Inundation modeling of local tsunamis in Puget Sound, Washington, due to potential earthquakes

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Abstract. A project is underway to assess the tsunami hazards that threaten Puget Sound communities and to provide information for tsunami planning and mitigation. It is one of the Tsunami Inundation Modeling Efforts within the National Tsunami Hazard Mitigation Program. It is recognized that the Seattle Fault zone and other active faults in this region have the potential to generate local tsunamis. Using a finite difference model based on nonlinear shallow water wave theory and a high-resolution digital elevation model, we simulate the generation, propagation, and inundation of tsunamis in Puget Sound. The tsunamis are generated as a result of possible earthquake scenarios for the Seattle Fault and the Southern Whidbey Island Fault. The initial focus is on the major population centers and ports within the Main Basin, its bays, and side-inlets.

1. Introduction

It is recognized in western Washington State that significant seismic hazards threaten the major populated regions in the Puget Lowland. An earthquake of $M_w = 6.8$ occurred at Nisqually, Olympia on 28 February 2001, and six earthquakes of $M \geq 6$ have occurred in western Washington State in historic times. These events were intraslab earthquakes, so called Benioff Zone earthquakes, except for the 1872 event at the eastern side of the Cascadia range. However, the lack of seismicity in the shallower crust does not demonstrate that no concern is required for shallow crustal earthquakes and the tsunamis they might generate.

Paleoseismic studies in the Puget Lowland of western Washington demonstrate that an earthquake of $M \geq 7$ occurred on the shallow crustal fault, which is called the Seattle Fault, about 1100 years ago (Bucknam *et al.*, 1992). It is believed that a tsunami accompanied this earthquake. Atwater and Moore (1992) found tsunami deposits at West Point and Cultus Bay which are located north of the Seattle Fault. The present authors simulated the tsunamis generated by the Seattle Fault earthquake and estimated that a more than 4 m tsunami would strike the Seattle waterfront area (Koshimura *et al.*, 2001). Also, recent geophysical investigations suggest that the Seattle Fault is active and capable of generating a large earthquake of $M \geq 7$ (Pratt *et al.*, 1997, Johnson *et al.*, 1999, Brocher *et al.*, 2000). Besides the Seattle Fault, Johnson *et al.* (1996) documented that the Southern Whidbey Island Fault, which is located 40 km north of the Seattle Fault, has been active recently and should be considered capable of generating earthquakes of $M \geq 7$. It is evident that these active faults have the potential to generate local tsunamis.

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This study aims to simulate and map the tsunami hazard to Puget Sound communities that might be induced by the potential shallow crustal earthquakes, using a conventional finite difference model based on the nonlinear shallow water theory and high-resolution bathymetry/topography data of Puget Sound. The results reported here are for communities around the Main Basin of Puget Sound and its side-inlets.

2. Earthquake Scenarios

2.1 Seattle Fault—Review

According to recent seismological studies, the Seattle Fault is believed to be a zone of thrust or reverse faults that runs through Seattle, within the densely populated Puget Lowland of western Washington (Johnson *et al.*, 1999). There is still great uncertainty about the structure of the Seattle Fault Zone and there exists a number of interpretations for the associated field observations.

Based on the seismic reflection data, Pratt *et al.* (1997) proposed the thrust sheet hypothesis on the Seattle Fault structure, in which the deeper portions (>5 km) of the fault are dipping southward at an angle of $20°(\pm 5°)$ and shallower portions (<5 km) are dipping at an angle of about 45°. They estimated the possible magnitude on the Seattle Fault to be $M_w = 7.6$ to 7.7.

Based on the distribution of exposed bedrock, anomalies in the earth's magnetic and gravity fields and seismic-reflection data, Johnson *et al.* (1999) inferred that the Seattle Fault forms a west-trending zone of three or more south dipping reverse faults. They also interpreted that the Seattle Fault forms a 4 to 6 km wide, west-trending zone and mapped the zone in waterways across the Puget Lowland for at least 40 km from Dyes Inlet to Lake Washington. They concluded that the fault was not evident in Hood Canal.

More recently, a group of geophysicists working on a project (Brocher *et al.*, 2000), called Seismic Hazard Investigations of Puget Sound (SHIPS), conducted their investigations of the upper crustal structure of the Puget Lowland, by making marine airgun observations in 1998 (Wet SHIPS), obtaining the seismic refraction line of the study area in 1999 (Dry SHIPS) and recording the demolition of the Seattle Kingdome sports stadium with an array of seismic recorders in 2000 (Kingdome SHIPS). They concluded that the length of the Seattle Fault is at least 70 km, and the fault could produce a $M = 7.2$ to 7.5 earthquake for a fault length of 70 km and fault plane depths between 20 to 30 km. The dip angle of the fault plane has not yet been well resolved by SHIPS.

