New Cascadia Subduction Zone Tsunami Inundation Modeling to Guide Relocation of Coastal Infrastructure for Indian Tribes on the Northern Washington Coast

by

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ABSTRACT

There have been advances in understanding the potential for great tsunamigenic earthquakes on the Cascadia subduction zone, motivating an effort to update the assessment of tsunami hazards on the Washington coast. Fine-resolution (1/3 arc-second) digital elevation models (DEMs) of the Strait of Juan de Fuca and northern Olympic Peninsula have recently been made available, and coastal Indian tribes (Quinault, Hoh, and Quileute) have made plans to move important infrastructure out of their tsunami hazard zones. We have made numerical simulations of tsunamis incident on the Quinault, Hoh, Quileute, and Makah Reservations and adjacent coast with the GeoClaw numerical model for a local tsunami generated by a 9.1M Cascadia subduction zone earthquake, designated 'L1' by Witter and others (2011). This scenario is estimated to have a 2% probability of nonexceedance in 50 years, which would be comparable to the International Building Code standard for seismic loading on structures of high importance, and provides appropriate guidance to the affected communities for siting of their significant infrastructure.

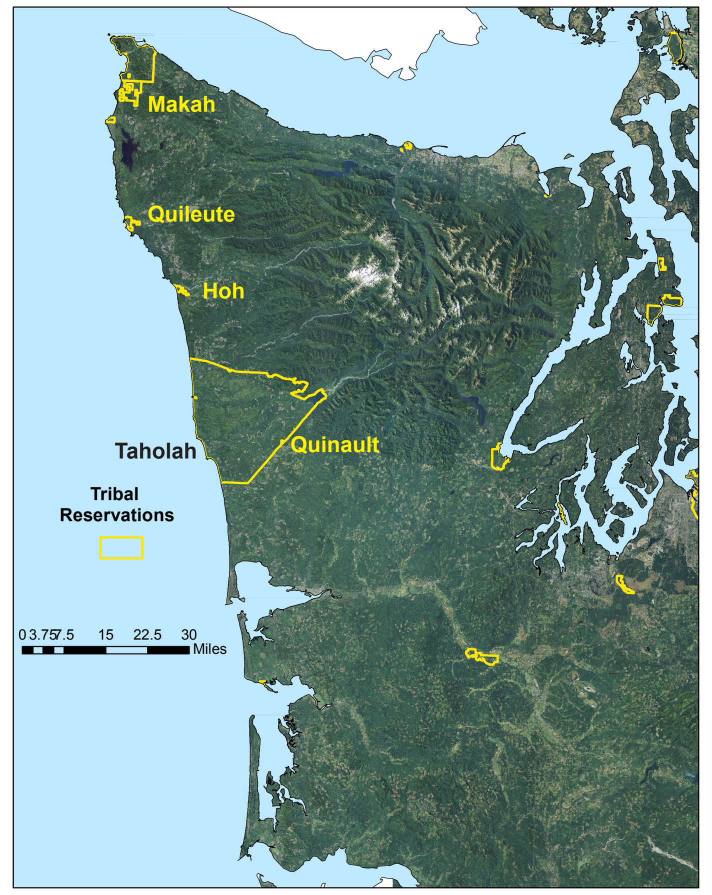


Figure 1. Regional map of the Olympic Peninsula showing Tribal lands.

