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# Modeling Tsunamis in Washington State and Integrating Universal Design: Incorporating Universal Design into Tsunami Modeling Results for Cascadia Subduction Zone Faults to Create and Inundation and Universal Design Evacuation Map for Washington State

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**Abstract**
Current tsunami hazard inundation and evacuation maps in the Puget Sound are based primarily on Cascadia and Seattle fault tsunamis. The standard evaluation process for tsunami impacts focuses on elevation and hypothetical fault rupture of known and predicted earthquakes. However, there are several known tsunami deposits in the Puget Sound that are not from Cascadia or Seattle fault tsunamis, potentially from other faults within the region, that could affect tsunami mitigation. Work to understand newly discovered crustal deformation and faults in Puget Sound is ongoing, therefore evacuation and inundation maps need to be updated to include these new faults and integrate universal design more broadly. Methods involved using GeoClaw software to map tsunamis from the Cascadia Subduction Zone (CSZ), Leech River fault (LRF), and Utsalady Point fault (UPF). Modeled tsunamis determined the overall inundation of Port Angeles, Washington through a wide range of earthquake inputs of magnitude, proximity, and recurrence. The output simulations were evaluated with key components of universal design to create a new tsunami hazard map. Comparison between the universal design-based map to current the tsunami hazard map allowed for an evaluation of the current evacuation map. This evaluation can improve the assessment of bridges and other evacuation mechanisms. This research can contribute to future tsunami hazard map revisions saving lives, can help with emergency management planning, and spur reevaluating evacuation plans within the tsunami impact area.

**Keywords**
‘tsunami inundation’, ‘GeoClaw’, ‘universal design’, ‘vulnerable populations,' 'modeling'

**Peer Review**

This work has undergone a double-blind review by a minimum of two faculty members from institutions of higher learning from around the world. The faculty reviewers have expertise in disciplines closely related to those represented by this work. If possible, the work was also reviewed by undergraduates in collaboration with the faculty reviewers.

## SUBDUCTION ZONE HAZARDS

Earthquakes and tsunamis along subduction zones pose a hazard, especially for vulnerable populations. However, the principle of universal design (UD) is not integrated broadly in tsunami mitigation and planning. Interdisciplinary studies that combine geoscience and UD research are critical for building evacuation maps that can meet a diverse population's needs.

In the Pacific Northwest, the chief earthquake threat is the Cascadia Subduction Zone (CSZ) located off the coast of Washington, Oregon, and Northern California (*Figure 1)* (Witter et al., 2013). The CSZ can generate earthquakes that can cause large-scale tsunamis and endanger citizens (Heaton & Hartzell, 1987.) The CSZ is a 1,000-kilometer-long fault formed from the subduction of the Juan de Fuca plate under the North American Plate (*Figure 1*) (NOAA, 2019). Washington state has the second highest risk in the U.S. for a significant subduction zone rupture (Allen, 2020). The city of Port Angeles, located on the Strait of Juan de Fuca, is at high risk from tsunami inundation from both the CSZ and from local crustal faults.

This study will model CSZ tsunamis and hypothetical tsunamis generated from two local faults - the Leech River (LRF) and Utsalady Point fault (UPF) *(Figure 1)*. Although models of large Cascadia subduction zone earthquakes and tsunamis exist, these two local faults near Port Angeles have not been modeled for inundation. For Port Angeles, tsunamis generated from smaller but closer faults could pose a greater hazard due to quick arrival and less evacuation time. With nearby geologic evidence for Holocene tsunami activity (Williams and Hutchinson, 2000; Williams et al., 2005; Hutchinson et al., 2013), local faults need to be included to help design and update current inundation and evacuation maps to protect vulnerable populations. Landslides also pose a threat to Port Angeles because they can produce tsunamis (Smith & Karlin, 2003), however, this study will focus on earthquake-triggered tsunamis.