Considering the above interpretations, we assume a $M = 7.2$ earthquake on the Seattle Fault, over an area of 60 km by 19 km as the possible tsunamigenic earthquake. We adopt the interpretation of Johnson *et al.* (1999) for the horizontal structure of the Seattle Fault. Also we adopt and slightly modify the thrust sheet hypothesis of Pratt *et al.* (1997) for the vertical structure of the fault, using a dip angle of 25° for the deeper fault plane ($\geq$5.5 km) and 60° for the shallower fault plane ($\leq$5.5 km). Figure 1 shows

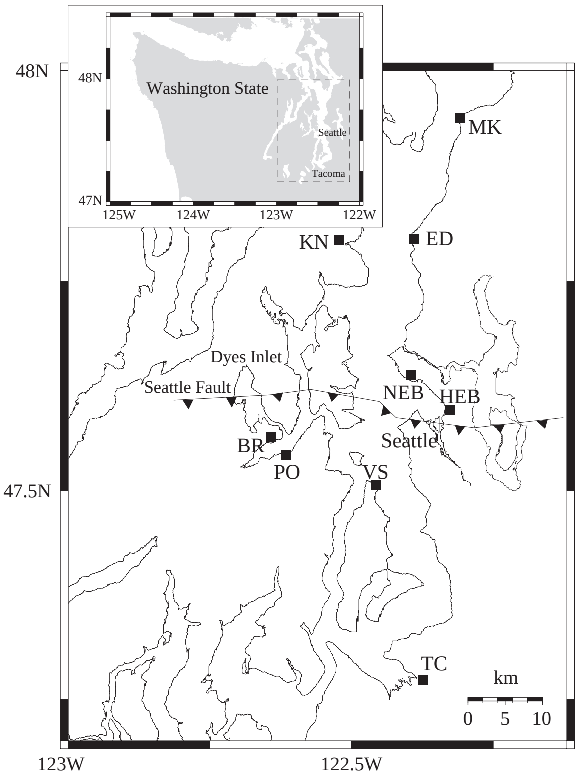

Figure 1: Inferred structure of the Seattle Fault. Abbreviations as follows: MK = Mukilteo, ED = Edmonds, KN = Kingston, NEB = Northern Elliott Bay, HEB = Head of Elliott Bay, BR = Bremerton, PO = Port Orchard, VS = Vashon, and TC = Tacoma.

the inferred horizontal structure of the Seattle Fault. We divide the fault plane into 12 segments to fit the structure inferred by Johnson *et al.* (1999). The strike angle of each segment is determined by the inferred structure shown in Fig. 1.

For the determination of the fault displacement, we apply the empirical relationship between fault displacement and earthquake magnitude proposed by Wells and Coppersmith (1994). The empirical relationships are obtained as (1) and (2).

$$\log D_M = -5.46 + 0.82\ \mathrm{M_w} \tag{1}$$

$$\log D_A = -4.80 + 0.69\ \mathrm{M_w} \tag{2}$$

where D_M is the maximum displacement on the fault plane, D_A is average displacement and $\mathrm{M_w}$ is the moment magnitude. Assuming an earthquake of $\mathrm{M_w} = 7.2$, we obtain the values, $D_M = 2.8$ m and $D_A = 1.5$ m. Here, we take $D = 2.8$ m as the amount of slip on the fault.

Table 1 indicates the resulting fault parameters for estimating the seismic deformation by the fault movement. n indicates the number of segments of

