tsunami-safe ground where some pathways such as older, seismically vulnerable bridges are assumed to be blocked and impassable
- Tsunami fatalities and injuries. For Port Orford, numbers are rounded to the nearest 10 (Bauer and others, 2020)
- Full time (permanent) residents and visitors are included for an earthquake occurring at 2 am during a summer weekend. Visitor populations are estimated for motels, vacation rental homes, campsites, RV sites, and boat slips at 100% nighttime occupancy. It should be noted that higher population situations within the tsunami zones do occur, such as during special events with large influxes of daytime visitors, but have not been modeled
- Local building inventory, including locations, use, year built, and size

Tsunami casualty estimates for injuries and fatalities following an expected magnitude 9 Cascadia earthquake for full time residents and visitors are provided for Clatsop, Tillamook and Lincoln counties and Port Orford based on DOGAMI's work. For Lane, Douglas, Coos and Curry counties, the tsunami casualty estimates were based on work by Wood and others (2015). The only exception is Port Orford in Curry County, which is based on DOGAMI's work (described above; Bauer and others, 2020, see Table 3-6). Analyses by Wood and others used the DOGAMI Large (L) tsunami and 2010 census block data. For these counties, Wood and others' modeling assumptions included:

- 15-minute tsunami wave arrival time at the wave's maximum inland extent after the onset of the Cascadia earthquake
- "Delay time" of 0 minutes, where people begin their tsunami evacuation immediately after earthquake shaking starts
- An evacuation walking speed of 3.6 feet per second (fps), regardless of age
- Most efficient route by foot to safe ground (Pedestrian travel times to safety are based on an anisotropic, path distance model that focuses on the slope and land cover of an area to calculate the most efficient paths on foot to safety from every location in a hazard zone).
- Combined tsunami fatalities and injuries
- Full time (permanent) residents only. No visitors are included.

Tsunami casualty estimates for combined injuries and fatalities following an expected magnitude 9 Cascadia earthquake for full time residents are provided for Lane, Douglas, Coos and Curry counties based on work by Wood and other (2015). For the purposes of this study, temporary residents were added by applying a factor of 5, which is based on work by Bauer and others (2020; see *Table 3-1 Permanent and temporary resident demographics per tsunami inundation zone,* where summer weekend temporary resident population can increase by as much as a factor of seven times). An injury ratio of 5% was applied based on work by Bauer and others (2020; see *Table 3-6 Estimated injury and fatalities associated with a CSZ (Mw = 9.0) earthquake and XXL1 tsunami, based on a 2 AM summer weekend scenario by community.*

Population/injury/fatality numbers are limited to occupants within the community's urban growth boundary. Earthquake injury estimates combine Level 1–3 estimates (Table 2-3), while fatality estimates are Level 4. Tsunami injury and fatality estimates assume a departure time of 10 minutes after earthquake commencement, where the injury ratio ranges from 1% to 9%).

