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MODELING TSUNAMI INUNDATION FOR HAZARD MAPPING AT EVERETT, WASHINGTON, FROM THE SEATTLE FAULT

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Modeling tsunami inundation for hazard mapping at Everett, Washington, from the Seattle Fault

C. Chamberlin[1] and D. Arcas[2,3]

1. Introduction

This report describes the process and results of tsunami inundation modeling for the city of Everett, Washington. The purpose of the present modeling work is to produce data for use in the development of tsunami inundation maps, as part of a tsunami mapping project funded by the National Tsunami Hazard Mitigation Program. Puget Sound is known to be at risk for local tsunami events (González et al., 2003), and previous studies conducted by the NOAA Center for Tsunami Research (NCTR) have modeled the potential effects of tsunamis on the nearby cities of Seattle (Titov et al., 2003) and Tacoma (Venturato et al., 2007). The source scenarios investigated are two potentially tsunamigenic seismic events on the Seattle Fault, including one scenario previously modeled for Seattle and Tacoma.

2. Study Area

The study area incorporates the city of Everett, Washington, and the surrounding waterways including Possession Sound and the lower Snohomish River (**Fig. 1**). The Everett waterfront is the site of Naval Station Everett, which was constructed in the 1980s and is homeport to seven United States Navy vessels. Other major features of the waterfront include a major recreational and commercial marina operated by the Port of Everett, and a pulp mill owned by Kimberly-Clark Corporation that operated until 2012.

Jetty Island is located close to the Everett waterfront, separated from the mainland by the dredged channel of the lower Snohomish River. Low-lying Jetty Island is a minimally developed Everett city park; during summer months a passenger ferry operates to the island.

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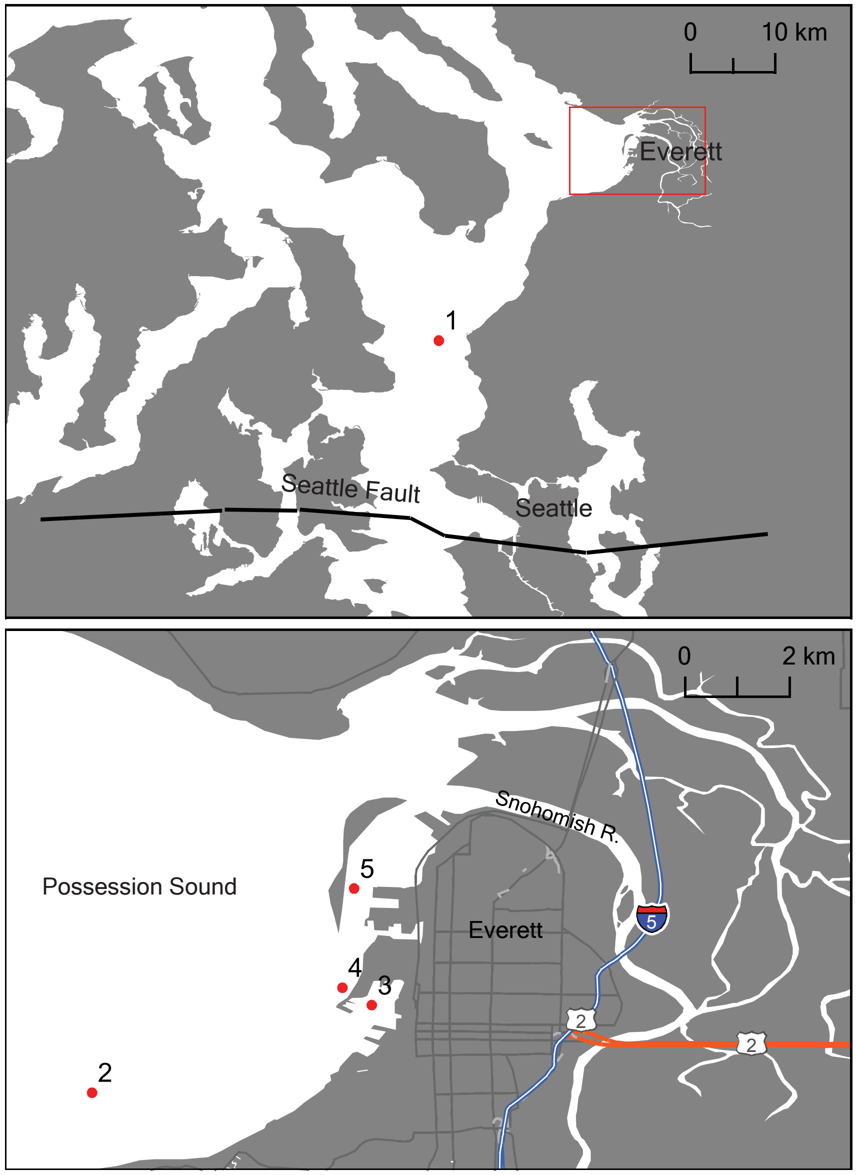

Figure 1: Overview of the Everett study area, showing the relative location of the fault used in the tsunami source scenarios. Numbered points are locations of time series plotted in **Fig. 6**.