## FAULTS, EARTHQUAKES, AND TSUNAMIS AROUND PORT ANGELES

The most recent CSZ earthquake, a $M_w$ 9.0 in 1700 A.D., left significant tsunami records throughout the Pacific (Atwater et al., 2005). There have been up to seven earthquakes with corresponding tsunamis in the last 3,000 years (Goldfinger et al., 2012). If it were to rupture again, at its worst, the CSZ is considered capable of producing a $M_w$ 9.3

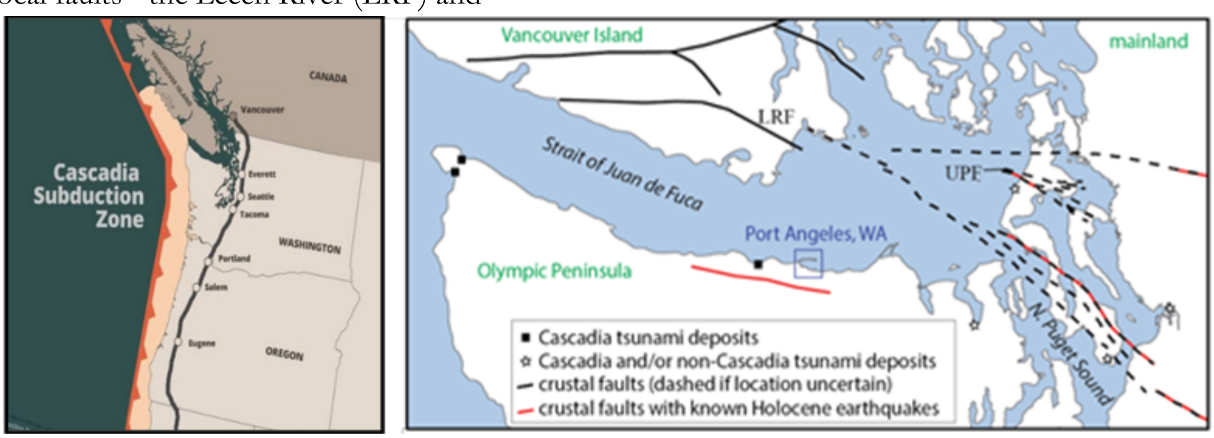


*Figure I.* (LEFT). The CSZ (in orange) denotes where the Juan de Fuca plate is subducting below North America (from NOAA, 2019). (RIGHT). Part of Puget Sound, Washington with site area Port Angeles. Crustal fault traces marked by solid and dashed lines; LRF stands for Leech River fault and UPF stands for Utsalady Point fault. Sites with previously identified tsunami deposits near Port Angeles are shown by black squares or white stars (locations from Williams and Hutchinson, 2000; Williams et al., 2005; Hutchinson et al., 2013; Peterson et al., 2013).

earthquake (Nelson et al., 2006). Earthquake studies in Puget Sound are advancing our understanding of the regional hazards, including recognition of crustal fault activity (Morell et al., 2017; Sherrod and Gomberg, 2014). Currently, the CSZ, the Tacoma fault, and the Seattle fault are the only faults that have corresponding tsunami simulations within Puget Sound (Allen, 2020). Therefore, this research focuses on two previously unmodeled faults, the Leech River fault (LRF) and the Utsalady Point fault (UPF). The LRF has demonstrated Quaternary surface ruptures, potentially crossing the vast expanse of Puget Sound (*Figure 1)* (Morell et al., 2017). The UPF produced two earthquakes affecting Whidbey Island in the last 2200 years. If they extended into the Strait of Juan de Fuca, they likely might have produced tsunamis (Johnson et al., 2004). However, no tsunami research has been published on either of these two faults.

## NEED FOR ADDITIONAL MODELING AND UNIVERSAL DESIGN

Port Angeles citizens could be at a significant disadvantage if a large tsunami occurred off the coast with present-day evacuation routes based on current inundation maps, specifically the tourist, children, and elderly populations within the tsunami hazard areas. Updating evacuation route maps based on universal design (UD) will save a higher percentage of the population. Currently, the ADA requires public accommodations to be accessible, but these evacuation routes transcend individual business responsibility. Despite that, it is a civic responsibility assumed by the authorities tasked with assessing the risk and providing an evacuation strategy to provide accessible routes.