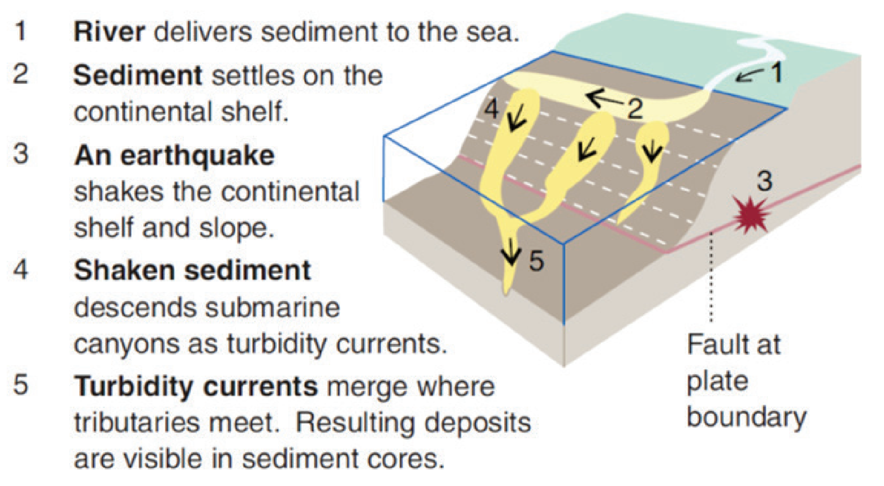
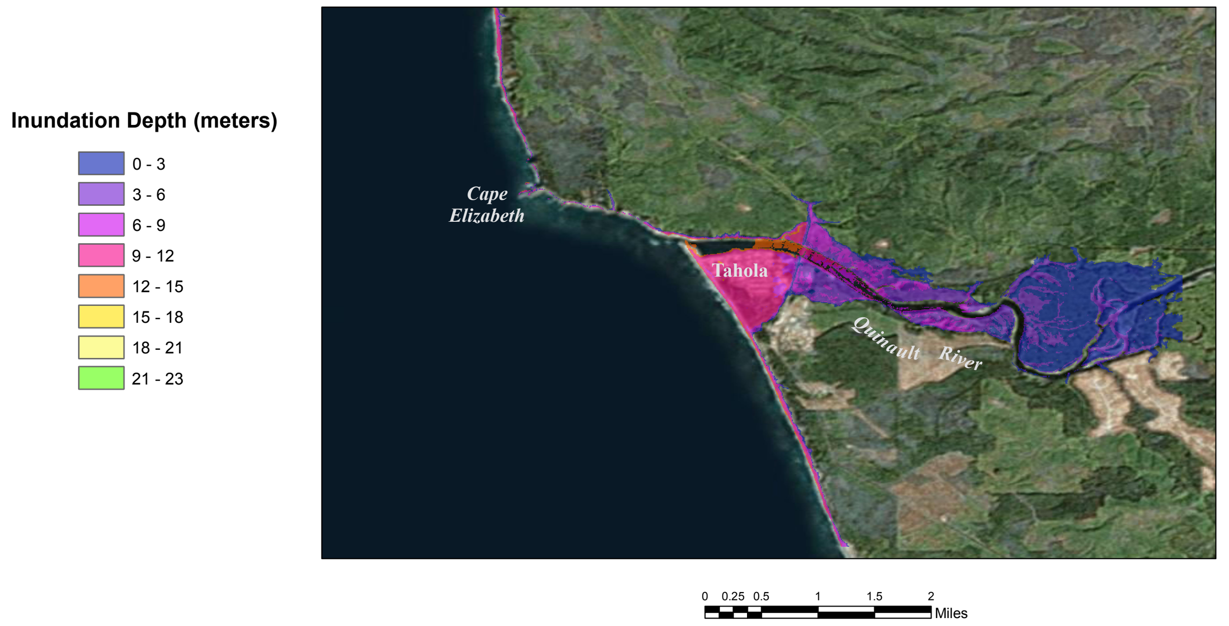
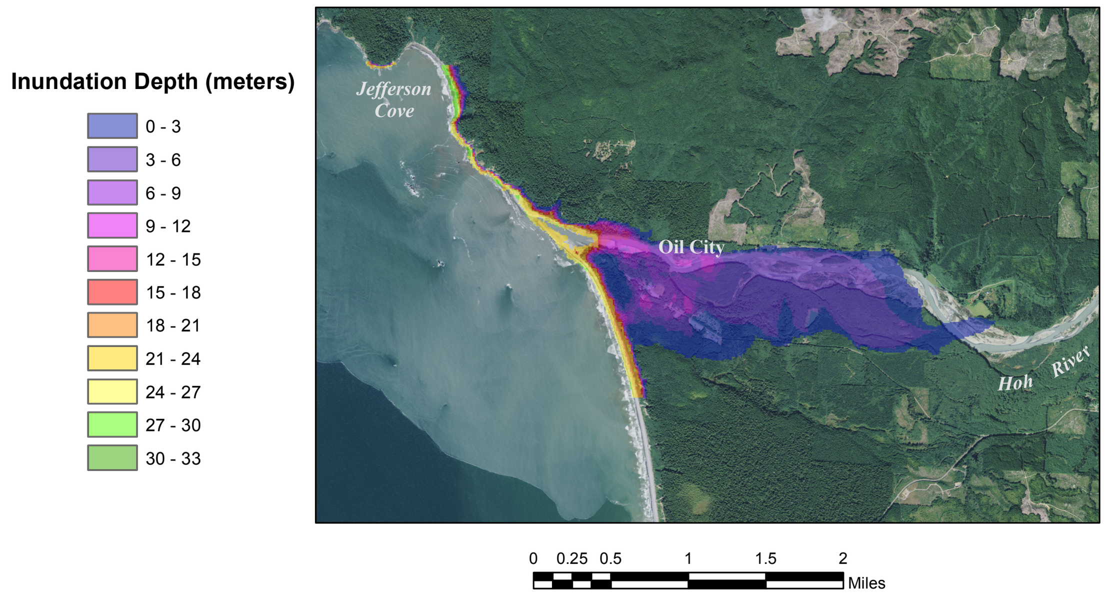