While it has several important waterfront features, the majority of the city of Everett, including the downtown commercial district, is built on higher ground, 20–40 m above sea level. North and east of the city is the low-lying Snohomish River delta region. This area is threaded by several sloughs in addition to the main river channel; much of the area is very close to mean high water and protected from inundation by levees. The delta is crossed by bridges and raised causeways of three major highways: State Route 529, Interstate 5, and US Highway 2.

3. Tsunami Event History

There have been no recorded tsunamis near Everett, Washington, since the establishment of the modern city, but there is evidence of previous tsunami impacts in the area (González et al., 2003). Surveys of exposed banks in the Snohomish River delta by Bourgeois and Johnson (2001) found sand deposits attributed to inundation of the region by tsunami. The clearest deposits appear to have been produced by an earthquake and tsunami which occurred in roughly AD 900 (Atwater and Moore, 1992). Other deposits identified by Bourgeois and Johnson (2001) may indicate up to two additional older tsunamis, and surveys have also found evidence of localized seismic liquefaction. The AD 900 tsunami is also believed to have produced sand deposits at Cultus Bay, on the south end of Whidbey Island, 16 km southwest of Everett (Atwater and Moore, 1992).

Landslides, both subaerial slides originating on upland slopes, and underwater landslides occurring on the Snohomish River delta deposits, may also pose a risk to the Everett area (González et al., 2003). Native American oral tradition records the collapse of Camano Head, 13 km northwest of the Everett waterfront, in the early nineteenth century. According to the account, the landslide caused a large wave on Gedney (Hat) Island, killing several people, and may have caused limited flooding of a village near the mouth of the Snohomish River, close to the modern city of Everett (Shipman, 2001). The source scenarios discussed in this report are, however, all associated with seismic fault ruptures.

4. Tsunami Source Scenarios

This study investigated two seismic source scenarios along the same fault zone. Scenarios A and B are variations on an earthquake along the Seattle Fault, which crosses Puget Sound between Seattle and Bainbridge Island, Washington. The resulting vertical ground deformations for each scenario are shown in **Fig. 2**.

4.1 Scenario A: Seattle Fault Mw 7.3

This scenario is identical to the Seattle Fault scenario defined by Titov et al. (2003), and also previously used for modeling inundation in Tacoma (Venturato et al., 2007). This scenario was designed to be a maximum credible event, within the constraints of the vertical deformation caused by the AD 900 earthquake along the Seattle Fault (Bucknam et al., 1992). It is described by six fault segments of varying length and strike, with slip ranging from 1 to 12 m (**Table 1**).

4.2 Scenario B: Seattle Fault Mw 6.7

This scenario, also along the Seattle Fault, is a modified version of the earthquake scenario used by the Earthquake Engineering Research Institute (EERI) and Washington Emergency Management Division for recent seismic hazard assessment studies (Venturato et al., 2007). This scenario represents a less severe, but more likely event than Scenario A; a Seattle Fault earthquake of Mw 6.5 or greater is forecast to have a 5% chance of recurring over a 50-year period (Stewart, 2005).

The scenario earthquake used in the EERI studies used a 24 km fault centered under the cities of Seattle and Bellevue, and thus has little vertical deformation under the water of Puget Sound. For the present study, the scenario was therefore modified by shifting the event west along the Seattle Fault, such that the fault begins at the western end of the original EERI fault, and continues west 24 km under central Puget Sound. This scenario uses a simplified fault model with a constant depth and dip angle, and uniform 2.8 m slip throughout (**Table 2**).