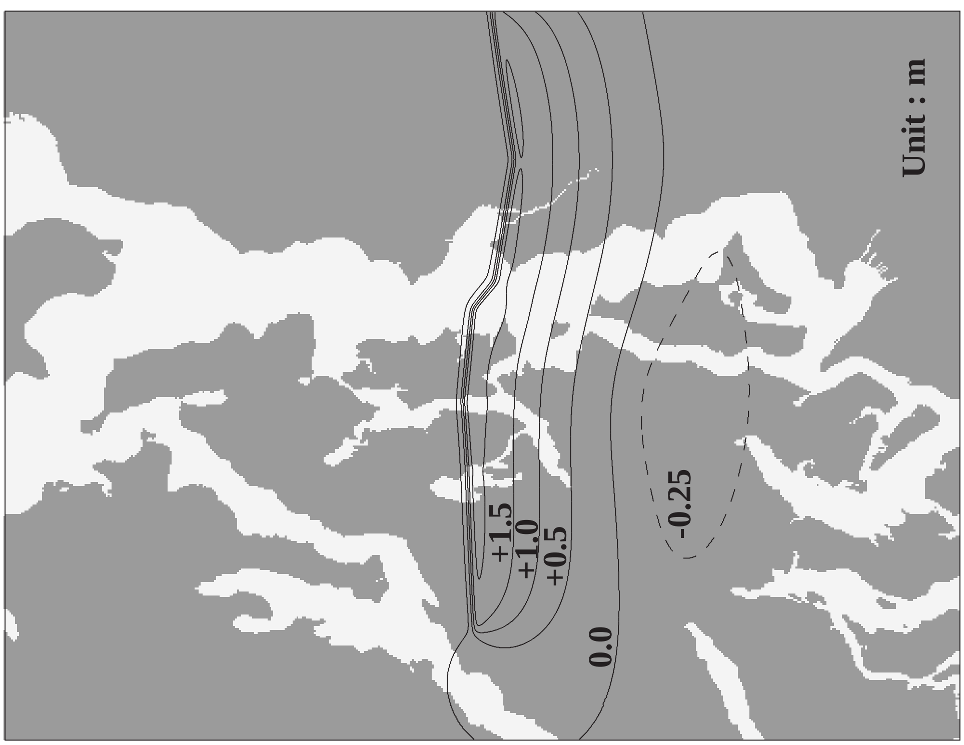

Figure 2: Computed seismic deformation due to the hypothetical earthquake on the Seattle Fault.

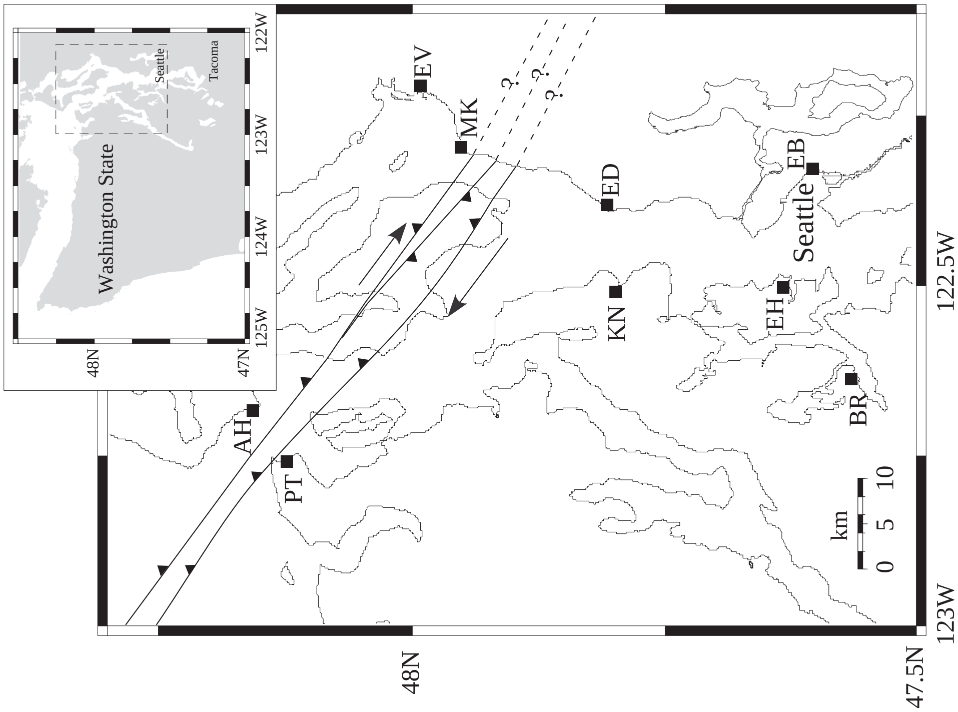

Figure 3: Location and inferred structure of the Southern Whidbey Island Fault. Abbreviations as follows : PT = Port Townsend, AH = Admiralty Head, EV = Everett, MK = Mukilteo, ED = Edmonds, KN = Kingston, EB = Elliott Bay, BR = Bremerton, and EH = Eagle Harbor.

Table 1: Dimension of the fault and source parameters of the Seattle Fault earthquake.

	Shallower fault	**Deeper fault**
n	6	6
L	60.0 km	60.0 km
W	6.0 km	13.0 km
D	2.8 m	2.8 m
H	0.5 km	5.5 km
Dip angle	60°	25°
Slip angle	90°	90°

Table 2: Focal mechanisms of historical earthquakes in the Southern Whidbey Island Fault zone.

Year	**1976**	**1979**	**1981**
Magnitude	4.7	3.8	3.7
Strike	315°	325°	340°
Dip angle	75°	85°	45°
Depth (km)	22.6	23.7	26.6

upper and lower fault plane, L and W are the strike length and downdip width of each segment, and H is the depth of the top edge of each segment. Based on the parameters shown in Table 1, we estimate the vertical seismic deformation of the land and sea bottom by using the theory of Okada (1985) to compute the static displacement due to inclined and tensile fault in a half space. Figure 2 shows the computed vertical seismic deformation of the land and sea bottom within the Puget Lowland. The results yield a maximum uplift of 2.3 m on the sea bottom between Bainbridge Island and Elliott Bay, Seattle.