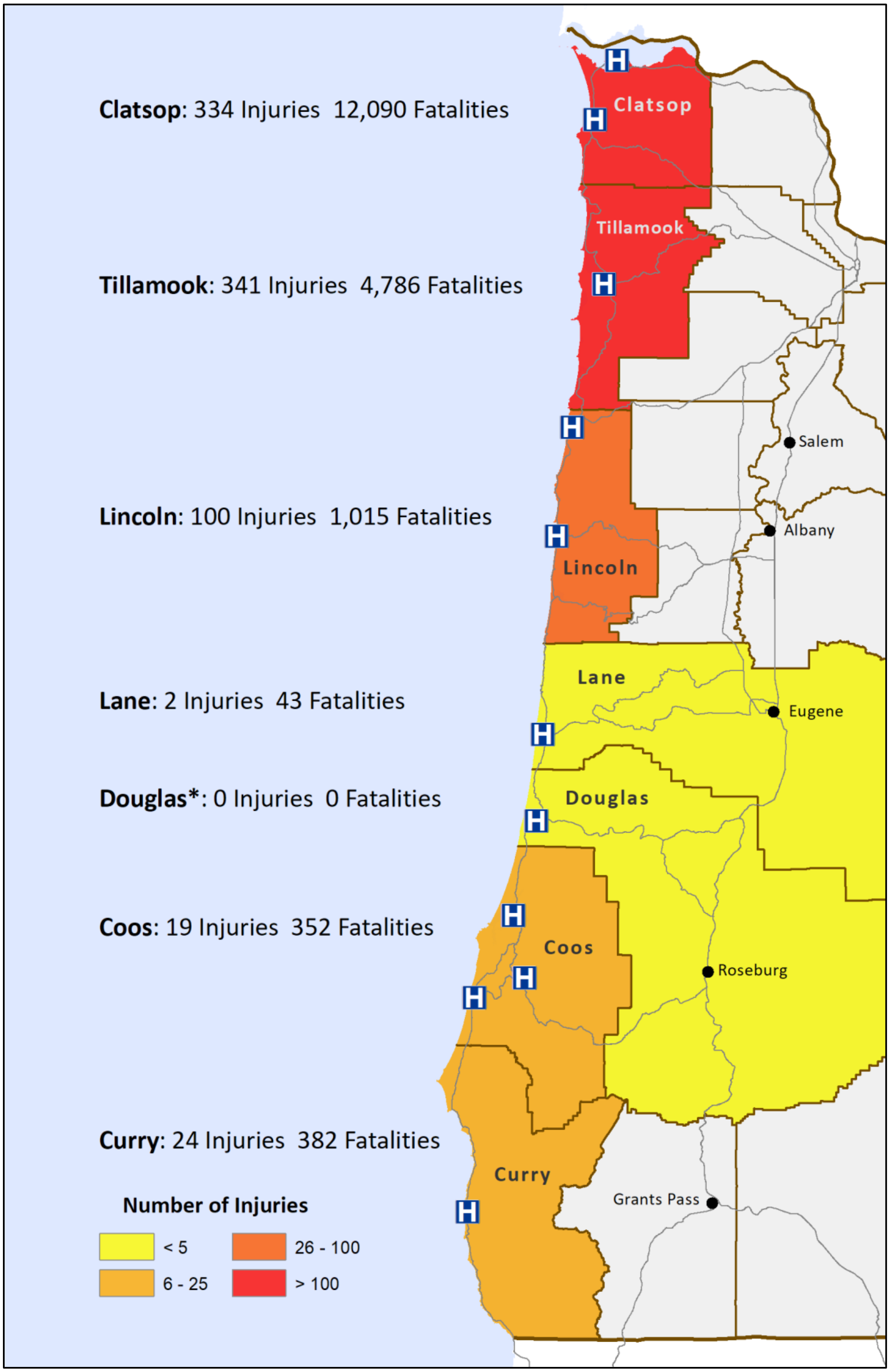
Estimates are not a prediction for an actual Cascadia earthquake event and the actual number of casualties will be different. A subject matter expert reviewed the tsunami casualty estimates provided herein for accuracy, appropriateness and clarity. It is possible that researchers will release new estimates in the future. Future estimates may involve different conditions, such as other hazards (e.g., incorporating sea level rise), bathymetry and topography (e.g., lower sand dunes), demographics (e.g., increased older populations or updated temporary population estimates, including summer weekend daytime), exposure (e.g., new developments), advancement in tsunami evacuation preparedness (e.g., improved evacuation pathways), and integration of newer safe technologies (e.g., tsunami resistant structures).