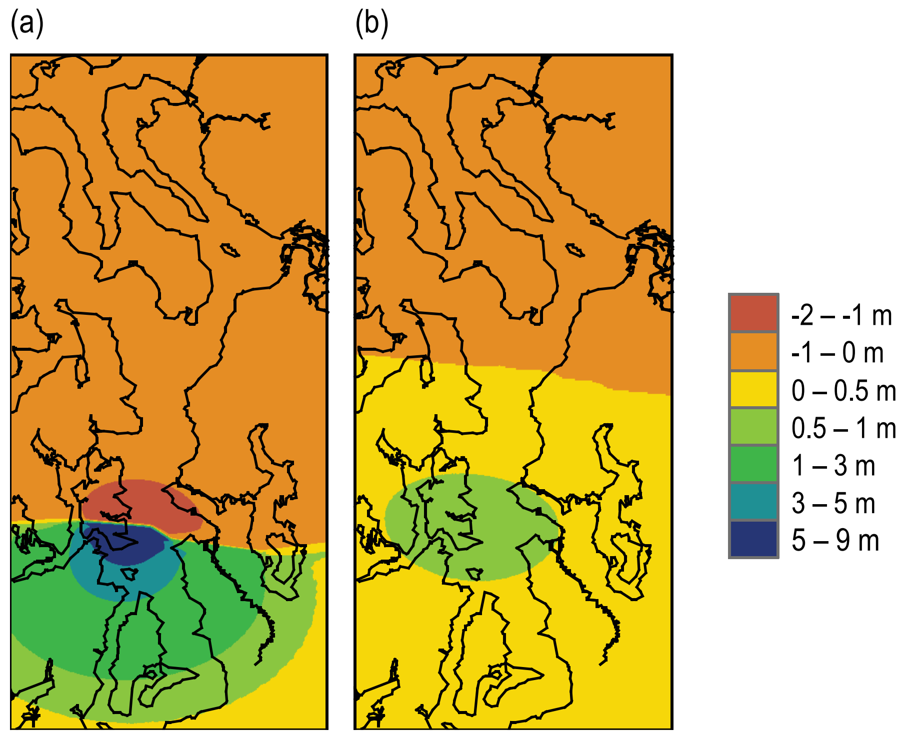

Figure 2: Vertical seismic displacement for (a) Scenario A: Seattle Fault Mw 7.3 (Titov et al., 2003); and (b) Scenario B: Seattle Fault Mw 6.7 (Stewart, 2005).

Table 1: Scenario A seismic fault parameters for a Seattle Fault Mw 7.3 earthquake, after Titov et al. (2003).

Fault Segment	Width (km)	Length (km)	Strike (deg.)	Dip (deg.)	Slip (m)
A1	35.0	15.2	87.9	60.0	1.0
A2	35.0	6.3	86.6	60.0	1.0
A3	35.0	8.9	96.0	60.0	12.0
A4	35.0	3.2	128.8	60.0	11.0
A5	35.0	11.5	99.3	60.0	4.0
A6	35.0	14.9	81.0	60.0	1.0

Table 2: Scenario B seismic fault parameters for a Seattle Fault Mw 6.7 earthquake, derived from earthquake scenario used by EERI (Stewart, 2005).

Fault Segment	Width (km)	Length (km)	Strike (deg.)	Dip (deg.)	Slip (m)
B1	35.0	6.3	86.6	45.0	2.8
B2	35.0	8.9	96.0	45.0	2.8
B3	35.0	3.2	128.8	45.0	2.8
B4	35.0	5.8	99.3	45.0	2.8

5. Tsunami Model Development

Tsunami wave dynamics for the hazard assessment were modeled with the MOST model, a finite-difference numerical tsunami model (Titov and Synolakis, 1998). In addition to the initial source deformations described above, the model takes as its major input a series of structured grids describing the bathymetry and topography of the study area.

5.1 Digital elevation model development

Bathymetry and topography for the inundation model was derived from an existing digital elevation model (DEM) of Puget Sound (Finlayson, 2005), with modifications to incorporate recently collected data. The base DEM was derived from multiple data sources, including topographic and bathymetric LIDAR, multibeam bathymetry, single beam hydrographic surveys, and surveyed USGS topography.

The Finlayson source DEM, as well as the other survey data described below, were converted to a local mean high water (MHW) vertical datum. The vertical offset between MHW and the original datums used for the source datasets, North American Vertical Datum of 1988 (NAVD88) and Mean Lower Low Water (MLLW), varies substantially throughout Puget Sound. Surfaces defining the datum offsets were created from the grids used by the VDatum tool for Puget Sound (Hess and White, 2004). VDatum is designed to perform vertical transformations only over water; to produce an estimated offset from NAVD88 to adjust topographic datasets, land-grid cells were linearly extrapolated from the adjoining water-grid cells. The vertical offset between MLLW and MHW ranges from 2.25 to 4.13 m in the Puget Sound area; the offset between NAVD88 and MHW ranges from -1.96 to -2.96 m.