2.2 Southern Whidbey Island Fault

The Southern Whidbey Island Fault (SWF) is located approximately 40 km north of the Seattle Fault. It comprises a broad steep, northeast dipping zone that includes several sprays with inferred strike-slip and thrust displacement. It is unexposed at the surface. Figure 3 shows the location and inferred structure of the SWF. Based on the information from industry seismic reflection profiles, boreholes, outcrops and geophysical surveys, Johnson *et al.* (1996) suggest that the structure has a long-lived history associated with continental margin rifting, strike slip faulting, and transpressional deformation. They conclude that this fault has been active recently and should be considered capable of generating earthquakes of $M \geq 7$.

The area of the SWF has experienced minor seismicity since 1970. Three earthquakes of $M > 3.5$ (the largest was $M = 4.7$) occurred in 1976, 1979 and 1981. The focal mechanism of each event is shown in Table 2.

Table 3: Dimension of the fault and source parameters of the Southern Whidbey Island Fault earthquake in the present scenario.

L	40.0 km
W	19.0 km
D	2 m
H	0.5 km
Strike	320°
Dip angle	80°
Slip angle	135°

Using the interpretation of Johnson *et al.* (1996) and the focal mechanisms of historical earthquakes, we assume an earthquake of $M_w = 7.0$ as the scenario of SWF earthquake tsunami and determine the fault parameters shown in Table 3. The amount of fault slip is determined by the empirical relationships of (1) and (2). We choose the position of the fault origin (southeastern edge) based on the interpretation of Johnson *et al.* (1994), assuming the origin is at the southern tip of Whidbey Island.

Figure 4 shows the computed vertical deformation due to the SWF earthquake. The maximum uplift of 73 cm is revealed at the sea bottom between the southern tip of Whidbey Island and the southern shore of Everett. As shown in Fig. 4, the major part of the uplifted region is within the land of Whidbey Island.

3. Numerical Modeling Setup

3.1 Numerical model for tsunami propagation and inundation

We use the TUNAMI-N2 model (Imamura, 1995) for modeling propagation and coastal inundation of tsunamis in Puget Sound. In this model, a set of nonlinear shallow water equations with bottom friction term are discretized by the leap-frog finite difference scheme. This model is widely used to simulate tsunami propagation and inundation on a dry land.

We assume that seismic deformation of the sea floor push up the overlying water instantaneously and use the feature shown in Figs. 2 and 4 as the initial conditions of tsunami inundation modeling in each scenario.

3.2 Bathymetry and topography data

For the modeling of tsunamis, we use the digital elevation data provided by PRISM (Puget Sound Regional Synthesis Model). This data is compiled from USGS digital elevation models and NOS GODAS Bathymetry. The original grid size is 30 m and the datum for the elevation is based on NAVD29. We focus on an area of (47.2°N, 123.0°W)–(48.0°N, 122.1°W) as the computational domain for the Seattle Fault earthquake tsunami (see Fig. 1), and (47.5°N, 123.0°W)–(48.3°N, 122.1°W) for the SWF tsunami (see

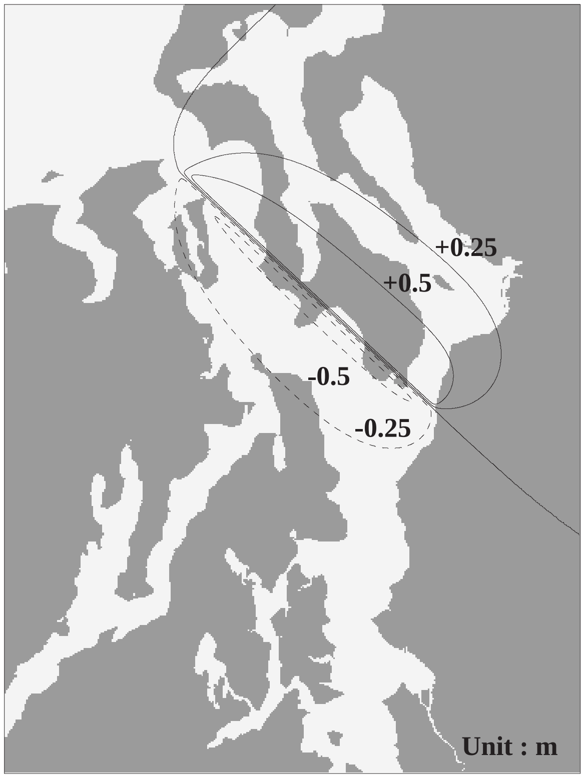

Figure 4: Computed seismic deformation due to the scenario earthquake on the Southern Whidbey Island Fault.