Tsunami Casualty Estimates

Tsunami casualty estimates following an expected magnitude 9 Cascadia earthquake are provided from North to South. Casualty estimates, which combine injuries and fatalities, are assumed to occur within hours of the earthquake (as opposed to days after the earthquake). Estimates, which include permanent residents and visitor populations, are for a summer "night" (i.e., 2 AM) when visitor populations are high. It is important to note the modeling assumes that *all* persons quickly evacuate by foot using the most optimal tsunami evacuation route; these estimates are *not* a worse-case scenario; these estimates are *not* a prediction; given the Hazus modeling techniques, some value summations may vary by a value of one due to rounding; and, earthquake casualties have *not* been included in the estimates [although some countywide earthquake casualties are available elsewhere, including Clatsop, Tillamook and Lincoln Counties (Allan and others, 2020a; Allan and others 2020b; Allan and O'Brien, 2021)].

Figure 1 summarizes the county injury estimates from a tsunami, and includes locations of coastal hospitals. Table 1 and Table 2 provides results by counties, and cities and communities, respectively. Table 2 includes areas listed as "other" at the bottom of each county, and includes some unincorporated communities. Unlike most other natural disasters, for tsunamis, the proportion of fatalities to injuries is reversed where most victims die rather than only suffer injuries. In general, if a person is caught where the tsunami is over six feet deep, then death is likely (FEMA, 2017).

Figure 1. Tsunami Casualty Estimates by County. Map includes locations of the eleven coastal county hospitals and selected state highways.



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* Estimates were developed assuming that *all* persons quickly evacuate by foot for a DOGAMI Large tsunami scenario. Does not include earthquake casualties.
** See text for comments on Douglas County and the likely under-reporting of estimates.

Table 2: Tsunami Casualty Estimates by Cities and Communities*

County	City or Community	Injuries	Fatalities	Total Casualties
Clatsop	Astoria	1	0	1
	Jeffers Garden	7	165	172
	Warrenton	35	1,111	1,146
	Gearhart	4	27	31
	Seaside	276	10,734	11,010
	Cannon Beach	5	24	29
	Arch Cape	2	8	10
	Other	3	22	25
Tillamook	Manzanita	1	6	7
	Nehalem Bay State Park	25	280	305
	Nehalem	0	0	0
	Wheeler	0	0	0
	Rockaway Beach	97	1,629	1,726
	Barview	37	338	375
	Garibaldi	1	3	4
	Bay City	0	0	0
	Tillamook	0	0	0
	Cape Meares	1	2	3
	Oceanside	0	0	0
	Netarts	0	1	1
	Cape Lookout State Park	28	673	701
	Sand Lake Recreation Area	24	200	224
	Tierra Del Mar	14	65	79
	Pacific City	18	100	118
	Neskowin	70	1,192	1,262
	Other	24	296	320
Lincoln	Lincoln City	30	236	266
	Gleneden Beach	10	224	234
	Lincoln Beach	0	0	0
	Depoe Bay	0	0	0
	Otter Rock	0	0	0
	Beverly Beach State Park	20	143	163
	Newport	9	49	58
	South Beach State Park	0	1	1
	Siletz	0	0	0
	Toledo	0	0	0
	Seal Rock	0	0	0
	Bayshore	21	302	323
	Waldport	3	15	18
	Beachside State Recreation Site	3	19	22
	Tillicum Beach Campground	0	1	1
	Yachats	0	1	1
	Other	4	23	27

Table 2: Tsunami Casualty Estimates by Cities and Communities (continued)*

County	City or Community	Injuries	Fatalities	Total Casualties
Lane	Florence	0	0	0
	Dunes City	0	0	0
	Unincorporated Lane Co.	2	43	45
****Douglas**	Reedsport	0	0	0
	Unincorporated Douglas Co.	0	0	0
Coos	Lakeside	0	0	0
	North Bend	0	0	0
	Coos Bay	0	0	0
	Coquille	0	0	0
	Bandon	0	0	0
	Unincorporated Coos Co.	19	352	371
Curry	Port Orford	20	310	330
	Gold Beach	0	5	5
	Brookings	0	0	0
	Unincorporated Curry Co.	4	67	71
Total		**819**	**18,667**	**19,486**

* Estimates were developed assuming that *all* persons quickly evacuate by foot for a DOGAMI Large tsunami scenario. Does not include earthquake casualties.
** See text for comments on Douglas County and the likely under-reporting of estimates.