Figure 2. General schematic showing coalescing offshore turbidity currents generated during subduction zone earthquakes.

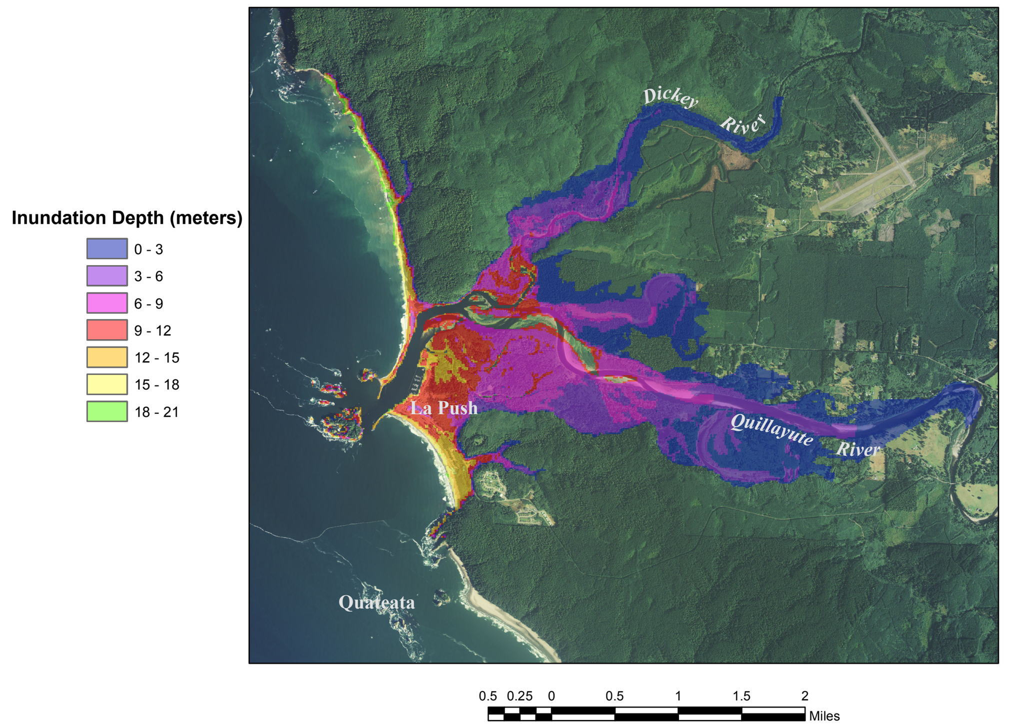
Tsunami Inundation Depth at Taholah for Scenario L1



