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TACOMA, WASHINGTON, TSUNAMI HAZARD MAPPING PROJECT: MODELING TSUNAMI INUNDATION FROM TACOMA AND SEATTLE FAULT EARTHQUAKES

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Tacoma, Washington, Tsunami Hazard Mapping Project: Modeling tsunami inundation from Tacoma and Seattle Fault earthquakes

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Abstract. As part of a tsunami hazard mapping project funded by the National Tsunami Hazard Mitigation Program, the NOAA Center for Tsunami Research (formerly known as the NOAA Center for Tsunami Inundation Mapping Efforts) modeled tsunami inundation for the at-risk coastal community of Tacoma, Washington. Three tsunamigenic moment magnitude 7.3 earthquake source scenarios within the lower Puget Sound region were investigated: one along the Seattle Fault, and two along the Tacoma fault based on the most recent geophysical evidence. A high-resolution tsunami model was applied to estimate tsunami propagation in the southern Puget Sound region and inundation along the greater Tacoma area. These model results (Appendix A) were provided to the State of Washington for use in tsunami hazard maps to assist in the design of evacuation plans for the at-risk study area.

1. Background

Puget Sound has a rich history of natural hazards, including large earthquakes, landslides, and delta failures. Geologic and historic evidence have shown that some of these past events have generated tsunamis (Johnson *et al.*, 1999; Brocher *et al.*, 2004; Sherrod *et al.*, 2004). A 2002 workshop reviewed these historic events and recommended potential sources for tsunami inundation modeling to further assess the coastal hazard (González *et al.*, 2003). These recommendations included sources for the Tacoma region.

Though historic tsunamis within the region suggest a higher recurrence rate for a landslide source (Table 1, Fig. 1), workshop participants suggested that the "worst-case" scenario would likely have a seismic trigger (González *et al.*, 2003). Therefore, this study focuses on tsunamigenic earthquakes from Seattle and Tacoma fault sources based on the parameters established by workshop participants and further refined by Tom Brocher and Tom Pratt from the U.S. Geological Survey.

2. Study Area

The study area (Fig. 2) covers the coastal communities of Tacoma, Ruston, Gig Harbor, northern University Place, and the Puyallup Nation reservation in Pierce County and Federal Way, southern Vashon and Maury Islands of King County, Washington. Dash Point State Park and several regional parks (including Point Defiance, Titlow Beach, Sunrise Beach, and Ruston Way) lie along the shores of the study area. The region also supports several

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recreational marinas, a major commercial port, two state ferry terminals, and the Tacoma Narrows Bridge.

Maritime activity in Commencement Bay includes eight privately owned marine terminals and the publicly owned Port of Tacoma. The Port of Tacoma, the sixth largest commercial port in North America and the major economic engine for Pierce County (Port of Tacoma, 2005), lies at the edge of the Puyallup River delta. Eight waterways along the delta (Fig. 2b) are maintained by the U.S. Army Corps of Engineers. A public esplanade lines the western side of Thea Foss Waterway where several local outdoor events take place.

The Puyallup River delta has a history of damaging submarine landslides (Table 1). A landslide in 1894 generated a 10-foot wave that led to three deaths, destroyed freight docks, and caused significant damage in historic downtown Tacoma (Pierce County, 2004). In 1943, another submarine landslide produced a tsunami that destroyed jetties at the mouth of the Puyallup River (González *et al.*, 2003). Several smaller, non-tsunamigenic landslides have occurred on the delta since these events (Gardner *et al.*, 2001).

The Narrows is a major recreational and commercial transit waterway nested between Tacoma and the Kitsap Peninsula (Fig. 2a). High current velocities occur in this channel with a range of 2–5 knots at ebb and flood tides (National Ocean Service, 2006). The Tacoma Narrows Bridge, a primary thoroughfare, spans the midsection of The Narrows and is currently under construction. The new bridge will consist of two suspension spans and is scheduled for completion in 2008 (Washington State Department of Transportation, 2005).

A tsunamigenic subaerial landslide at Salmon Beach occurred in 1949 three days after a surface-wave magnitude (Ms) 7.1 Olympia earthquake. Estimated 6- to 8-foot tsunami waves were generated in The Narrows, damaging piers and boats in Gig Harbor and Salmon Beach (Lander, 1993; Chleborad, 1994).

3. Tsunami Sources

Three source scenarios were investigated for this study. One is based on a moment magnitude (Mw) 7.3 earthquake along the Seattle Fault as described in Titov *et al.*, 2003. The other source scenarios are based on Mw 7.3

Table 1: Known historic tsunami events in the study area. Event numbers are associated with estimated locations displayed in Fig. 1 (Chleborad, 1994; Gardner *et al.*, 2001; González *et al.*, 2003).

Event Number	Date	Type
1	1894	Deltaic submarine landslide
2	1943	Deltaic submarine landslide
3	16 April 1949	Subaerial landslide