Fig. 3). For the computation of tsunamis within the broad area of Puget Sound, we reprojected the original data to create a 90 m grid. For the inundation modeling within populated regions such as Seattle or Bremerton, we use the original 30 m grid, constructing a nested grid system inside the 90 m grid.

4. Modeling Results

4.1 Seattle Fault earthquake tsunami

For the Seattle Fault generated tsunami, we assume that the background water level is constant in time and at mean tide level. The propagation features of tsunamis generated by the Seattle Fault earthquake are similar to that described in Koshimura *et al.* (2001), i.e., the tsunami generated by the Seattle Fault earthquake 1100 years ago ($M_w = 7.6$). Figure 5 shows the computed tsunami waveforms at major ports and harbors in Puget Sound: Mukilteo (MK), Kingston (KN), Edmonds (ED), Northern shore of Elliott Bay (NEB), Head of Elliott Bay (HEB), Bremerton (BR), Port Orchard (PO), Vashon (VS), and Tacoma (TC). The location of each port is shown in Fig. 1. The tsunami strikes Elliott Bay with more than 3 m of its water level at the northern shore and 1.5 m at the head of the bay right after the earthquake. This result suggests that we should expect inundation at the Seattle waterfront area. At Bremerton and Port Orchard, local seismic uplift generates a 1.5 m tsunami at the moment of the earthquake, after which the water recedes. At Tacoma, positive tsunami waves arrive within approximately 10 minutes and a 1.5 m tsunami appears at 20 min. Tsunamis less than 1 m strike the other ports and harbors. However, note that the tidal range within Puget Sound is approximately 3 m. If the tsunami strikes during high tide, we should expect more serious hazards to impact local coastal communities.

Figures 6 and 7 show the tsunami inundation maps of the Seattle waterfront area, and Bremerton and Port Orchard area, which are both developing populated waterfront communities. The figures describe the distribution of maximum inundation depths on the land, which is measured from the local ground to the surface of surging water. For these areas, we carried out the detailed modeling of tsunami inundation based on the nested 30 m grids. The inundation map of the Seattle waterfront area shows that the heavy inundation occurs at Pier 90 and 91, with the inundation depth of more than 2 m, and at Pier 55 to 77 and Pier 36 to 54 with approximately 1 m depth. The inundation map of Bremerton and Port Orchard area shows that the inundation mainly occurs along the southern shore of Sinclair Inlet and the northern and southern shore of Dyes Inlet. The estimated inundation depths are up to 2 m at the shore 1 km east of Port Orchard, 4 m at the northern shore of Dyes Inlet and 2 m at the southern shore of the inlet, because of local seismic uplift and trapped tsunamis within it.

4.2 Southern Whidbey Island Fault earthquake tsunami

As shown in Fig. 4, the SWF seems not to generate destructive tsunamis, at least for the case presented here. Figure 8 shows the computed tsunami waveforms at major ports and harbors in Puget Sound : PT = Port Townsend, AH = Admiralty Head, EV = Everett, MK = Mukilteo, ED = Edmonds, KN = Kingston, EB = Elliott Bay, BR = Bremerton, and EH = Eagle Harbor. The results show that the tsunami heights are less than 50 cm at the major ports and harbors within Puget Sound. We see that a tsunami >1 m strikes only the eastern coast of Marrowstone Island, which is west of Whidbey Island, facing the source region (maximum tsunami height is estimated to be 2 m at the beach of the eastern shore of Marrowstone Island).

In the present scenario, we conclude that a SWF earthquake does not have the potential to induce strong inundation on the coastal communities within Puget Sound. However, the structure of SWF is still uncertain and the interpretation of the SWF zone suggests that it continues to the sea bottom of the Strait of Juan de Fuca. It is still possible that destructive tsunamis could be generated locally within the Strait of Juan de Fuca, which would then strike populated coastal communities such as Port Angeles. Further investigation is required to map the hazards within this area, due to locally generated tsunamis.