Due to the extensive low-lying coastal plains on the north coast and the development patterns that exposes many people to tsunami hazards, the expected casualties in Clatsop and Tillamook Counties are the highest. Both counties may experience several thousands of fatalities and many hundreds of injuries. Unless more safety precautions are taken, both counties are expected to lose a high percentage of people in the tsunami zone, which is referred to as a high loss ratio. In contrast, with exception of low-lying communities and developments, the remaining counties have a lower tsunami exposure both in terms of low-lying vulnerable geography and people at-risk.

Actual tsunami casualties may be higher than the estimates herein for a variety of factors. One reason is that casualty estimates e*xclude* secondary injuries, such as heart attacks, electrocutions, bridge failures, and auto accidents. Also, populations with social characteristics that could slow or inhibit their tsunami evacuation were not explicitly accounted for. As an example, based on 2013-2017 data from the American Community Survey (ACS), about 19% of people in Oregon may have disabilities (Bauer and others, 2020; taken from https://www.census.gov/topics/health/disability/guidance/data-collection-acs.html). Across the state of Oregon, an average of 7.5% of people have non-institutionalized ambulatory difficulties. Another example is that, on average 2.6 % of Oregon's population has limited English speaking households (Source: slide 29 from the DOGAMI Tsunami Building Damage and Casualty Estimation presentation in Newport Oregon, dated January 24, 2019, as determined using ACS data).

Another limitation of current tsunami casualty modeling in Oregon relates to estimating daytime populations including visitors. The DOGAMI studies assume a "2 AM" situation for people in the tsunami zone – they are in homes, hotels/motels, tents, or RVs, and begin their evacuation from that starting point. However, on any given summertime day, especially weekends, Oregon beaches are typically full of visitors, who are closer to the ocean and further away from tsunami safety. Commercial downtown areas, such as Cannon Beach and Newport, have many visitors and staff. Bauer and others (2020, Figure NP-12) developed a summer daytime usage model and resulting casualty estimates for South Beach State Park in Newport, but to date this has not been extended to other popular beaches. Wood and others (2015) provided estimates for employees at commercial facilities within the tsunami zone, but did not provide estimates of daytime visitor numbers of those facilities.

The tsunami casualty modeling done by Wood and others (2015) did not include the particular situation at Winchester Bay RV Resort in Douglas County, which has no permanent residents but a large summertime visitor population. As identified by Gabel and others (2018, Figures 3-7 and 3-8), the current evacuation routes are limited. Some deaths and injuries for the visitor population in the RV park resulting from the tsunami are likely, though currently unquantified. We mention the Winchester Bay situation, along with the daytime usage situation at Oregon Dunes National Recreation Area (discussed in Gabel and others, 2018, Figure 3-10) to emphasize that the Douglas County estimate of zero casualties in Tables 1 and 2 are likely underestimates.

Uses of Tsunami Casualty Estimates

A Cascadia disaster will result in a high demand of hospital patients at the same time as reduced capacity of functionality of hospitals. Emergency departments (ED) are expected to be over-crowded, which will lead to significant detrimental effects on patient safety. In order to improve Oregon's coastal hospitals and health care systems level of readiness, preparing in advance of Cascadia disasters is needed. Information on uses of tsunami casualty estimates was researched from existing, publicly available information and further developed by expert opinion. Uses involve (but are not limited to): Emergency Department Demand and Capacity Planning; Training and Exercises; Emergency Transportation; Search and Rescue; Mass Fatality Management; and, Local Natural Hazard Mitigation Plans.