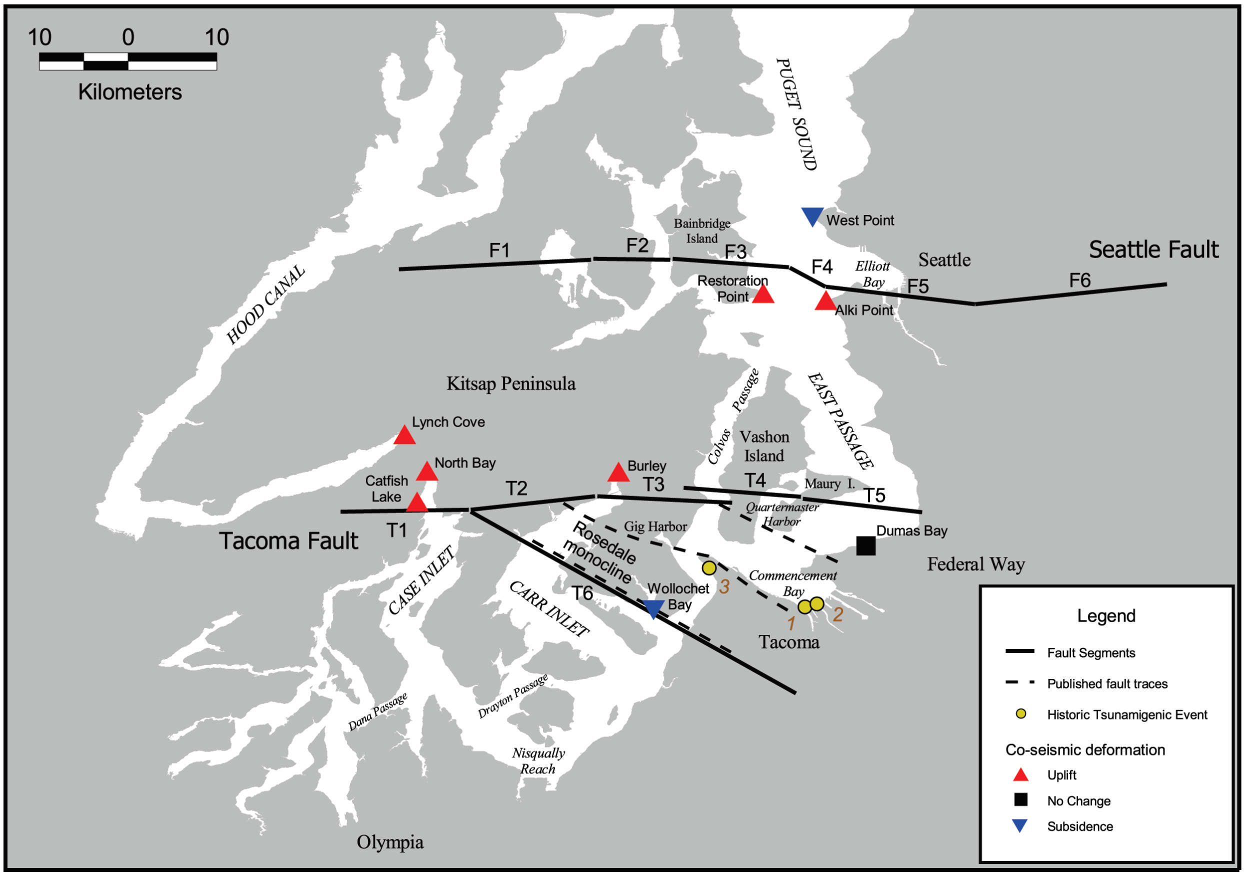

Figure 1: Seattle and Tacoma fault segments used for the study (Brocher *et al.*, 2004). Published fault traces, co-seismic deformation, and known historic tsunami events are also displayed (Sherrod *et al.*, 2004; Johnson *et al.*, 1999, 2004; González *et al.*, 2003; Gardner *et al.*, 2001).

earthquakes along the Tacoma Fault provided by Brocher and Pratt based on recent fault scarps detected through LIDAR mapping (Sherrod *et al.*, 2004). The detailed structure of both the Seattle and Tacoma faults are under much debate; however, tsunamigenesis depends primarily on surface displacement, which is fairly well determined by recent work in the field to provide reasonable assessments of these fault structures (Pratt *et al.*, 1997; Johnson *et al.*, 1999; Sherrod *et al.*, 2004).

Brocher *et al.* (2004) suggest that the Seattle and Tacoma faults are linked, such that a seismic event on one fault may trigger movement on the other. Recent field evidence suggests displacements occurred along both faults approximately 1100 years ago (Sherrod *et al.*, 2004). Though the scenarios are constrained by these measured vertical displacements, this duality was not considered in this study. Each fault model is described in detail in the following subsections.

3.1 Seattle Fault Scenario

The Seattle Fault scenario is based on six segments of varying length, strike, and slip (Table 2). The length and strike parameters are well within the

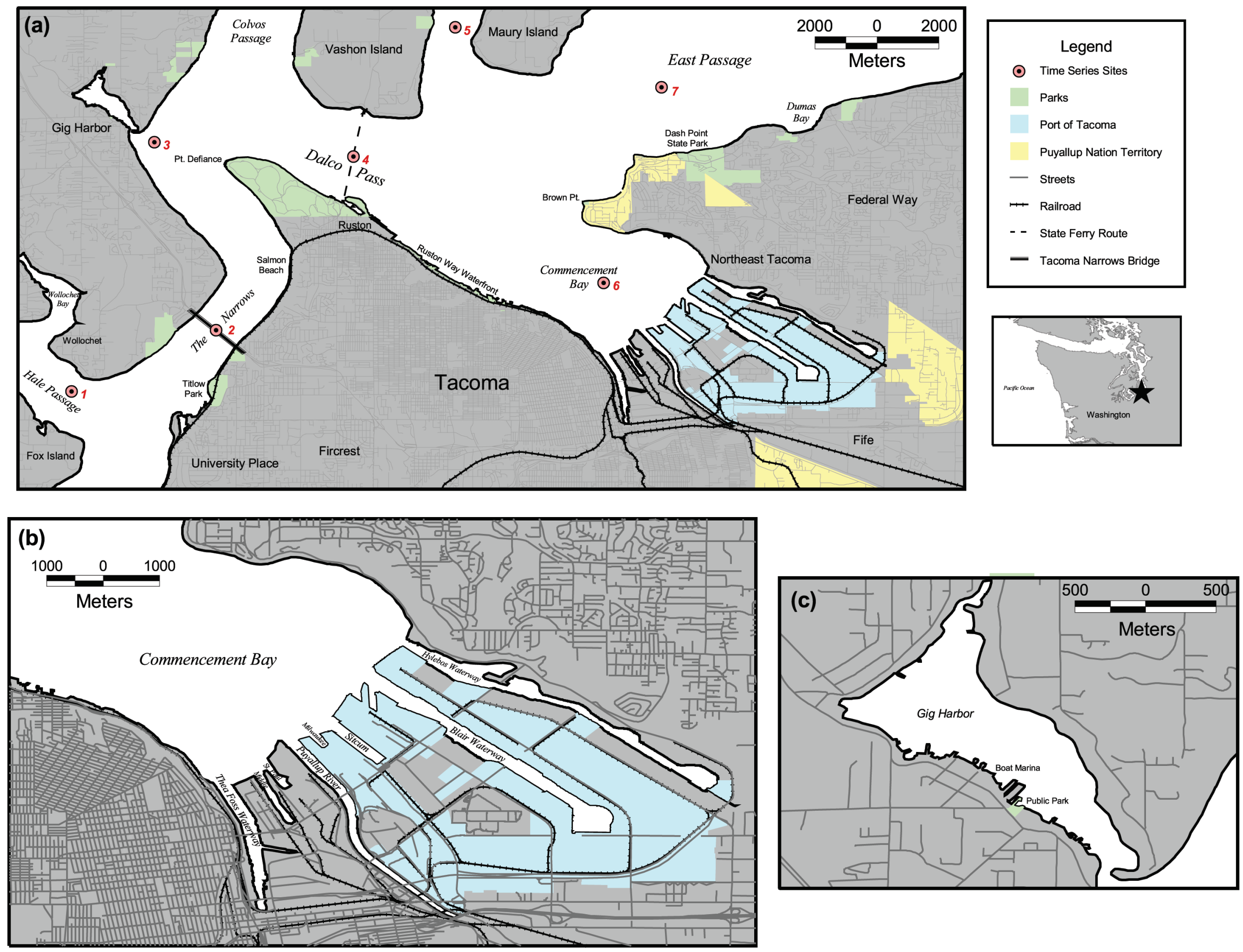

Figure 2: Study area of the tsunami hazard mapping project for Tacoma, Washington (a). Details of the (b) Puyallup Delta region and (c) Gig Harbor. Seven sites were selected to delineate time series of tsunami wave heights and current speeds (Fig. 6).