The Finlayson source DEM was modified in the Possession Sound and Snohomish River delta areas to add additional data sources and improve resolution of the harbor area. Survey data received from the US Army Corps of Engineers, and parts of NOAA hydrographic surveys H08174 (1955) and H10662 (1996), which were apparently not incorporated into the Finlayson grid, were included. Inclusion of these surveys was essential to properly resolve the bathymetry of the Snohomish River and northern Steamboat Slough areas.

Most of the waterways of the Snohomish River delta area are unsurveyed, so depths are estimated for these areas. These unsurveyed areas include:

- Snohomish River main channel upstream of the confluence of the southern end of Steamboat Slough, approximately 1.25 km below the US Highway 2 bridge;
- Union Slough upstream of the BNSF railroad bridge;
- Steamboat Slough upstream of the BNSF railroad bridge;
- Ebey Slough.

Depth values estimated by extrapolation from nearby surveys were available, with generally deeper values applied to larger waterways. Because of the probable error in the estimated depths, modeled wave dynamics for these waterways are rough estimates only.

An additional Snohomish County LIDAR survey, completed in 2005 and available as a 2 m resolution grid, provided substantially improved topographic resolution for the essential central Everett area.

Further modifications were applied to topography values in the Snohomish delta area to provide reasonable estimates of inundation in that region. Extensive portions of the delta are below mean high water (zero) datum, but protected from inundation by levees. The MOST model assumes that any grid cells below the zero datum are underwater at the beginning of the model run, and thus cannot produce a flooding forecast for those cells. To work around this limitation, elevation values below zero that are dry (based on inspection of satellite photography and USGS topographic maps) were brought up to be slightly above zero. In addition, where the levees protecting these areas are too narrow to be properly represented in the model grid, the grid was modified to add artificially widened levee structures, with minimum elevation values estimated from the original Snohomish County LIDAR dataset.

Because tsunami waves can propagate under structures built on pilings over water, several piers in the Mukilteo, Clinton, and Everett harbor areas were clipped from the Finlayson grid, and depth values instead interpolated from adjacent bathymetry. These structures not represented in the bathymetry grid include the two large fixed piers used by Naval Station Everett for mooring naval vessels.

Survey points and grid node values from the edges of the gridded regions were combined into a tight spline surface and sampled to a 10-meter grid using the MBSystem software (`http://www.ldeo.columbia.edu/res/pi/MB-System/` accessed 19 March 2015). The gridded LIDAR data and clipped Finlayson grid were overlaid on top of this intermediate grid to create the final high-resolution source grid.

The two source grids—a 1/3-arc-sec grid covering Everett and a 1-arc-sec grid covering all of Puget Sound—provide the base data for creating model grids.

5.2 Tsunami model setup

The MOST model runs with three nested bathymetry grids, called A (large extent, low resolution), B, and C (small extent, high resolution). For this study, the A-grid extent was set to cover Puget Sound from near Tacoma north to Admiralty Inlet, including all of the region with a vertical deformation over 0.5 m, in all three scenarios. The B grid covers southern Whidbey Island and the adjoining areas of Puget Sound and Possession Sound. The C grid covers the city of Everett, Possession Sound, and the Snohomish River delta (**Fig. 3**; **Table 3**).