Tsunami casualty estimates can be used for planning and decision making by hospitals, healthcare system partners including the HPP coalitions, federal, state and local governments, and community stakeholders. The casualty estimates can be used by many stakeholders for a variety of purposes, including disaster planning to reduce service disruptions, facility master planning, as well as planning within the community. Uses of the tsunami casualty estimates are generally consistent with the needs and recommendations in the Oregon Resilience Plan (OSSPAC, 2013) and planning efforts relating to the State of Oregon's Emergency Support Function (ESF) 8 on public health and medical services, in particular medical surge and patient care. For example, in addition to providing a bases for the number of people requiring hospital care, it also provides information on the need for medical examiners and others to handle fatalities. As guided by ESF 8, coordination among these stakeholders is of key importance.

Emergency Department Demand and Capacity Planning

The tsunami casualty estimates are for use in pre-disaster planning, for both demand and capacity needs. The casualty estimates can be used to understand more about the number of patient arrivals at the hospital's ED. The casualty estimates can be used to help optimize emergency plans to reduce patient waiting time and provide timely provision of care. This will require coordination with various stakeholders.

If the tsunami casualty estimates far exceed the hospital's ED bed capacity, an evaluation on the need for local disaster care centers can be conducted. Similarly, if the casualty estimates far exceed the hospital's ED staff capacity, an evaluation on the need for staff rotations and volunteers can be performed.

To address shortages of licensed medical staff as a result of the earthquake, advanced coordination with the OHA-administered State Emergency Registry of Volunteers in Oregon (SERV-OR) can be conducted. SERV-OR includes the Medical Reserve Corps (MRC) and the State Managed Volunteer Pool, and provides a system of pre-certified health care professionals to volunteer their services during emergencies (OSSPAC, 2018). Establishing new medical reserve corps (MRC) and increasing the capacity of existing MRCs may be helpful.

To address hospital overcapacity conditions, it may involve promoting citizen preparedness and business preparedness to reduce the number of tsunami victims (i.e., reduce the demand).

In the Health Effects of Tsunamis section, information on the nature of injuries is provided to help with planning for patient care. Hospital emergency planners can use the information to help determine the type and amount of supplies and equipment that will be needed. As examples, it may be possible to stockpile certain supplies or apply lessons from the COVID 19 pandemic to improve the reliability of various supply chains.

Training and Exercises

The tsunami casualty estimates may be used for training purposes, such as in conjunction with testing emergency communication systems between the coast and Interstate-5 corridor. They may also be used for exercises, such as the national Cascadia Rising 2022 exercise.

Emergency Transportation

Injured people are mostly transported to the hospitals by private vehicles and not by ambulances and other trained personnel. The tsunami casualty estimates can be used to improve the community's emergency transportation planning for transporting victims to hospitals and other disaster care centers. Keep in mind that the road system and other aspects of the transportation network will be damaged. After an earthquake, a typical 10-minute commute time may take much longer or even be impossible to reach by driving on roads. Emergency planners can use this information as a bases on the number of people requiring patient air transport evacuation and local transportation, keeping in mind that it will be very challenging and limited to evacuate patients to other inland hospitals.

Search and Rescue (SAR)

Post-disaster experience indicates that untrained survivors carry out most of the Search and Rescue (SAR) activities, and that citizen SAR augments trained personnel. The tsunami casualty estimates can be used to improve the community's search and rescue capacity.

Mass Fatality Management

The tsunami casualty estimates can be used for mass fatality management planning. A surge of fatalities will require medical examiners and other personnel, search and rescue, identification of corpses, and transportation and management of corpses (e.g., burial).

Local Natural Hazard Mitigation Plans

Hospital planning can be integrated with the local natural hazard mitigation plans, including counties, cities and special districts. Recent natural hazard mitigation plans are available for Clatsop, Tillamook, Lincoln and Curry counties (Williams and others, 2020a; Williams and others, 2020b; Williams and others, 2020c; Williams and others, 2020d).

Discussion

Coastal hospitals can better manage the surge of expected tsunami injuries through disaster resilience planning and actions. Further actions can be taken to reduce expected tsunami casualties. Continued hospital leadership as well as community involvement will be necessary.