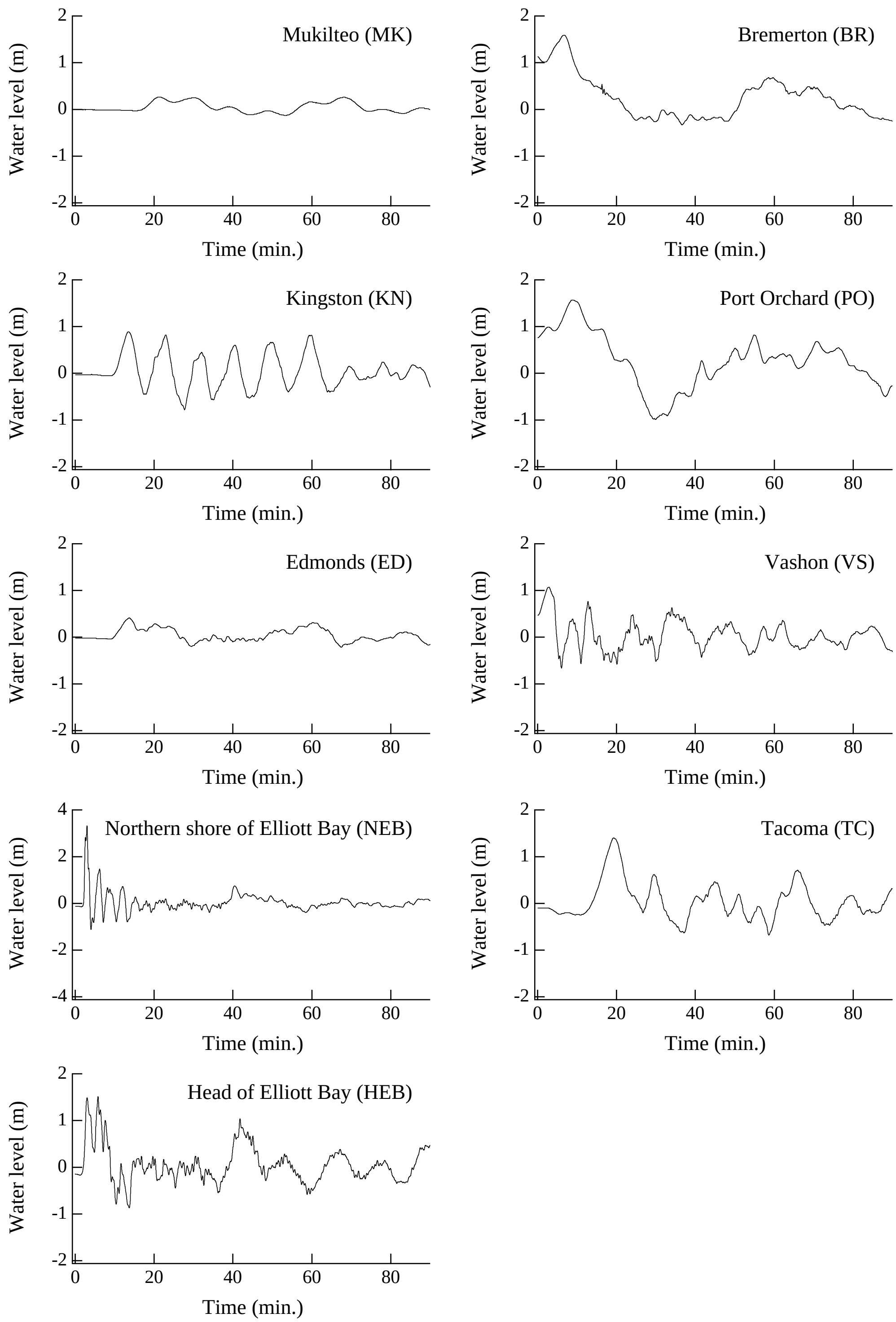

Figure 5: Computed tsunami waveforms at major ports and harbors in Puget Sound, due to the Seattle Fault earthquake. Abbreviations as follows: MK = Mukilteo, ED = Edmonds, KN = Kingston, NEB = Northern Elliott Bay, HEB = Head of Elliott Bay, BR = Bremerton, PO = Port Orchard, VS = Vashon, and TC = Tacoma.