range of possibilities described in González *et al.*, 2003. The slip distribution was constrained to match vertical displacement estimates at Restoration Point, Alki Point, and West Point (Fig. 1) from a Seattle Fault earthquake in A.D. 900–930 (Bucknam *et al.*, 1992; Atwater, 1999). Table 3 provides a comparison of the computed model displacement (Fig. 3) with field estimates.

3.2 Tacoma Fault Scenarios

The Tacoma Fault scenarios were prepared by Tom Pratt and Tom Brocher. Two scenarios of equal probability are considered due to geophysical evidence (Brocher *et al.*, 2004; Sherrod *et al.*, 2004). The west end (fault segment T1) of both scenarios is based on a prominent geophysical lineament that extends through Case Inlet as evidenced by seismic tomography and trenching (Sherrod *et al.*, 2004). The eastern end from Case Inlet to Dumas Bay is less defined, with at least three fault lines found north and

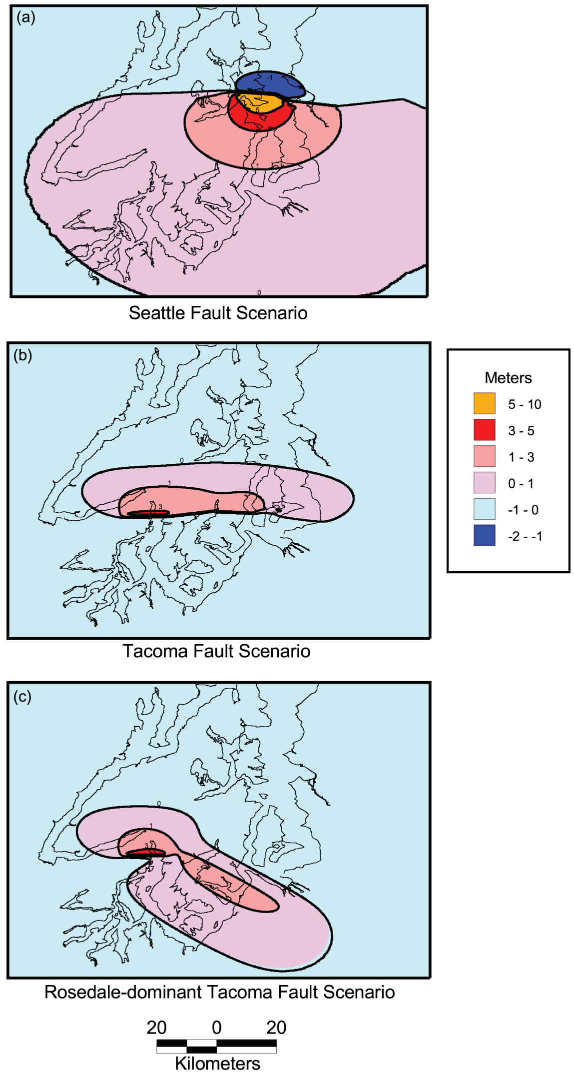

Figure 3: Modeled source scenarios for the (a) Seattle Fault, (b) Tacoma Fault, and (c) Rosedale-dominant Tacoma Fault. Vertical ground displacements are shown in meters.

south of Commencement Bay (Fig. 1). Given the uncertainty, two fault scenarios are considered: (1) the Tacoma Fault scenario based on published fault traces from Johnson *et al.* (1999, 2004) and (2) the Rosedale-dominant Tacoma Fault scenario based on an inferred wedge tip along the Rosedale monocline (Brocher *et al.*, 2004). The Tacoma Fault scenario is based on fault segments T1 through T5 and the Rosedale-dominant Tacoma Fault scenario is based on fault segments T1 and T6 (Table 4). The modeled slip distribution (Fig. 3) for each scenario matches fairly well with preliminary vertical displacement estimates at six field stations (Table 5) described by Sherrod *et al.* (2004).

Table 2: Seattle Fault segment seismic parameters as described in Titov *et al.* (2003) and displayed in Fig. 1.

Fault Segment	Length (km)	Width (km)	Strike (deg.)	Dip (deg.)	Displacement (m)
F1	15.2	35.0	87.9	60.0	1.0
F2	6.3	35.0	86.6	60.0	1.0
F3	8.9	35.0	96.0	60.0	12.0
F4	3.3	35.0	128.8	60.0	11.0
F5	11.5	35.0	99.3	60.0	4.0
F6	14.9	35.0	81.0	60.0	1.0

Table 3: Vertical deformation comparison based on field estimates and the Mw 7.3 Seattle Fault model. Vertical deformation sites are displayed in Fig. 1.

Site	Field (m)	Model (m)
Alki Point	4–6.5	3.6
Restoration Point	7	7.2
West Point	-1 ± 0.5	-1.1

Table 4: Tacoma fault segment seismic parameters based on Sherrod *et al.* (2004) and displayed in Fig. 1. The Tacoma Fault scenario is based on segments T1–T5; the Rosedale-dominant Tacoma Fault is based on segments T1 and T6 only.

Fault Segment	Length (km)	Width (km)	Strike (deg.)	Dip (deg.)	Displacement (m)
T1	10.0	14.1	268.9	45.0	5.6
T2	10.0	14.1	260.8	45.0	4.2
T3	10.0	14.1	274.0	45.0	2.8
T4	8.0	14.1	276.3	45.0	1.4
T5	8.0	14.1	279.5	45.0	1.4
T6	33.0	14.1	129.2	45.0	3.0

Table 5: Vertical deformation comparison based on preliminary field estimates (Sherrod *et al.*, 2004 and Sherrod, personal communication) and the Mw 7.3 Tacoma and Rosedale-dominant Tacoma Fault models. Vertical deformation sites are displayed in Fig. 1.