Many tools and guidance documents are available to help hospitals plan for catastrophic disasters. One new important document is Recommended Options for Improving the Built Environment for Post-Earthquake Re-occupancy and Functional Recovery Time [National Institute of Standards and Technology (NIST) and Federal Emergency Management Agency (FEMA), 2021]. To comply to a Congressional mandate, NIST and FEMA assessed and recommended options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time.

New and emerging opportunities and technologies may be evaluated and integrated into hospitals' disaster plans to prepare for and manage tsunami victims. Examples include:

- Building tsunami-resistant structures to protect hospital buildings and people from tsunami hazards
- Incorporating ShakeAlert, which has been providing earthquake early warnings to Oregonians since March 2021 via government Wireless Emergency Alerts. Hospital exercises and drills can be performed integrating ShakeAlert warnings. Hospital equipment can be automated using ShakeAlert warnings, such as shutting off pumps and operating room equipment.
- Flying drones to help with situational awareness, such as locations of tsunami damage

- Establishing advanced emergency communication systems to ensure the ability to communicate when normal means are unavailable
- Establishing, perhaps through partnerships, advanced reliable energy and water capabilities that will be functional during disasters (e.g., microgrids, desalinization) for the purposes of patient care
- Providing telemedicine for virtual medical assistance
- Participating in Cascadia Rising 2022, a national preparedness exercise that is centered around a hypothetical Cascadia earthquake and tsunami, and other exercises
- Coordinating with tsunami assembly area stakeholders to triage tsunami victims and transport the seriously injured to hospitals
- Encouraging more volunteers and provide training, such as medical reserve corps

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References

Allan, Jonathan C., Fletcher E. O'Brien, John M. Bauer, and Matthew C. Williams, 2020a, Earthquake and tsunami impact analysis for coastal Clatsop County, Oregon, including community-specific profiles for Astoria, Jeffers Garden, Warrenton, Gearhart, Seaside, Cannon Beach, and Arch Cape, Oregon Department of Geology and Mineral Industries Open-File Report O-20-10, 86 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-10.htm

Allan, Jonathan C., Fletcher E. O'Brien, John M. Bauer, and Matthew C. Williams, 2020b, Earthquake and tsunami impact analysis for coastal Tillamook County, Oregon, including community-specific profiles for Manzanita, Nehalem Bay State Park, Nehalem, Wheeler, Rockaway Beach, Barview, Garibaldi, Bay City, Tillamook, Cape Meares, Oceanside, Netarts, Cape Lookout Sate Park, Sand Lake Recreation Area, Tierra Del Mar, Pacific City, and Neskowin; Oregon Department of Geology and Mineral Industries Open-File Report O-20-14, 121 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-14.htm

Allan Jonathan C., and Fletcher E. O'Brien, 2021, Earthquake and tsunami impact analysis for coastal Lincoln County, Oregon, including community-specific profiles for Lincoln City, Gleneden Beach, Lincoln Beach, Depoe Bay, Otter Rock, Beverly Beach State Park, Newport, South Beach State Park, Toledo, Seal Rock, Bayshore, Waldport, Beachside State Recreation Site, Tillicum Beach Campground, and Yachats, Oregon Department of Geology and Mineral Industries Open-File Report O-21-02, 117 p. report, https://www.oregongeology.org/pubs/ofr/p-O-21-02.htm

Bauer, John M., Jonathan C. Allan, Laura L. S. Gabel, Fletcher E. O'Brien, and Jed T. Roberts, 2020, Analysis of earthquake and tsunami impacts for people and structures inside the tsunami zone for five Oregon coastal communities: Gearhart, Rockaway Beach, Lincoln City, Newport, and Port Orford**,** Oregon Department of Geology and Mineral Industries Open-File Report O-20-03, 185 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-03.htm

Centre for Research on the Epidemiology of Disasters (CRED), 2006, Gupa-Sapir, D., Parry LV, Degomme O, Joshi PC, and Arnold JP Saulina, Risk Factors for Mortality and Injury: Tsunami Epidemiological Findings from Tamil Nadu, CRED School of Public Health, Catholic University of Louvain, Brussels Belgium. https://www.undrr.org/publication/risk-factors-mortality-and-injury-post-tsunami-epidemiological-findings-tamil-nadu