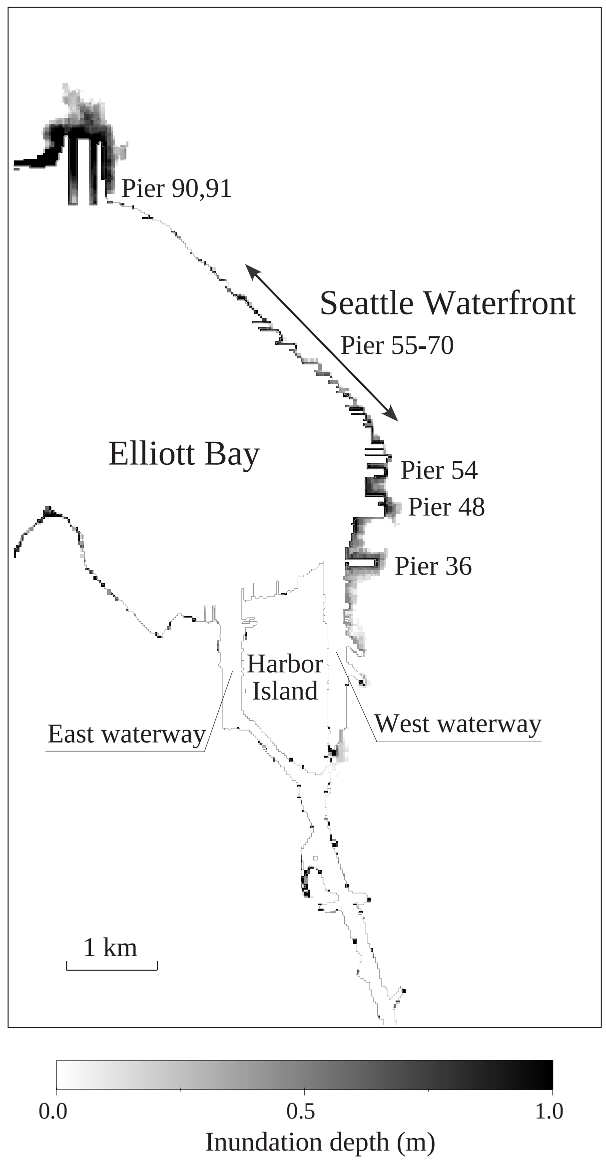

Figure 6: Tsunami inundation map of the Seattle waterfront area.

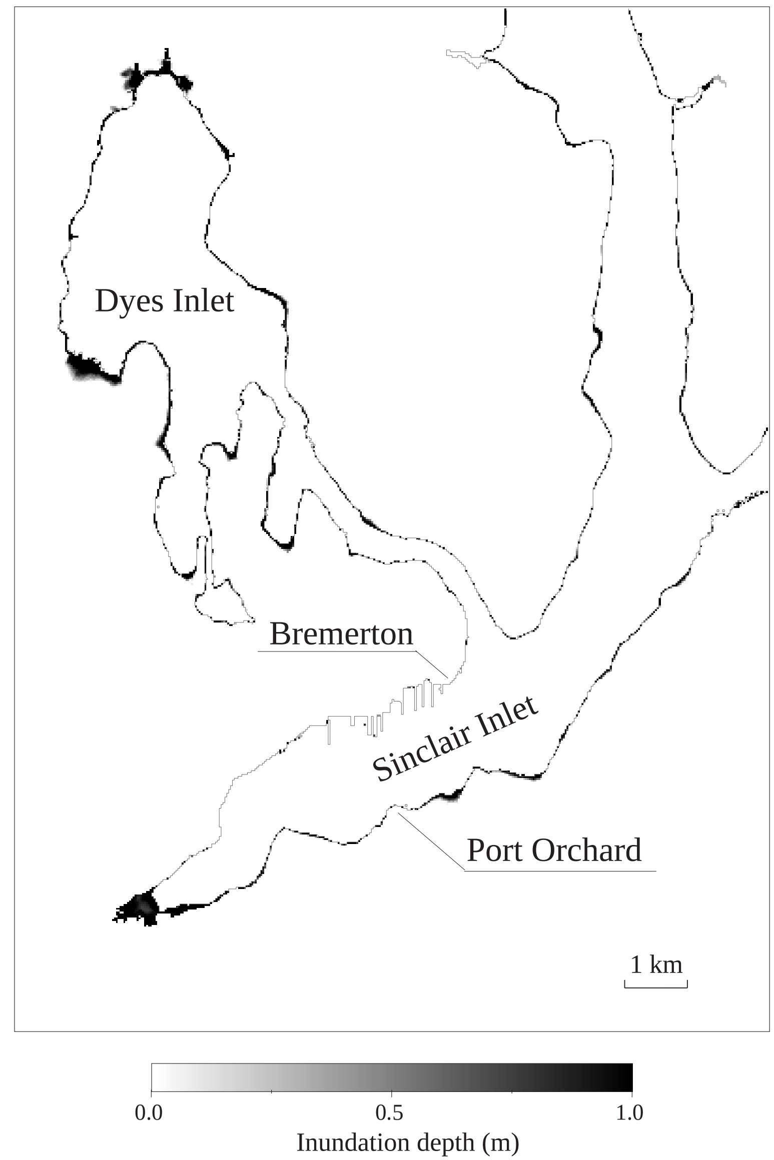

Figure 7: Tsunami inundation map of Bremerton and Port Orchard area.