Site	Field (m)	Tacoma Fault Model (m)	Rosedale-dominant Model (m)
Lynch Cove	3	1.1	1.0
North Bay	4	2.3	2.2
Catfish Lake	4	3.2	3.4
Burley	1	1.3	-0.1
Wollochet Bay	-1	-0.1	1.3
Dumas Bay	0	-0.1	-0.1

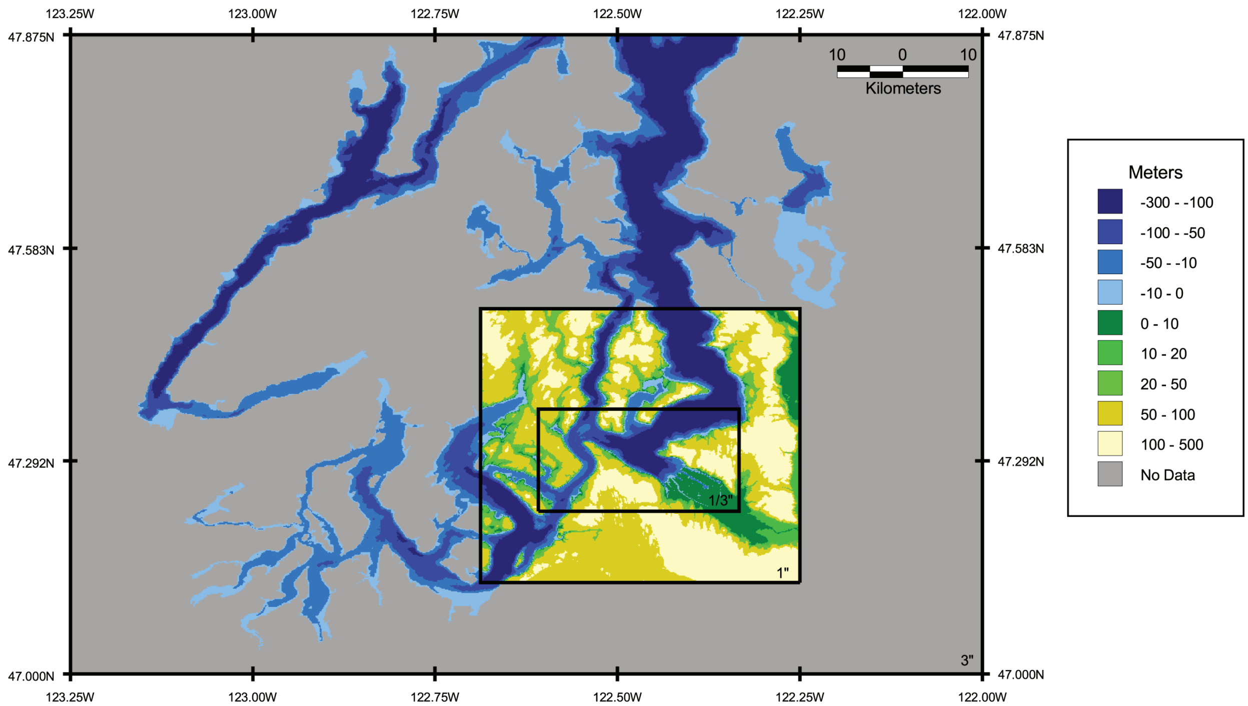

Figure 4: Extent and resolution of each digital elevation model (DEM) used in the study. The low-resolution DEM consists of only bathymetric depth values; the medium- and high-resolution DEMs consist of both bathymetric depth and topographic elevation values relative to Mean High Water.

4. Tsunami Model

Tsunami propagation and inundation for the study region is computed using the Method of Splitting Tsunami (MOST) model (Titov and González, 1997; Titov and Synolakis, 1995). MOST is a finite-difference long wave approximation model that has been extensively tested against laboratory experiments (Titov and Synolakis, 1998) and field data from historic tsunamis (Titov *et al.*, 2004). Titov *et al.* (2003) describes the application of the MOST model for a tsunami in Puget Sound. The following sections briefly describe the computational grids and specific modeling parameters used for this inundation study.

4.1 Digital Elevation Model Development

The MOST model requires nested computational grids to calculate the complicated wave dynamics of tsunami generation, propagation, and inundation. Three digital elevation models (DEMs) were developed for this study (Fig. 4). Bathymetric and topographic data were collected from government agencies and analyzed to select sources of the best quality (Appendix B). The spatial density of the selected data ranged from 0.6 to 30 m.

The selected data were converted to geographic decimal degrees (North American Datum of 1983) with vertical units of meters with respect to Mean High Water. Bathymetric data were converted to Mean High Water using

Table 6: Vertical control. Values are with respect to Mean Lower Low Water based on the Tacoma National Ocean Service secondary water-level control station 944-6484.

Datum	**Meters**
TIDE22 (Local datum)	5.901
Mean High Water	3.336
Mean Sea Level	2.094
North American Vertical Datum 1988	0.758
Port datum (Local datum)	0.137
Mean Lower Low Water	0.000

Table 7: Quantitative root mean square (RMS) error estimate of the DEMs. Estimated RMS error was calculated based on source references (Hess and Smith, 2004; Snyder, 1987) and methods described in Venturato (2005). The total error is the sum of the quantitative values. Subjective interpretation due to combining multiple data sources adds unknown error to the DEMs.

Error Type	**Horizontal Error Range (m)**	**Vertical Error Range (m)**
Projection/datum conversion	0.15–0.25	0.03–0.20
Comparison with vertical control benchmarks	N/A	0.27–1.81
Comparison with original data sources	0.67–10	0.35–0.98
Total known quantitative error	0.82–10.25	0.65–2.99

local datum conversions from the U.S. Army Corps of Engineers, the Port of Tacoma, and the vertical datum conversion tool known as VDatum (Hess and White, 2004). Topographic data were converted to Mean High Water using tidal and geodetic benchmark information from the National Ocean Service. Table 6 provides more information about vertical datum conversion values.

A shoreline file representing the Mean High Water line was generated based on data from the Washington State Department of Ecology and the Port of Tacoma. Piers with open pile foundations were removed from the shoreline data since tsunami waves can propagate under them.

DEMs of 1/3-, 1-, and 3-arc-second resolution for tsunami inundation, propagation, and generation regions, respectively, were developed using Delauney triangulation and natural neighbor interpolation. Though assessing the quality of a DEM based on multiple data sources is difficult, an attempt to quantify some factors of error (Table 7) were made using methods described in Venturato (2005).