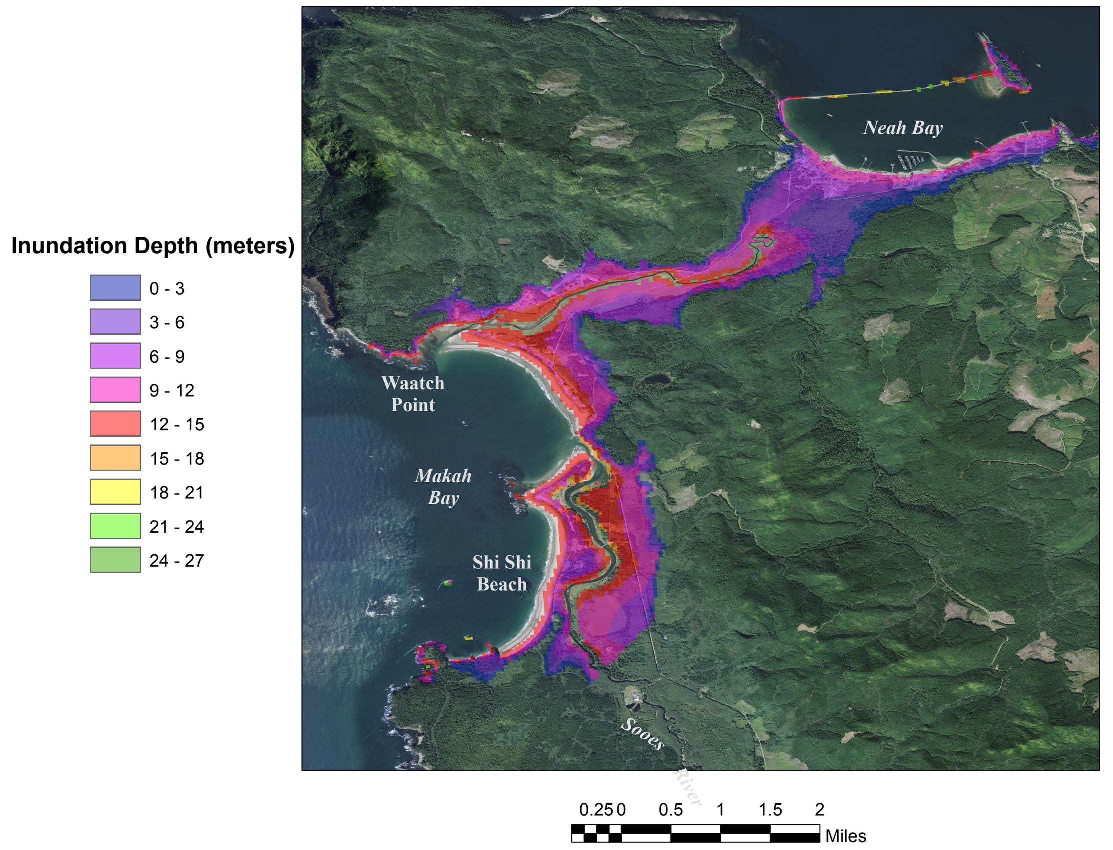
Tsunami Inundation Depth at Hoh Reservation for Scenario L1



Tsunami Inundation Depth at La Push for Scenario L1



Tsunami Inundation Depth at Neah Bay for Scenario L1



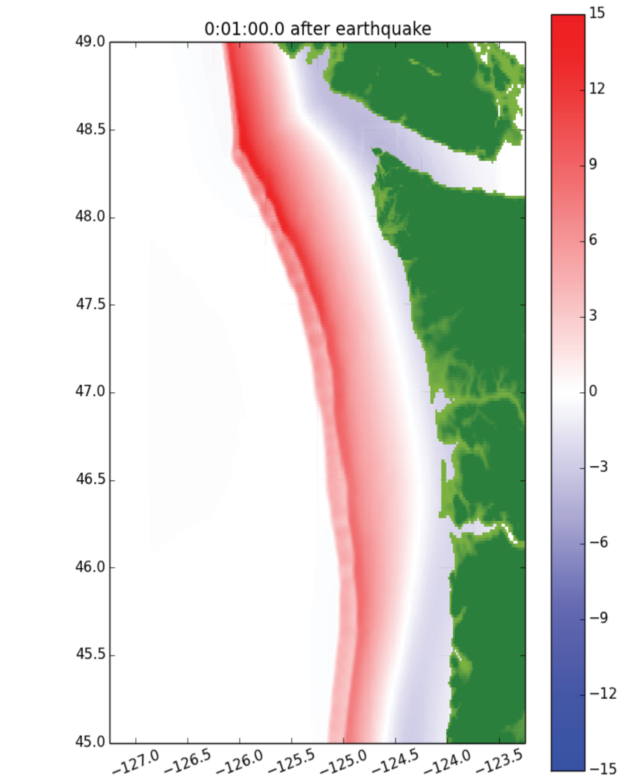


Figure 3. Modeled coseismic uplift (red) and subsidence (blue) for Scenario L1.