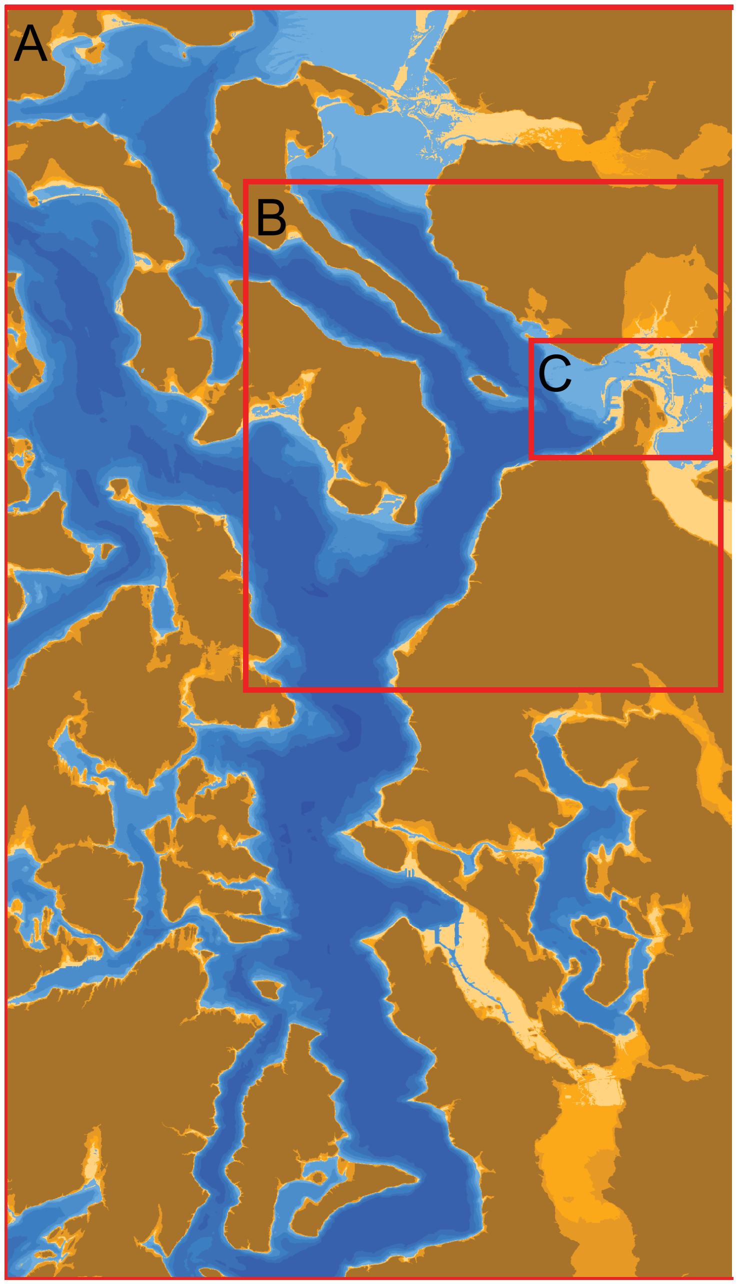

Figure 3: The MOST model runs on three nested bathymetric grids: A, B, and C. See **Table 3** for grid resolution and extent details.

Table 3: Bathymetric grid details.

Grid	Extent	Resolution
A	(122.70°W, 48.31°N) – (122.13°W, 47.31°N)	9 arc sec
B	(122.51°W, 48.17°N) – (122.14°W, 47.77°N)	3 arc sec
C	(122.28°W, 48.05°N) – (122.14°W, 47.96°N)	0.5 arc sec

The present study uses the same revision of the MOST model currently in use in NOAA's real-time tsunami forecast system (Tang et al., 2008; Wei et al., 2008), with minor modifications to incorporate the initial deformation specifications described above instead of the database-backed propagation model used by the operational system. This operational version of the model, internally called MOST version 2, implements one-way coupling between the nested grids; amplitudes and velocities in the lower-resolution grids are used as boundary conditions in the higher-resolution grids, but not in the other direction. In operational testing, this was found to substantially improve the numerical stability of the model. Limited comparison in this study with an older, bidirectionally coupled model implementation found comparable results.

6. Modeling Results

6.1 Scenario A: Seattle Fault Mw 7.3

The fault for this source, the larger of the two scenario sources, causes a sharp vertical deformation along the fault, stretching from southern Bainbridge Island to just north of Alki Point in West Seattle. The uplift south of the fault produces a large initial wave that travels north through Puget Sound. In central Puget Sound, the initial wave has a height of approximately 1.3 m; the larger second wave 7.8 min later is 1.6 m high. The first of these wave peaks reaches the south end of Whidbey Island approximately 16 min after the event, and divides to propagate northwest up Admiralty Inlet and northeast up Possession Sound toward Everett. Wave heights, especially of the first wave, diminish somewhat as the wave propagates north into Possession Sound. Near the Mukilteo ferry terminal, the first wave is 0.8 m and the second wave is 1.2 m (**Fig. 4a**).