4.2 Model Setup

The 1/3-, 1-, and 3-arc-second DEMs were converted to ASCII raster grids and then sub-sampled to 1-, 3-, and 9-arc-second grids to ease the computational load on the MOST model. Since the grids are based on a "bald-earth" (Venturato *et al.*, 2005), a bottom friction coefficient is used in the model. The Manning parameter for this study was set to 0.055.

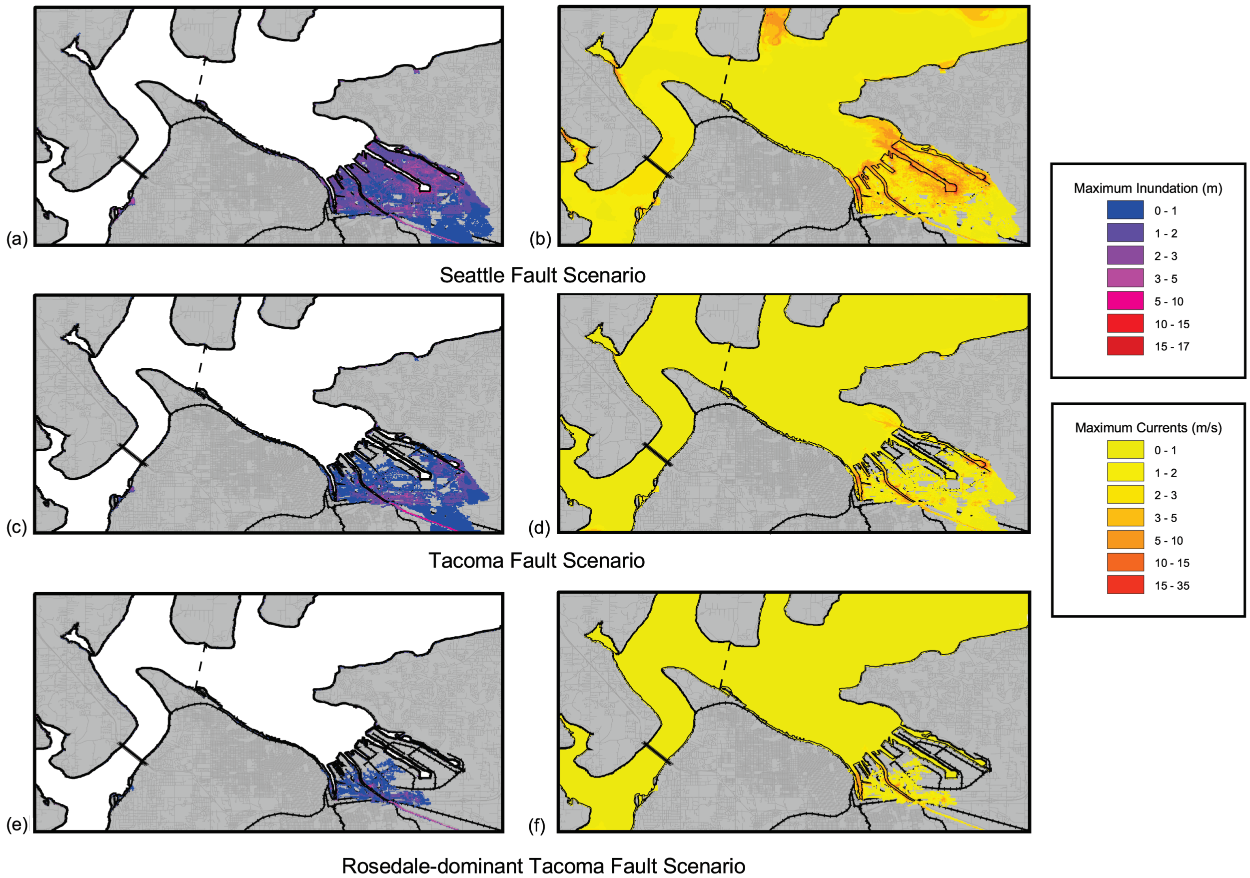

Figure 5: Maximum inundation (a, c, e) and maximum wave speeds (b, d, f) for each source scenario. The Seattle Fault scenario has the most inundation and highest currents. The Tacoma Fault scenario has significant inundation in the Port of Tacoma region, but with smaller amplitudes. The Rosedale-dominant Tacoma Fault scenario depicts the least inundation and lowest current speeds.

5. Discussion of Modeling Results

All three scenarios create significant vertical displacements along their respective fault surfaces. The Seattle Fault scenario creates the most intense currents and inundation (Figs. 5, 6) within the study area due to the large displacement of water in the deepest and widest region of Puget Sound. The Tacoma Fault scenario causes less inundation overall since much less water is displaced in the narrower and shallower regions of Carr Inlet, Colvos Passage, and East Passage. The Rosedale-dominant Tacoma Fault scenario causes the least amount of inundation in the study region due to relatively small displacements in the regional channels.

Most inundation occurs within low-lying, relatively flat regions of the study area such as the Port of Tacoma harbor in Commencement Bay. Minimal inundation occurs along steep topographical slopes. Consequently, the inundation is determined primarily by local topography rather than offshore wave dynamics. This correlates well with previous observations of long period tsunami waves, which lose their energy via bottom friction over long penetration distances (Titov *et al.*, 2003). The following sections provide more details on the offshore wave dynamics and inundation of each tsunamigenic scenario.

Due to constraints of the inundation grid, the model does not cover the full extent of wave propagation in the upper Puyallup River; subsequently, the wave reflects off the edge of the grid boundary leading to potentially nonphysical inundation within the City of Fife and Puyallup Nation territory.

5.1 Seattle Fault Scenario

Offshore Dynamics

The Seattle Fault source creates a sharp dislocation along the fault plane extending across northern Kitsap Peninsula and eastward through south Seattle. Minor subsidence occurs on the north side of the fault. South of the fault, a large uplift occurs with a maximum 8 m in the southern Bainbridge Island region and diminishing in intensity throughout the southern Puget Sound region (Fig. 3). This rupture forms the initial tsunami wave between Alki Point and Restoration Point, which is one of the deepest regions of central Puget Sound. Two wave fronts are formed: one traveling north impacting Elliott Bay and northern Puget Sound, and the other traveling south toward Tacoma and southern Puget Sound. The southern wave front splits into two upon striking the northern tip of Vashon Island 4 min after initial deformation. The eastern and more intense front travels down East Passage striking northern Maury Island and Dumas Bay and then reflecting off the Ruston Way waterfront and southern Vashon Island 12 min after generation (Fig. 7). The weaker west front travels down Colvos Passage striking Point Defiance before joining with the stronger reflected wave in Dalco Pass. Maximum wave crests of approximately 3.5 m amplitudes reach Commencement Bay and Gig Harbor approximately 19 min after generation (Fig. 6). Part of the primary front's reflected wave energy travels north into Quartermaster Harbor and back up East Passage toward Elliott Bay and northern Puget Sound. The remaining wave energy travels into The Narrows and then dissipates in southern Puget Sound. Smaller though still significant waves continue to reflect back and forth within the study region for 3 hr.