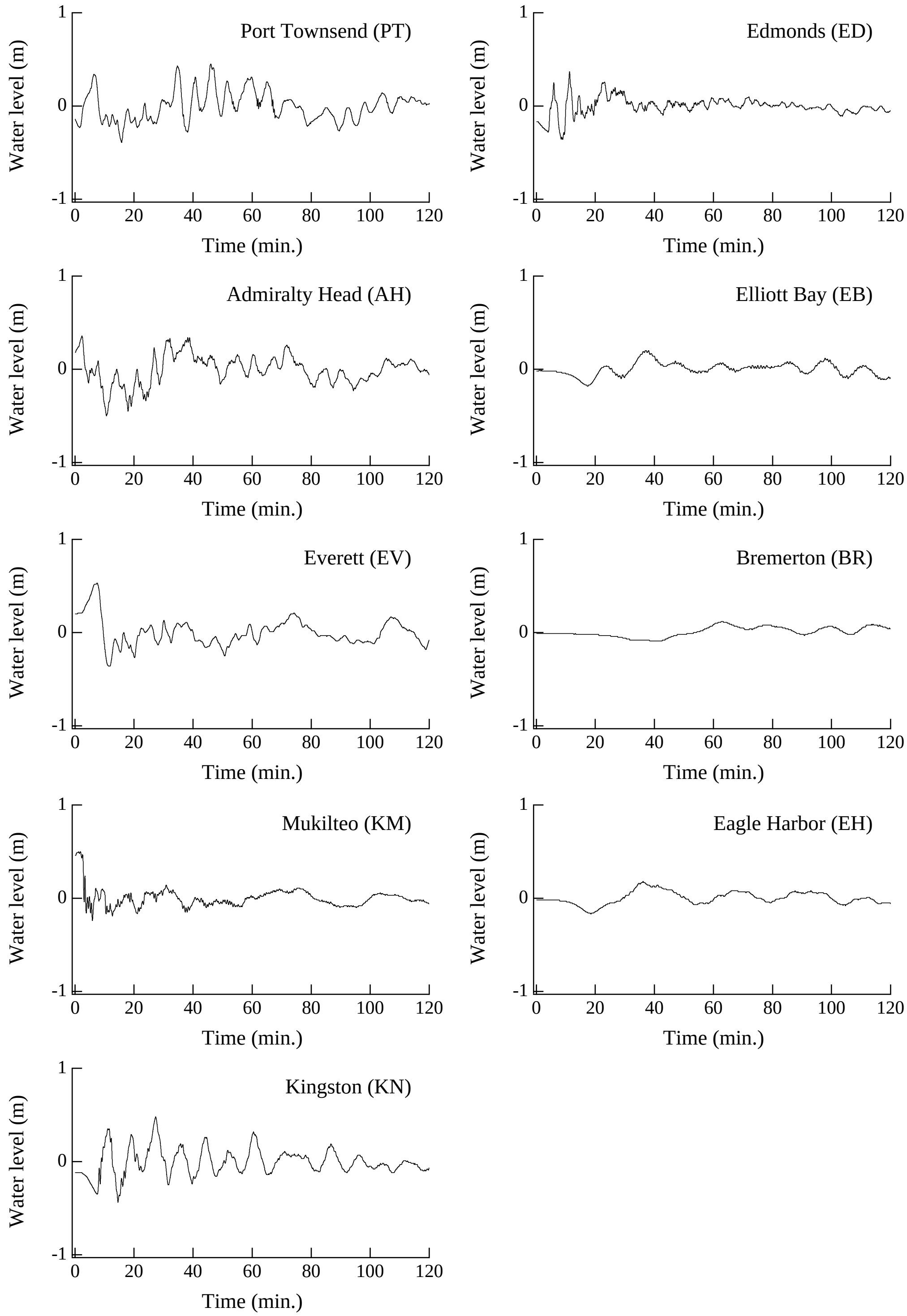

Figure 8: Computed tsunami waveforms at major ports and harbors in Puget Sound, due to the SWF earthquake. Abbreviations as follows: PT = Port Townsend, AH = Admiralty Head, EV = Everett, MK = Mukilteo, ED = Edmonds, KN = Kingston, EB = Elliott Bay, BR = Bremerton, and EH = Eagle Harbor.

5. Concluding Remarks

Based on the numerical modeling of tsunami generation, propagation, and inundation due to the potential earthquakes within the Puget Lowland, we mapped the tsunami hazards at the populated coastal communities in Puget Sound. If an earthquake of magnitude 7.2 occurs on the Seattle Fault, we should expect tsunami inundation of up to 2 m depth at the northern shore of Elliott Bay, and 1 m depth at the head of the Bay. Also, 2 to 4 m of inundation depths will be expected along the shores of Dyes Inlet and Sinclair Inlet.

If an earthquake of magnitude 7 occurs within the Southern Whidbey Island Fault zone, minor tsunamis will be generated. The modeling result based on the present scenario does not suggest the occurrence of strong inundation at the coastal communities. However, further investigation will be required to create the more credible tsunami hazard maps, including the area of the Strait of Juan de Fuca.

Also, we should note that the tidal range in the broad area of Puget Sound is approximately 3 m. We should consider the effect of tidal range for more detailed tsunami hazard mapping in Puget Sound.

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