INTRODUCTION

In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the West Coast from tsunamis generated locally. A panel of representatives from NOAA, the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS) and the five Pacific coast states wrote the plan and submitted it to Congress, which created the National Tsunami Hazard Mitigation Program (NTHMP) in October of 1996. The National Tsunami Hazard Mitigation Program is designed to reduce the impact of tsunamis through warning guidance, hazard assessment, and mitigation. A key component of the hazard assessment for tsunamis is delineation of areas subject to tsunami inundation. Because local tsunami waves may reach nearby coastal communities within minutes of the earthquake, there will be little or no time to issue formal warnings; evacuation areas and routes will need to be planned well in advance.

The Division of Geology and Earth Resources published several tsunami hazard maps for the outer Washington coast in the early 2000s (Walsh and others, 2000;2003a,b). These maps were based on a scenario developed by Priest and others (1997) which was intended to simulate the last great earthquake on the Cascadia subduction zone (CSZ), and depicted significant tsunami hazards at the Hoh, Quileute, and Makah Reservations, and at Taholah on the Quinault Reservations (Fig. 1).

These tribes have all begun making plans to relocate some of their critical infrastructure out of the tsunami hazard zones. In the case of the Hoh and Quileute Tribes, their reservations were surrounded by the Olympic National Park and they had no room for expansion. As the chairman of the Hoh Tribe testified before Congress in 2010:

> "90% of the Hoh Reservation is now located within a 100 year flood plain, and 100% is located within a tsunami zone. Winter and spring floods now regularly impact Reservation homes, government facilities, and utility structures. Flooding restricts further development and causes ongoing problems with existing structures. In addition to the flooding danger, all of the Reservation facilities and homes are at or below 40 feet elevation and within inundation zones if a major tsunami were to strike."

In 2011, Congress passed the "Hoh Indian Tribe Safe Homelands Act" to "To transfer certain land to the United States to be held in trust for the Hoh Indian Tribe, to place land into trust for the Hoh Indian Tribe, and for other purposes." In 2012, congress passed Public Law 112-97, "An Act To provide the Quileute Indian Tribe Tsunami and Flood Protection, and for other purposes." Both of these acts provided the tribes with lands outside their reservations that would be safe from both tsunami and riverine flooding. The Quinault and Makah reservations are both large enough that they did not need to acquire new land to be able to move to higher ground. Since the original tsunami hazard maps were developed, there have been significant advances in the the understanding of the CSZ, tsunami modeling technology, and the accuracy and resolution of bathymetric and topographic digital elevation models.

CASCADIA SUBDUCTION ZONE

Recurrence Interval

Research over the last few decades about the occurrence of great earthquakes off the British Columbia, Washington, Oregon, and northern California coastlines and resulting tsunamis (Atwater, 1992; Atwater and others, 1995) has led to concern about locally generated tsunamis that will leave little time for response. Numerous workers have found geologic evidence of tsunami deposits attributed to the CSZ in at least 59 localities from northern California to southern Vancouver Island (Peters and others (2003). While most of these are on the outer coast, inferred Cascadia tsunami deposits have been identified as far east as Discovery Bay, just west of Port Townsend (Williams and others, 2005) and on the west shore of Whidbey Island (Williams and Hutchinson, 2000). Heaton and Snavely (1985) report that Makah stories may reflect a tsunami washing through Waatch Prairie near Cape Flattery, and Ludwin (2002) has found additional stories from native peoples up and down the coast that appear to corroborate this and also include apparent references to associated strong ground shaking. Additionally, correlation of the timing of the last CSZ earthquake by high-resolution dendrochronology (Jacoby and others, 1997; Yamaguchi and others, 1997) to Japanese historical records of a distant source tsunami (Satake and others, 1996) demonstrate that it almost certainly came from the CSZ. This tsunami may have lasted as much as 20 hours in Japan and contributed to a shipwreck about 100 km north of Tokyo in A.D. 1700 (Atwater and Satake, 2003; Atwater and others, 2005).

Estimates of the frequency of occurrence of Cascadia subduction zone (CSZ) earthquakes are derived from several lines of evidence. Great subduction zone earthquakes cause coseismic subsidence (Plafker, 1969; Plafker and Savage, 1970), and where this subsidence occurs in coastal marshes, marsh deposits may be abruptly overlain by estuarine mud, indicating sudden submergence and drowning of upland surfaces (Atwater, 1992). Atwater and Hemphill-Haley, 1997) reported six sudden submergence events in Willapa Bay over the last 3,500 years implying an average recurrence interval of about 500–540 years, but varying from as little as 1–3 centuries to as much as 1,000 years.