High (>1.5 m/s) wave velocities occur within Commencement Bay, Gig Harbor, East Passage, Quartermaster Harbor, The Narrows, and Wollochet Bay. Since the model does not dynamically include tidal currents, the current speeds may be more substantial if these events occurred during a flood tide.

Inundation Details

Dumas Bay Park is the first area to be inundated in the study region approximately 10 min after tsunami generation (Fig. 8). Tsunami vertical runup reaches 3.2 m with inundation extending 250 m inland.

Inundation along the Ruston Way waterfront starts approximately 12 min after earthquake generation. This popular recreational area would be struck

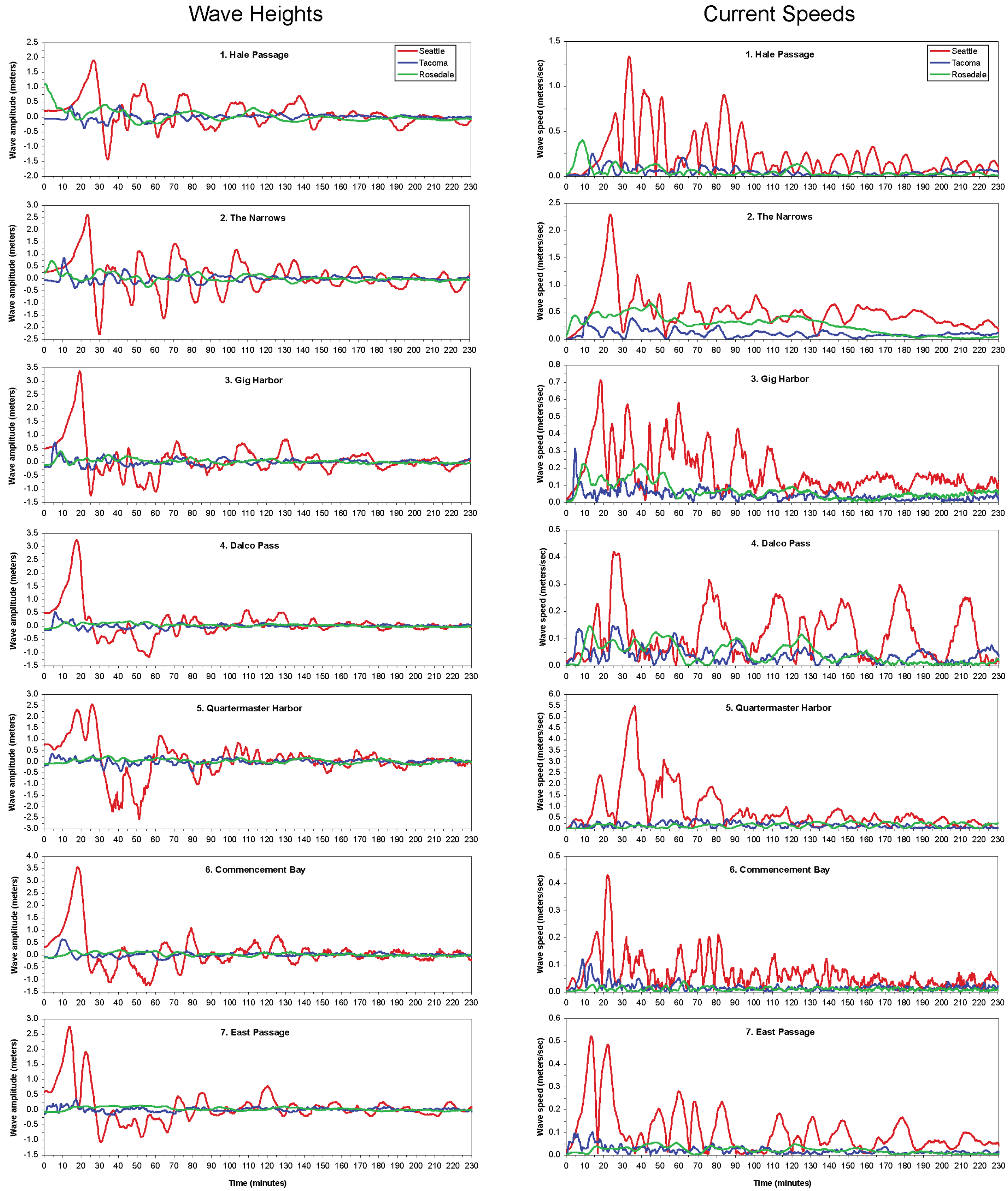

Figure 6: Time series of tsunami wave heights and current speeds at select sites of the study region. Figure 1 displays the associated site locations.