Federal Emergency Management Agency (FEMA), 2017, Hazus tsunami model technical guidance: Washington, D.C., Federal Emergency Management Agency, 111 p. https://www.fema.gov/media-library/assets/documents/24609

Gabel, Laura L. S., Fletcher O'Brien, and Jonathan C. Allan, 2018, Local tsunami evacuation analysis of Reedsport and Florence, Douglas and Lane Counties, Oregon. Oregon Department of Geology and Mineral Industries Open-File Report O-18-05, 88 p. with GIS data, https://www.oregongeology.org/pubs/ofr/p-O-18-05.htm

Gabel, Laura L. S., Fletcher O'Brien, and Jonathan C. Allan, 2020, GIS data and method for determining maximum-considered local and distant tsunami wave arrival data for the Oregon Coast, Oregon Department of Geology and Mineral Industries Open-File Report O-20-09, 27 p. with GIS data, https://www.oregongeology.org/pubs/ofr/p-O-20-09.htm

Oregon Department of Geology and Mineral Industries (DOGAMI) Beat the Wave Open-File Reports (OFR):

- Local tsunami evacuation analysis of Seaside and Gearhart, Clatsop County, Oregon, OFR O-15-02
- Local tsunami evacuation analysis of Warrenton and Clatsop Spit, Clatsop County, Oregon, OFR O-16-08
- Local tsunami evacuation analysis of Rockaway Beach, Tillamook County, Oregon, OFR O-17-06
- Tsunami evacuation analysis of Florence and Reedsport, Land and Douglas Counties, Oregon OFR O-18-05
- Tsunami evacuation analysis of Pacific City, Tillamook County, Oregon, OFR O-18-06
- Tsunami evacuation analysis of some unincorporated Tillamook County communities: Building community resilience on the Oregon coast, OFR O-19-08
- Tsunami evacuation analysis of Lincoln City and unincorporated Lincoln County: Building community resilience on the Oregon coast, OFR O-19-06
- Tsunami evacuation analysis of Newport, Lincoln County, Oregon, OFR O-19-05
- Tsunami evacuation analysis of Nehalem Bay, Tillamook County, Oregon, OFR O-20-07
- Tsunami evacuation analysis of Port Orford, Curry County, Oregon, OFR O-20-05

Kawakami, Yutaka, Takashi Tagami, Takashi Kusakabe, Norihiro Kido, Takanori Kawaguchi, Mariko Omura and Ryoichi Tosa, 2012, Disseminated Aspergillosis Associated with Tsunami Lung, Respiratory Care, October 2012, 57 (10) 1674-1678; DOI: https://doi.org/10.4187/respcare.01701

National Institute of Standards and Technology and Federal Emergency Management Agency, NIST-FEMA Special Publication, 2021, Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time, FEMA P-2090/ NIST SP-1254, January 2021
https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1254.pdf

Oregon Seismic Safety Policy Advisory Commission (OSSPAC), 2013, Oregon Resilience Plan, https://www.oregon.gov/oem/Documents/Oregon_Resilience_Plan_Final.pdf

OSSPAC, 2018, Mass Care and Mass Displacement after a Cascadia Subduction Zone Earthquake OSSPAC Publication 18-02 September 25, 2018

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013a, Tsunami animations, time histories, and digital point data for flow depth, elevation, and velocity for the Central Coast Project Area, Coos, Douglas, Lane, and Lincoln Counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-16, GIS data. http://www.oregongeology.org/pubs/ofr/p-O-13-16.htm

Priest, G. R., Witter, R. C., Y. Zhang, Y., Wang, K., Goldfinger, C., Stimely, L. L., English, J. T., Pickner, S. G., Hughes, K. L. B., Wille, T. E., and Smith, R. L., 2013b, Tsunami inundation scenarios for Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-13-19, 14 p., GIS data. http://www.oregongeology.org/pubs/ofr/p-O-13-19.htm