Universal design (UD) is a set of seven principles that strategically minimize the need for individual accommodation by analyzing the design from multiple perspectives *(Repository Table 3*; *github.com/Spero-Hannah/GeoClawPortAngeles; doi:10.5281/zenodo.4646315)*. UD is the plan and composition of an environment to be accessed, understood, and used to the greatest extent possible by all people regardless of age, size, ability, or disability (Sanford, 2012). Through creative engineering, education, technology, more funding, and outreach, UD can save more lives and contribute to community preparedness and resiliency.

## RESEARCH OBJECTIVES

- Model $M_w$ 8.7 - 9.2 earthquakes on the CSZ and $M_w$ 7.0 - 7.5 earthquakes on two Puget Sound faults to determine tsunami inundation in Port Angeles, WA
- Identify areas with higher inundation from local fault tsunamis than CSZ tsunamis for UD integration
- Perform an assessment of roadways inundated within the Port Angeles area within each scenario's simulation
- Use UD to evaluate how the demographics of Port Angeles would be affected by both local fault and CSZ tsunami scenarios

## METHODS

GeoClaw software (www.clawpack.org; version 5.4.1 for this study) is used for tsunami assessment (LeVeque et al., 2011) by several research groups, including NOAA, Washington Geological Survey, University of Washington, and Central Washington University. GeoClaw solves nonlinear hyperbolic partial differential shallow-water wave equations with high-resolution finite volume methodology using an evolving wet/dry front (Mandli et al., 2016). For bathymetry, we used 1/3 arc-second resolution coastal digital elevation models for the Strait of Juan de Fuca and Port Townsend, with a WGS84 horizontal datum and NAVD88 vertical datum (National Centers for Environmental Information, 2011, 2015), and ETOPO1 1-second resolution bathymetry for the Pacific Ocean (Amante and Eakins, 2009). We created nine simulated gauges to monitor water levels where infrastructure damage could occur.

For earthquake input files, we used standard models for CSZ tsunamis (Witter et al., 2013), however, the local fault earthquakes were created from simple estimates of fault geometry. These earthquake input files are available in our open-source repository (*doi:10.5281/zenodo.4646315*). The simulation time was 3 hours for the models, and the Courant number condition controlled the time step 0.75<x<1.0. The CSZ earthquake were identified by labeling them as "t-shirt sizes" from Witter et al. (2013): SM ($M_w$ 8.7), M ($M_w$ 8.9), L ($M_w$ 9.1), and XL ($M_w$ 9.2). Using this nomenclature allows for accessibility of tsunami information with UD as simple, straightforward information. The current Washington Geological Survey tsunami inundation maps are based on the largest reliable potential earthquake rupture and tsunami events, a 'large' event (L). For reference, the largest historical earthquake and tsunami on the CSZ, the 1700 tsunami, is classified as a medium (M) (Witter et al., 2013).

The surface trace of the UPF and LRF (*Figure 1*) is estimated from the Quaternary faults database (USGS and WADNR, 2018), but other aspects of hypothetical ruptures on these faults are unknown. The scenarios we created included faults with a dip of 60° and 75° for the LRF and 90° for the UPF (*Repository Table 1*). The LRF had a width of 15 km and a length of 60 km, spanning the whole open waterway, or just 30 km, either closer to Vancouver Island or Whidbey Island. The slip was 5 m for every scenario, resulting in earthquakes being either a $M_w$ 7.3 or 7.5. The UPF had a width of 8 km and a length of 29 km, reflecting the open-ocean trace of the fault (*Figure 1*). In this case, the slip was 4 m, resulting in an earthquake of $M_w$ 7.0.

We calibrated the tsunami modeling results from the Leech River fault and Utsalady Point fault using the CSZ 't-shirt sizes' for reference. With UD, the average person will be able to digest critical information that is accessible, by using the 't-shirt design terminology.' Inundation modeling allows simulated tsunami heights to be compared to current maps, improving the safety of vulnerable demographics in Port Angeles, Washington. With mapping the LRF and the UPF, there is also the potential of identifying the inundation zone and non-Cascadia tsunami deposits in those zones (*Figure 1).*

# RESULTS

## CASCADIA SUBDUCTION ZONE

We used the CSZ inundation maps and waveforms at our gauges for the CSZ SM, M, L, and XL scenarios as a reference for UPF and LRF tsunamis. The L ($M_w$ 9.1) is considered the credible worst-case scenario from the CSZ *(Repository Figure 1)*. The simulated L tsunami wave height had maximum flow depths between 5-10 m, although most of the scenario was <5 m. The XL ($M_w$ 9.2) scenario, in comparison, reached tsunami wave heights over 20 m *(Repository Figure 2)*.