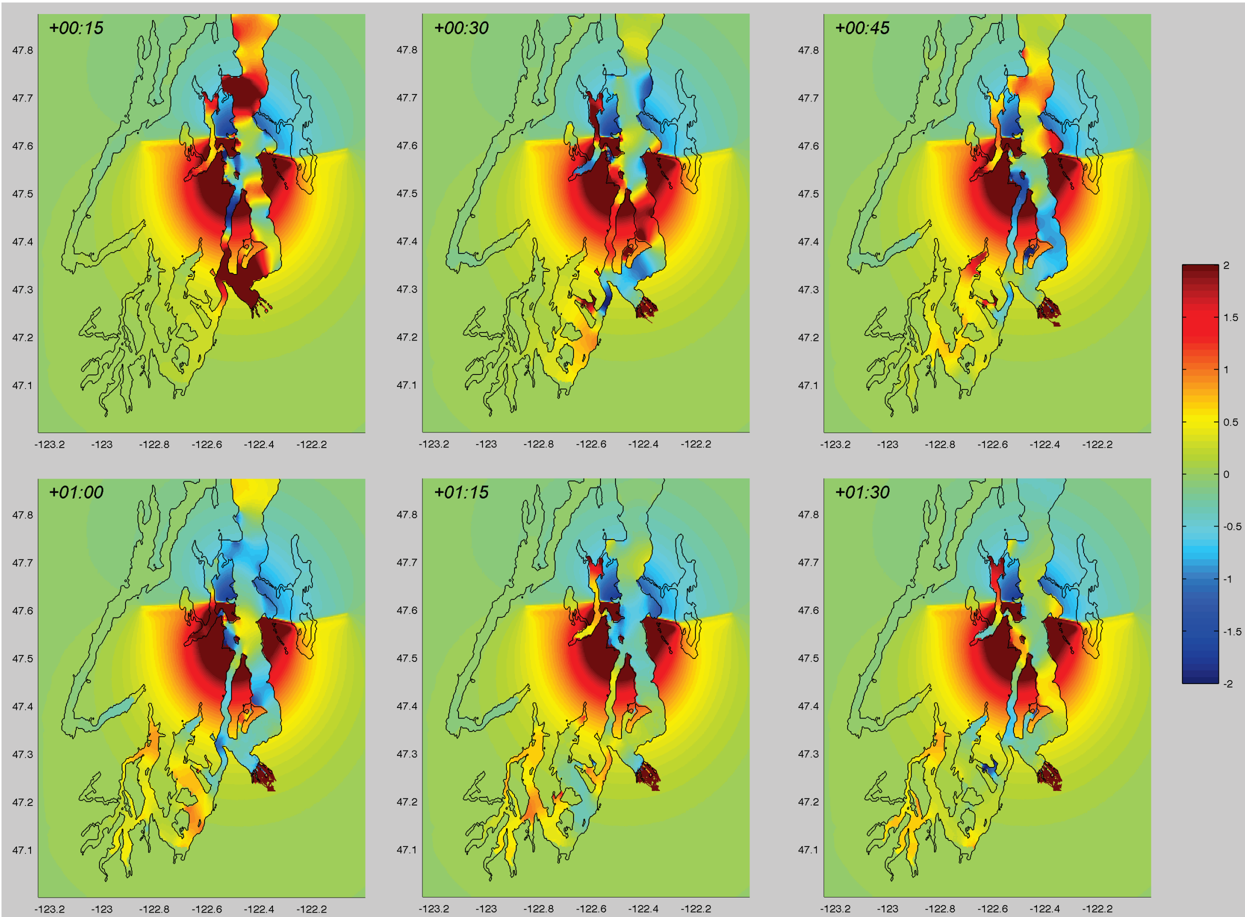

Figure 7: Modeled tsunami propagation in Puget Sound from the Seattle Fault scenario. Snapshots are in 15-min intervals with wave amplitudes in meters.

with an initial maximum 3.2-m wave overtopping several piers and inundating the sole roadway along the waterfront.

Approximately 14 min after generation, the tsunami starts to inundate the Port of Tacoma and the Thea Foss Waterway, building to a 3.5-m wave that overtops port facilities, the public esplanade, and adjacent low-lying neighborhoods as harbor channels and the Puyallap River flood. The total inundation area extends over 5 km inland along the Puyallup River delta.

Inundation occurs at both State ferry terminals approximately 18 min after tsunami generation. The Tahlequah terminal at the southern point of Vashon Island is hit with an initial 3.3-m wave with speeds ranging from 5–7 m/s and overtopping the dock and staging area. A 3.9-m wave strikes the Point Defiance terminal and marina at speeds of approximately 3 m/s. Inundation extends 80 m inland on a slag fill peninsula, an Environmental Protection Agency Superfund site (Washington State Department of Transportation, 2006), flooding the main marina access road northeast of the terminal.

The tsunami wave arrives at Gig Harbor approximately 19 min after

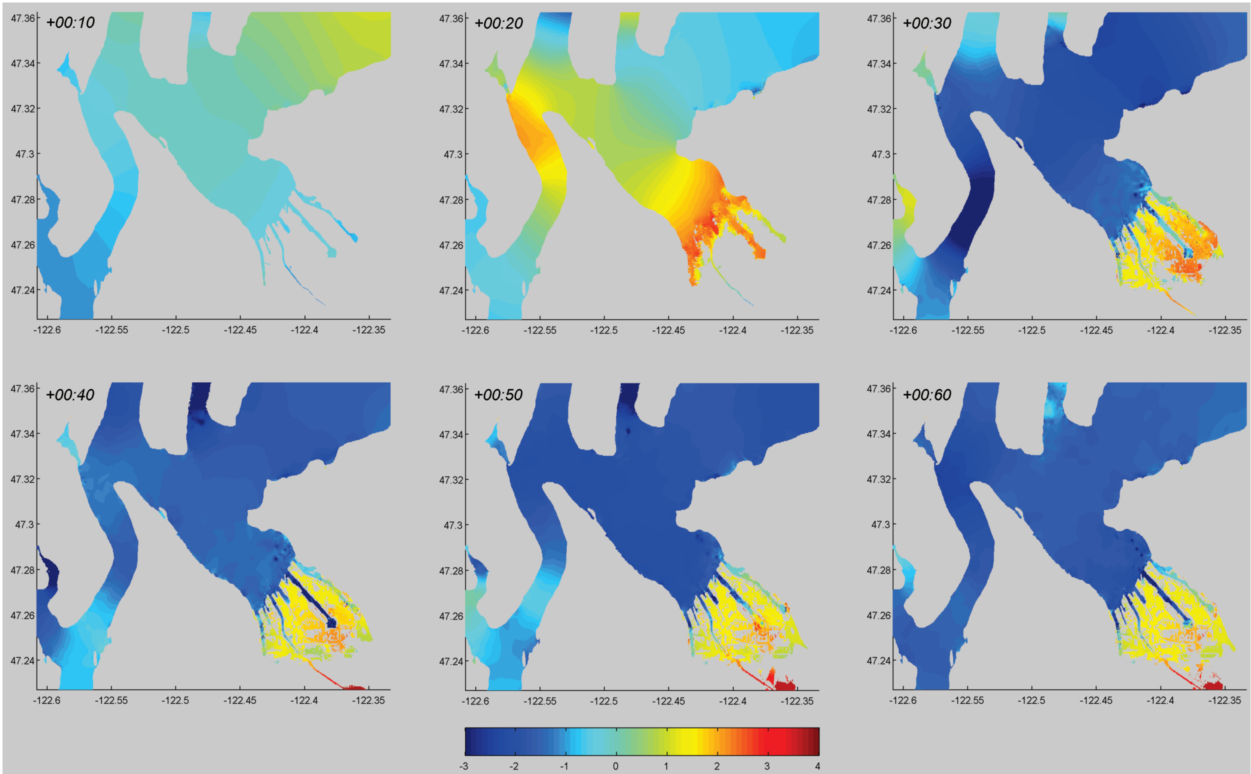

Figure 8: Modeled tsunami inundation in the study region from the Seattle Fault scenario. Snapshots are in 10-min intervals starting near the time of initial inundation at the Port of Tacoma. Wave heights are in meters with respect to Mean High Water.

generation. Tsunami vertical runups above 2 m occur along the northernmost tip of the harbor, inundating a local park. Current speeds are 1–2 m/s within the harbor, and reach above 5 m/s at the harbor entrance.