Researchers working farther south found a somewhat different record, using marsh stratigraphy and inferred tsunami deposits. Kelsey and others (2002) found a 5,500-year record at Sixes River, southern Oregon, that included an abrupt subsidence event not observed on the southern Washington coast. Kelsey and others (2005) examined a coastal lake in southern Oregon and found that it recorded more inferred tsunami deposits than abrupt subsidence events, implying that tsunamis were generated in Cascadia events that did not produce abrupt subsidence and therefore probably did not rupture the entire length of the subduction zone and represented an additional event not seen in the southern Washington record. Nelson and others (2006) examined the degree of overlap and amount of abrupt subsidence at eight sites along the Oregon and Washington coasts and concluded that rupture lengths and therefore earthquake magnitudes varied, with ruptures in northern Cascadia being generally long and ruptures in southern Cascadia being more variable both in length and recurrence interval.

Another approach to inferring recurrence intervals is the occurrence of turbidites below the continental shelf. Adams (1990) inferred that turbidite deposits in Cascadia Channel and Astoria Canyon were triggered by great earthquakes. If turbidity currents are triggered independently at different times and at multiple submarine canyon heads that are tributary to a main channel, their deposits should be additive in the main channel, that is, if a channel has three tributaries, each of which has ten turbidites, then there would be 30 turbidites in the main channel. If, however, they are triggered simultaneously, which would likely be the case if they were triggered by a great earthquake, they should coalesce, so that the maximum number of turbidites in the main channel would be no more than the maximum number found in any individual channel (Fig. 2). In both Cascadia Channel and Astoria Canyon, Adams (1990) reported that Oregon State University researchers logged 13 turbidites stratigraphically above the Mazama ash in multiple deep sea cores, which was radiocarbon dated at about 6,845 radiocarbon yrs BP (calibrated to about 7,700 cal yrs). Adams therefore inferred an average recurrence interval of 590 +170 years.

Goldfinger and others (2012) tested Adams' hypothesis, collecting numerous cores along the Cascadia continental margin, greatly expanding the geographic and chronologic range as well as the density of observations. They inferred from the record of turbidite deposits that the Cascadia subduction zone is segmented, with ruptures of its entire length having a recurrence interval similar to those estimated by Adams (1990) and Atwater and Hemphill-Haley (1997), but with shorter ruptures offshore Oregon and northern California. Combining full-length and partial ruptures on Cascadia, they estimated a recurrence interval of ~240 years for earthquakes off Oregon and northern California but still 500–530 years offshore of Washington and British Columbia. Williams and others (2005), however, describe evidence for more tsunami deposits at Discovery Bay, just west of Port Townsend, than are represented in the turbidite record. This implies either that not all Cascadia events leave turbidite deposits in Cascadia Channel or that some tsunami deposits were generated by other events, either local earthquakes or landslides. Atwater and others (2014), also questioned whether the absence of turbidites in northern Cascadia necessarily proved the absence of ground shaking or rather the absence of preservation potential. They also however, questioned some of the correlations among widely spaced sites used to infer the length of fault rupture.

Earthquake Magnitude and Slip Distribution

It is believed that the last earthquake on the CSZ was about magnitude (Mw) 9 (Satake and others, 1996, 2003). Satake and others (2003) tested various rupture lengths and slips combined with observed tsunami wave heights in Japan for the A.D. 1700 event and estimated that the A.D. 1700 event had a rupture length of ~1,100 km and slip of 19 m, suggesting a magnitude of 8.7–9.2. They inferred that the most likely magnitude was 9.0 based on the correlation between estimates of coseismic subsidence from paleoseismic studies and the subsidence predicted by the dislocation models of their scenarios.

The magnitudes and slip distributions of earlier Cascadia earthquakes is less well constrained. Inferences of shorter rupture zones affecting only the southern part of Cascadia generally imply smaller magnitude earthquakes. Priest and others (2014) modeled tsunamis from various shorter ruptures and concluded that their tsunamis in Washington were significantly smaller than those generated by full-length ruptures and they will not be considered further here.