## CRUSTAL FAULT RESULTS

For the Leech River fault, the most extensive inundation was equivalent to the CSZ medium (M) tsunami in Port Angeles. Maximum flow depths ranged up to 5 m (*Repository Figure 3),* and the farthest inundation reached ~700 meters inland. In contrast, the UPF scenario's inundation was equivalent to the CSZ large (L) tsunami in Port Angeles with maximum flow depths up to 10 m *(Repository Figure 4)*. The inundated area reached ~2,500 m inland at farthest, using stream channels for maximum inland range.

## SPECIFIC AREAS AFFECTED

Inundation mapping of our tsunami scenarios shows several ways that Port Angeles would be impacted in ways that would affect evacuation efforts. For example, roadway intersections are fully inundated, like Front Street and 1st Street, in the CSZ XL

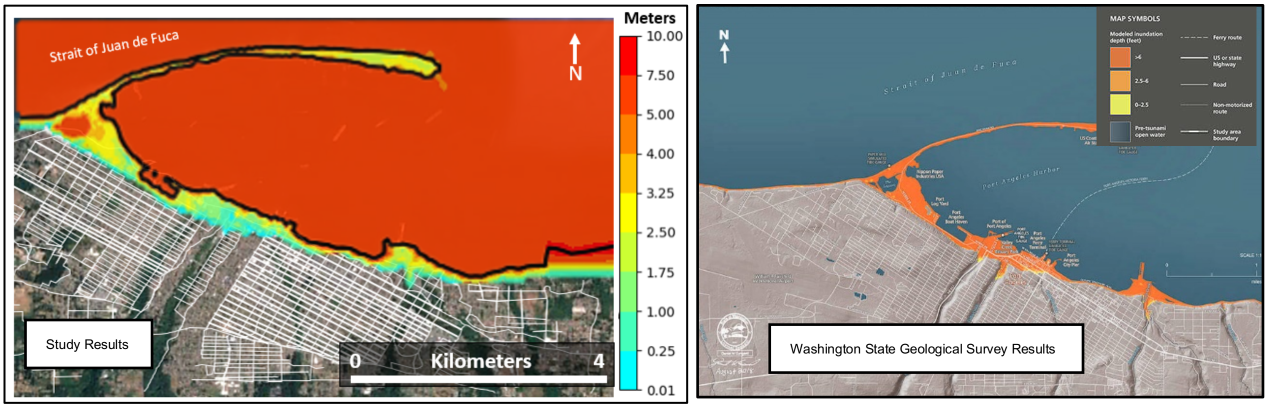


*Figure II.* (LEFT) Results from this study depict the CSZ-L maximum flow depth using the color scheme of the scale bar (meters). The background image for the maximum flow plot is from Google Earth. lines depict inundated or may be damaged during an earthquake triggered tsunami. (RIGHT) Publicly available tsunami inundation map with the tsunami hazard zone in orange (Eungard, 2018).

scenario. Additionally, some infrastructure in the simulation was impacted by 15-17 m high waves, such as the Port Angeles Ferry terminal *(Repository Figure 2)*. The Tesoro Port Angeles Terminal, US Coast Guard Station and the Olympic Medical Center would be impacted the most, along with other coastline infrastructure. Another concern from the modeling results is the Pettit Oil Co., which has an offshore drilling rig that could cause a small-scale oil spill with ecological effects. The Emergency Management Division's office, which oversees preparedness, warnings, and evacuation, is in the basement of a building within the CSZ M tsunami inundation zone.

In the CSZ XL scenario, several creeks, i.e., White Creek (48.097, -123.420), Lees Creek (48.076, -123.312), and Morse Creek (48.062, -123.212), would increase water surface height from the wave inflow, likely flooding roads within a 22.86-meter vicinity. Also, there is an inlet (48.103, -123.357) that would experience increased water levels. A substantial evacuation problem arises at West Highway 101, Tumwater Creek (48.107, -123.459), and Valley Creek (48.107, -123.451), as the creeks could serve as channels inland for the tsunami wave. If these creeks were to flood over US Highway 101 West, then it would only be passable on foot.