Wang, Y., 2017, Oregon hospital and water system earthquake risk evaluation pilot study: Oregon Department of Geology and Mineral Industries, Open-File Report O-17-01, 144 p., https://www.oregongeology.org/pubs/ofr/p-O-17-01.htm

Wang, Y., 2018, Oregon coastal hospitals preparing for Cascadia: Oregon Department of Geology and Mineral Industries Open-File Report O-18-03, 97 p., https://www.oregongeology.org/pubs/ofr/p-O-18-03.htm

Wang, Y., and Norse, K. L., 2019, Resilience guidance for Oregon hospitals: Oregon Department of Geology and Mineral Industries, Open-File Report O-19-02, 6 p. plus 3 Cascadia Region Earthquake Workgroup (CREW) guidance documents, https://www.oregongeology.org/pubs/ofr/p-O-19-02.htm

Wang, Y., Franczyk, J. J., Richer, K., Lamb, S., DePew, B., and Saito, A., 2019, Summary report on the Oregon Coastal Hospital Special Leadership Event: Oregon Department of Geology and Mineral Industries, Open-File Report O-19-01, 110 p., https://www.oregongeology.org/pubs/ofr/p-O-19-01.htm

Wang, Y., and Franczyk, J. J., 2020, Oregon Coastal Hospital Resilience Project: Oregon Department of Geology and Mineral Industries, Open-File Report O-20-02, https://www.oregongeology.org/pubs/ofr/p-O-20-02.htm

Williams, Matt C., and Lowell H. Anthony, 2020a, Natural Hazard Risk Report for Curry County, Oregon, including the Cities of Brookings, Gold Beach, Port Orford and Unincorporated Communities of Harbor and Nesika Beach**,** Oregon Department of Geology and Mineral Industries Open-File Report O-20-15, 82 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-15.htm

Williams, Matt C., Lowell H. Anthony, and Fletcher E. O'Brien, 2020b, Natural Hazard Risk Report for Clatsop County, Oregon, Including the Cities of Astoria, Cannon Beach, Gearhart, Seaside, and Warrenton and the Unincorporated Communities of Arch Cape, Svensen-Knappa, and Westport**,** Oregon Department of Geology and Mineral Industries, Open-File Report O-20-16, 93 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-16.htm

Williams, Matt C., Christina A. Appleby, Lowell H. Anthony, and Fletcher E. O'Brien, 2020c, Natural hazard risk report for Lincoln County, Oregon, including the Cities of Lincoln City, Depoe Bay, Siletz, Newport, Toledo, Waldport, and Yachats, and the Confederated Tribes of Siletz Indians, and the unincorporated communities of Otis-Rose Lodge, Salishan-Lincoln Beach, Otter Rock, Seal Rock-Bayshore, and Wakonda Beach**,** Oregon Department of Geology and Mineral Industries Open-File Report O-20-11,99 p. report, https://www.oregongeology.org/pubs/ofr/p-O-20-11.htm

Williams, Matt C., Christina Appleby, John Bauer, and Jed Roberts, 2020d, Natural hazard risk report for Tillamook County, Oregon, including the cities of Bay City, Garibaldi, Manzanita, Nehalem, Rockaway Beach, Tillamook, and Wheeler and the unincorporated communities of Neskowin, Oceanside, Netarts, and Pacific City, Oregon Department of Geology and Mineral Industries Interpretive Map Series 58**,** https://www.oregongeology.org/pubs/ims/p-ims-058.htm

Wood, Nathan J., Jeanne Jones, Seth Spielman, and Mathew C. Schmidtlein, 2015, Community clusters of tsunami vulnerability in the US Pacific Northwest, Proceedings of the National Academy of Sciences of the United States of America (PNAS), pp. 5354-5359, https://doi.org/10.1073/pnas.1420309112