Witter and others (2011) combined turbidite data from Goldfinger and others (2012), correlation of inferred tsunami deposits with turbidites in Bradley Lake (Witter and others, 2012) and inferred tsunami deposits in the Coquille River estuary at Bandon that extend as much as 10 km farther inland than the A. D. 1700 tsunami deposits (Witter and others, 2003) to infer that tsunamis generated by Cascadia over the last 10,000 years had been highly variable, with some larger than the one in A.D. 1700. They constructed 15 scenarios of full-length ruptures defining vertical seafloor deformation used to simulate tsunami inundation at Bandon, Oregon. Rupture models include slip partitioned to a splay fault in the accretionary wedge and models that vary the updip limit of slip on a buried megathrust fault. They estimated slip is from turbidite paleoseismic records (Goldfinger and others, 2012) and from tsunami simulations at Bradley Lake (Witter and others, 2011). They performed numerical simulations of the tsunamis generated by each scenario and evaluated them using a logic tree that ranked model consistency with geophysical and geological data. Witter and others (2011) concluded that scenario L1, which is a splay fault model with a maximum slip of 27 m and an average slip of 13 m, produced a tsunami that equalled or exceeded 95% of the variability in their simulations. Witter and others (2011) also estimated the size of the earthquakes that generated turbidites spanning the length of Cascadia and concluded that three earthquakes were probably L and only one was larger (their Table 1). The interevent times between pairs of inferred L earthquakes are ~1,800 and ~4,600 years. Another way to estimate recurrence frequency is that, if three earthquakes in the last 10,000 years are approximately L1, then it has an average recurrence interval between 2,500 and 5,000 years. If this truly represents 95% of the hazard over a 10,000 year period, then it has a long recurrence interval and likely is of a similar probability of occurrence as the International Building Code seismic standard of 2% probability of exceedance in 50 years, or colloquially, a 2,500-year event.

MAP DESIGN

The tsunami inundation is based on a numerical model of waves generated by the L1 scenario earthquake. The simulations of tsunami generation, propagation and inundation were conducted with the GeoClaw model (LeVeque and George, 2007; LeVeque and others, 2011). This model solves the nonlinear shallow water equations, has undergone extensive verification and validation and has been accepted as a validated model by the NTHMP after conducting multiple benchmark tests as part of an NTHMP benchmarking workshop (NTHMP, 2012).

The initial condition in the model is the L1 Scenario (Fig. 3)(Witter and others, 2011) which is a splay fault model in which some slip is partitioned into a thrust fault in the accretionary wedge that is subparallel to and with the same sense of movement as the plate interface, resulting in a broader uplift than a simple fault rupture. The land surface along the coast is modeled to subside between 2 and 3 m.

This model does not include potential tsunamis from landslides or nearby crustal faults, which are generally not well enough understood to be modeled. Apparently locally-generated-tsunami deposits have been found on Whidbey Island (Williams and Hutchinson, 2000; Atwater and Moore, 1992), in Discovery Bay, southwest of Port Townsend (Williams and others, 2005), in the Snohomish delta near Everett (Bourgeois and Johnson, 2001), and at West Point near Seattle (Atwater and Moore, 1992). Gonzalez (2003) summarizes the evidence for tsunamis generated within the Puget Lowland by local earthquakes and landslides and estimates their probabilities.

LIMITATIONS OF THESE MAPS

Because the nature of the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this modeling was selected to approximate the 2% probability of exceedance in 50 years, but the next earthquake will likely have a more complex slip distribution than the simplified scenario modeled herein—the ensuing tsunami may differ in detail. Witter and others (2011) suggest that the most likely earthquake will have an average slip of about 2/3 of the L1 scenario and generate a smaller tsunami.

Another significant limitation is that the resolution of the modeling is limited by the bathymetric and topographic data used to make the model grid. Lidar data with three-ft grid cells were used to build most of the topographic models, but the bathymetric data are lower resolution, 10 m or more.

The model run does not include the influences of changes in tides and is referred to mean high water. The tide stage and tidal currents can amplify or reduce the impact of a tsunami on a specific community. At the La Push tide gage, the diurnal range (the difference in height between mean higher high water and mean lower low water) is 8.45 ft (2.58 m)(http://www.tidesandcurrents.noaa.gov) and 7.96 ft (2.43 m) at Neah Bay. It also does not include interaction with tidal currents, which can be additive, or, if in opposite directions, can steepen the tsunami wave front and cause a breaking wave.

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