The first positive wave peak arrives at the Everett waterfront 25 min after the event; the second and largest wave arrives 34 min after the event. There are two major areas of inundation. First, the southern two-thirds of Jetty Island, the low-lying island off the central Everett waterfront, is inundated with flow depths of between 0.5 m and 1.0 m. The major area of inundation on the mainland is on the grounds of Naval Station Everett. Here, most of the land around the Naval Station's East Waterway is inundated to a depth of 0.6 m above the land surface (2.5 m above mean high water). This inundation zone reaches Marine View Drive, the major arterial road servicing the Naval Station. Much of this inundation occurs with the initial wave train, but additional inundation is caused by local oscillations occurring in the East Waterway; this area has by far the largest wave amplitudes in the Everett harbor area.

The tsunami will also cause severe currents reaching more than 4 m/s over a substantial area in the East Waterway area, especially along the waterway's west edge, the site of Naval Station Everett's large mooring pier, where peak currents reach 7 m/s. Similar currents are produced in the lower Snohomish River channel, and on the west side of Jetty Island (**Fig. 5a**).

The model predicts a wave of up to 1 m propagating up the Snohomish River channel as far as the US 2 highway bridge. This causes additional inundation on both sides of the dredged channel, largely in intertidal and floodplain areas, but also in a small industrial area located between State Route 529 and Interstate 5, north of the river channel. Both of these major highways are constructed on elevated ground, so the model does not predict inundation of either. The final area of substantial inundation is on the north side of Steamboat Slough, in a low-lying marsh area unprotected by continuous levees.

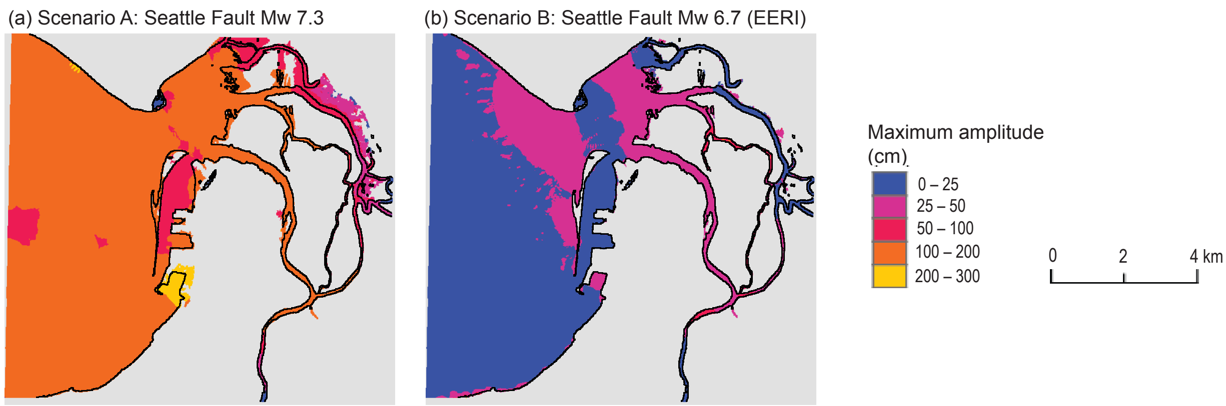

Figure 4: Maximum tsunami wave amplitudes in the Everett area for Scenarios A and B.

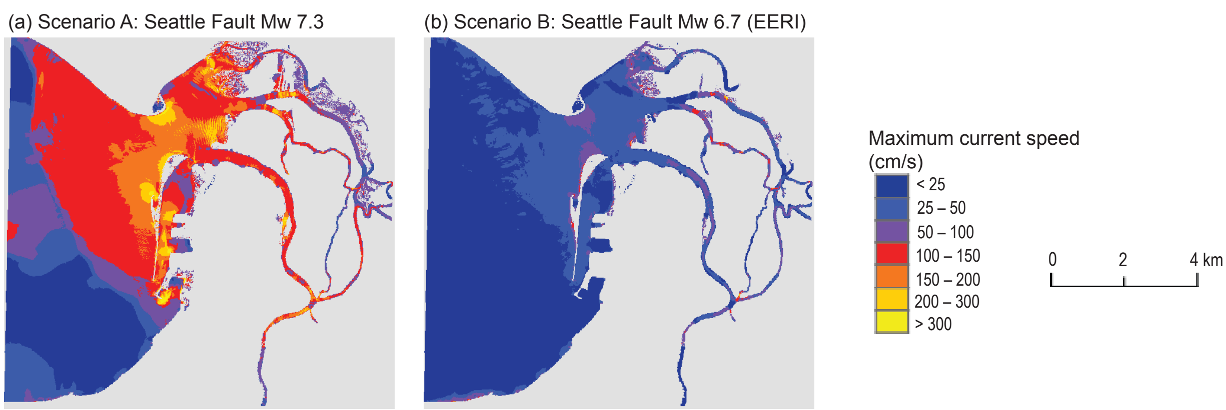

Figure 5: Maximum current speeds in the Everett area for Scenarios A and B.