## INTEGRATING UNIVERSAL DESIGN

Universal design principles (See Repository Table 3) are multidimensional, focusing on both function and the evacuation plan's functionality (Sanford, 2012). We performed a vulnerable demographic evaluation of the area (*Figure 2*) to determine which two of the vulnerable populations (*Repository Table 2)* would be at the highest risk in both CSZ L and the UPF scenarios).

### TOURISTS

Port Angeles is a popular destination for over 3 million people who visit the North Olympic Peninsula each year (.U.S. Census Bureau, 2010). There are six coastal motels or hotels within the L inundation area, totaling a maximum of 385 guest rooms, each with four-person capacity *(Repository Figure 1). List: Red Lion, Quality Inn Uptown, Uptown Inn, Flagstone, Royal Victorian, and Riviera Inn.* Although the current evacuation route (Eungard et al., 2018) would work in SM-M tsunami scenarios, it would not be adequate for L-XL scenarios.

Integrating UD with awareness of usability barriers could help save tourist's lives if a tsunami were to occur. By using simple graphics displaying visible and tactile information, tourists could gain information of the geohazard (See *Principle 3 and 4, Repository Table 3).* Maps of tsunami warning and evacuation plans within the hotels and motels are essential for tourists. However, current evacuation plans, and the inundation map include usability barriers that affect individuals with reduced motor abilities, mental cognizance, and auditory disabilities. Usability barriers could include lack of signage, cluttered information, or information not depicted sequentially. Usability could be improved by increasing the amount and accessibility of information, decluttering unnecessary information, and presenting information sequentially.

## ELDERLY

Approximately 18%, nearly 20,000 people, of the Port Angeles metropolitan area are elderly. (U.S. Census, 2010). Elderly individuals often have lower or upper extremity limitations, restricting their ability evacuate physically. Many have cognitive limitations and receive memory care. They may not remember tsunami warning information, where evacuation information is located, or how to evacuate. There are five assisted living facilities or senior centers that are within or near the L inundation area (*Repository Figure 5). List: Senior Citizens Center, Port A. Community Center, Caregivers Home Health Inc., and Olympic Elder Care.*

Auditory disability is also common, making it challenging to hear tsunami sirens or phone alerts. Auditory disability limitations could be overcome using pictorial explanations of essential evacuation instructions (See *Principle 4 Repository Table 3*. By designing for equitable use (*Principle 1, Table 3)* for differing ability levels, more people within this demographic would be informed enough to safely evacuate if there were a tsunami.

## UNIVERSAL DESIGN: FUTURE WORK

There are around 4.3 million people located within Puget Sound who live at risk from an earthquake and resulting tsunami (Wood & Soulard, 2008). This modeling aided in identifying areas where vulnerable demographics would be at great disadvantages. However, a significant amount of work left to do to (1) identify all vulnerable demographic spots in the maximum inundation scenarios and (2) integrate all UD principles.

Currently, modeling focuses on the CSZ and the Seattle fault and does not include other local fault ruptures or earthquake-triggered landslides that generate tsunamis. Moreover, geohazard mapping would be far more effective and save more lives if it followed the universal design principles. However, its application is rare, although compliance with WAG3 P.O.U.R. principles is expected of all Washington State agencies and their vendors according to Policy 188 (Office of the Chief Information Officer, 2020). It is critical to improve numerical modeling efforts for updated inundation maps and to translate those results into evacuation plan suggestions that minimize potential usability barriers. Future work on evacuation routes should quantify the flexibility in use and tolerance in error for different tsunami warning tools such as signage, sirens, and pamphlets.

Through improving inundation maps, evacuation maps, and tsunami evacuation tools in addition to continuing to improve tsunami modeling, populations will be more prepared, and lives will be saved. Using universal design for maps and scientific communication and planning evacuations with a holistic view of the population will lower vulnerable populations' risks and save lives.

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