Bourgeois and Johnson (2001) found a sand layer at multiple sites in the Snohomish delta area that were attributed to a tsunami inundation of the area, probably by the AD 900 Seattle Fault earthquake. The modeling results presented here indicate that such a tsunami could indeed propagate this far, causing substantial inundation in the area. However, these results are suggestive at best, because it is difficult to exactly reproduce the AD 900 topography of the area with sufficient accuracy for inundation modeling. In this low-relief region, small variations in elevation make a substantial difference in inundation extent. While the area is covered by accurate, high-resolution LIDAR topography, it has been substantially modified in the modern era by dredging, road building, and levee construction.

6.2 Scenario B: Seattle Fault Mw 6.7

The initial deformation of Scenario B, much smaller than Scenario A, triggers roughly equal waves traveling north and south in central Puget Sound. The initial northerly wave is 22 cm high in central Puget Sound; it maintains most of its energy as it enters Possession Sound. Wave height near the Mukilteo ferry terminal is approximately 18 cm. The initial wave reaches the Everett harbor area 20 min after the event, and a second, smaller wave arrives 31 min after the earthquake (**Fig. 4b**).

This event causes no substantial inundation above the mean high water line. Maximum wave heights in the East Waterway are 27 cm; wave heights in the Snohomish River channel behind Jetty Island are 22 cm.

In contrast to Scenario A, this scenario does not produce major currents in the Naval Station's East Waterway; currents here are less than 20 cm/s. The Snohomish River channel has the largest currents under this scenario; up to 40 cm/s (**Fig. 5b**).

Wave amplitudes for Scenarios A and B at five locations appear in the time series presented in **Fig. 6** below, with the maximum elevation recorded during the first two wave peaks at location 3 for Scenario A (Port Gardner).

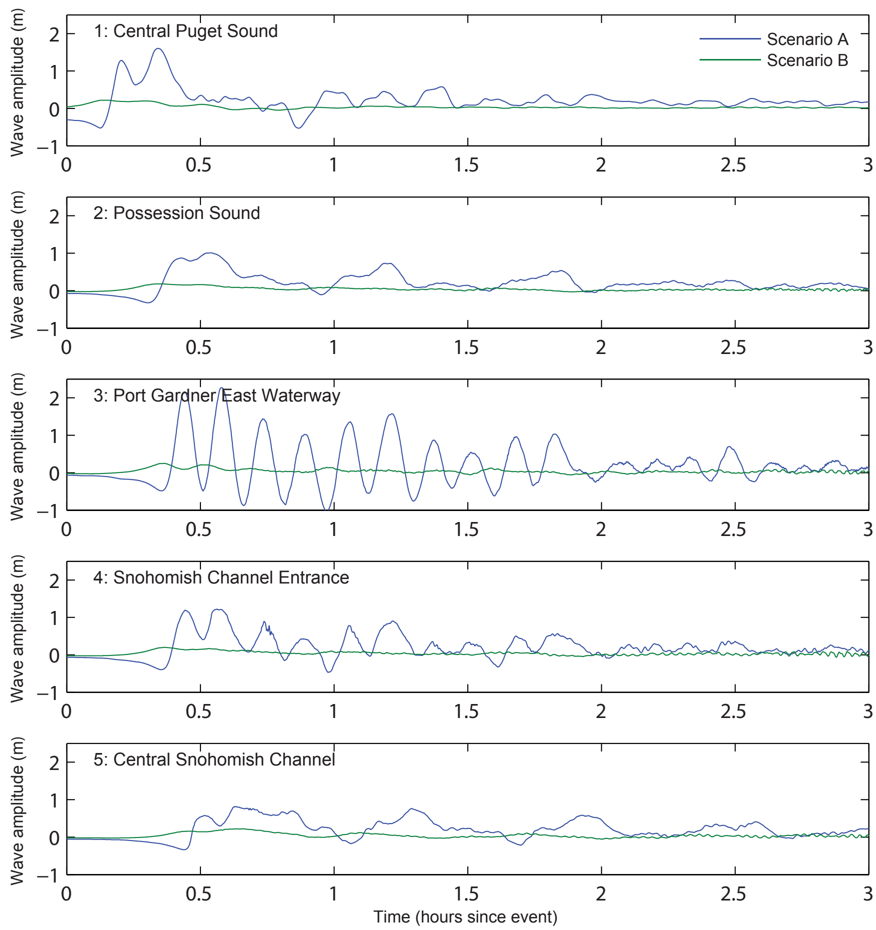

Figure 6: Wave amplitude time series at five locations in the model domain for Scenarios A and B. Time series locations are indicated in **Fig. 1**.

7. Conclusion

The results of modeling two local tsunami source scenarios in Everett, Washington, are presented. Both scenarios are based on the Seattle Fault. Of the two scenarios investigated in this study, Scenario A, a Mw 7.3 event, clearly emerges as the more dangerous of the two. Although the deformation of Scenario B covers approximately the same extent surface as that of Scenario A, the large seismic slip associated with Scenario A causes a much larger volume of water to be displaced. In both scenarios, areas most at risk for inundation are in the area of Naval Station Everett, Jetty Island, and low-lying areas north of the Snohomish River.

8. Acknowledgments

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9. References

Atwater, B.F., and A.L. Moore (1992): A tsunami about 1000 years ago in Puget Sound, Washington. *Science, 258*(5088), 1614–1617.

Bourgeois, J., and S.Y. Johnson (2001): Geologic evidence of earthquakes at the Snohomish delta, Washington, in the past 1200 yr. *Geol. Soc. Am. Bull., 113*(4), 482–494.

Bucknam, R.C., E. Hemphill-Haley, and E.B. Leopold (1992): Abrupt uplift within the past 1700 years at southern Puget Sound, Washington. *Science, 258*(5088), 1611–1614.

Finlayson, D.P. (2005): Combined bathymetry and topography of the Puget Lowland, Washington State. University of Washington (http://www.ocean.washington.edu/data/pugetsound/).

González, F.I., B.L. Sherrod, B.F. Atwater, A.P. Frankel, S.P. Palmer, M.L. Holmes, R.E. Karlin, B.E. Jaffe, V.V. Titov, H.O. Mofjeld, and A.J. Venturato (2003): Puget Sound Tsunami Sources - 2002 Workshop Report, NOAA/OAR/PMEL, In NOAA OAR Special Report: A contribution to the Inundation Mapping Project of the U.S. National Tsunami Hazard Mitigation Program, 34 pp.

Hess, K.W., and S.A. White (2004): VDatum for Puget Sound: Generation of the grid and population with tidal datums and sea surface topography. Technical Memorandum. NOS CS 4, NOAA OAR, 27 pp.

Shipman, H. (2001): The fall of Camano Head: A Snohomish account of a large landslide and tsunami in Possession Sound during the early 1800s. *TsuInfo Alert , 3*(6), edited, 13–14.

Stewart, M. (2005): Scenario for a magnitude 6.7 earthquake on the Seattle Fault. Earthquake Engineering Research Institute and Washington Military Department, Emergency Management Division, 162 pp.

Tang, L., V.V. Titov, Y. Wei, H.O. Mofjeld, M. Spillane, D. Arcas, E.N. Bernard, C. Chamberlin, E. Gica, and J. Newman (2008): Tsunami forecast analysis for the May 2006 Tonga tsunami. *J. Geophys. Res., 113*, C12015,10.1029/2008JC004922.

Titov, V.V., and C.E. Synolakis (1998): Numerical modeling of tidal wave runup. *J. Waterw. Port Coast. Ocean Eng., 124*(4), 157–171.

Titov, V.V., F.I. González, H.O. Mofjeld, and A.J. Venturato (2003): NOAA TIME Seattle Tsunami Mapping Project: Procedures, data sources, and products. NOAA Tech. Memo. OAR PMEL-124, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 21 pp.

Venturato, A.J., D. Arcas, V.V. Titov, H.O. Mofjeld, C.C. Chamberlin, and F.I. González (2007): Tacoma, Washington, tsunami hazard mapping project: Modeling tsunami inundation from Tacoma and Seattle fault earthquakes. NOAA Tech. Memo. OAR PMEL-132, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 23 pp.

Wei, Y., E. Bernard, L. Tang, R. Weiss, V. Titov, C. Moore, M. Spillane, M. Hopkins, and U. Kânoğlu (2008): Real-time experimental forecast of the Peruvian tsunami of August 2007 for U.S. coastlines. *Geophys. Res. Lett., 35*, L04609, doi: 10.1029/2007GL032250.