High current speeds ranging from 2–3 m/s also occur in the Narrows (Fig. 6). The initial wave reaches Titlow Park approximately 20 min after tsunami generation. The southern half of Titlow Park and a rail line are completely inundated with maximum wave runups reaching 3 m.

5.2 Tacoma Fault Scenario

Offshore Dynamics

The Tacoma Fault scenario creates a moderate uplift north of the fault plane with minimal subsidence (<0.5 m) south of the fault. The sharpest dislocation (3.4 m) occurs along the western edge of the fault, with diminishing intensity eastward. Much of the dislocation occurs on land and the shallow regions of Lynch Cove, North Bay, and Burley Lagoon. Smaller ruptures (0.7–2 m) along the eastern edge of the fault form the primary tsunami wave energy within Colvos Passage, Quartermaster Harbor, and East Passage (Fig. 3).

The initial displacement splits the wave energy into northbound and

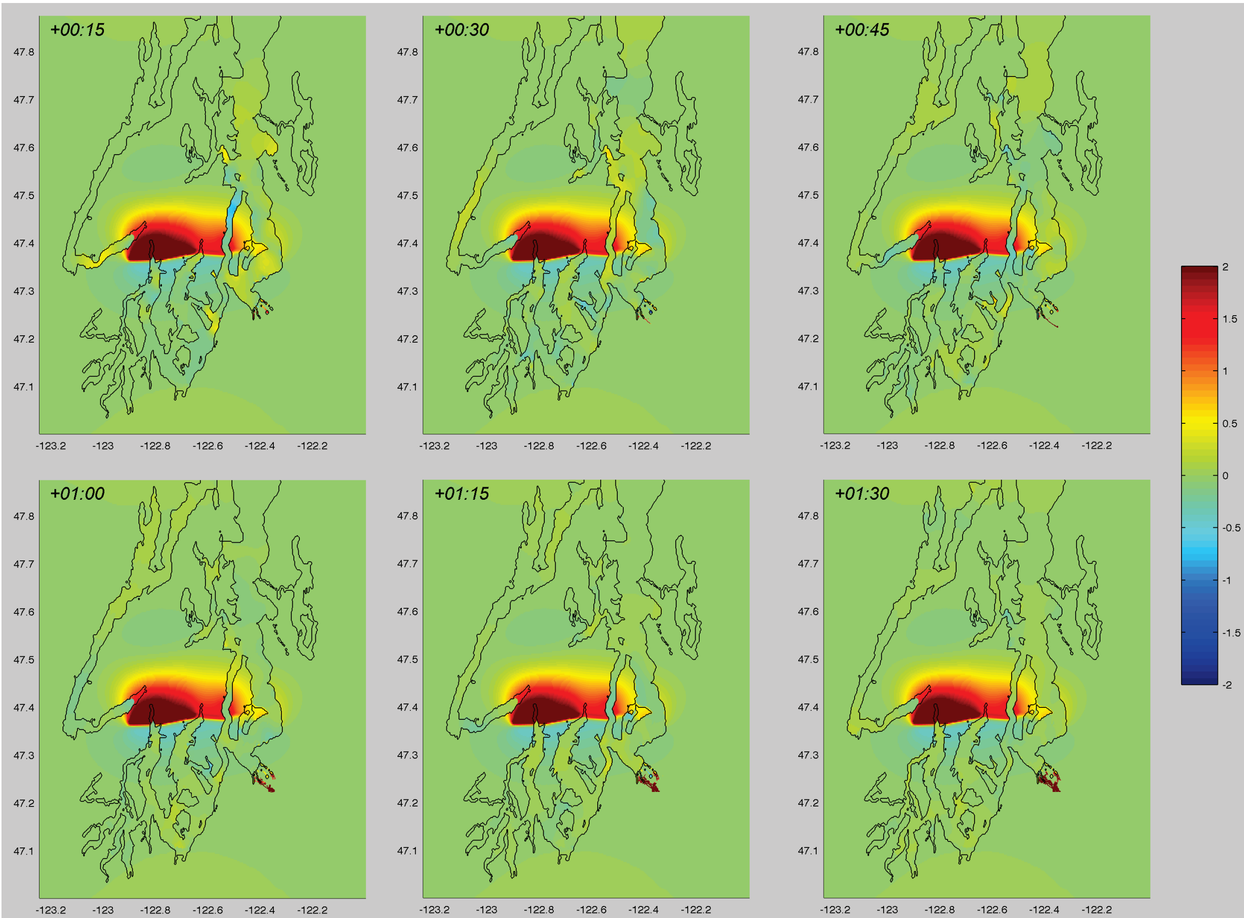

Figure 9: Modeled tsunami propagation in Puget Sound from the Tacoma Fault scenario. Snapshots are in 15-min intervals with wave heights in meters.

southbound fronts. The southbound front in Colvos Passage strikes Point Defiance 5 min after tsunami generation and subsequently splits further into a 0.5-m wave traveling into Dalco Pass, a 0.7-m wave into Gig Harbor, and a 0.8-m wave down The Narrows (Fig. 6).

The southbound front in East Passage creates a 1-m wave crest that strikes Dumas Bay 3 min after generation before joining the wave in Dalco Pass and a smaller wave from Quartermaster Harbor before reaching Commencement Bay. Part of the combined wave energy is reflected off the Ruston wave waterfront and travels back into East Passage. The remaining wave energy strikes the Port of Tacoma with a wave crest of 0.6 m approximately 10 min after generation.

The wave traveling down The Narrows reaches Fox Island 15 min after generation and then splits into a wave front traveling up Hale Passage and another toward Nisqually Reach dissipating in south Puget Sound (Fig. 9). Wave crests of 0.8 m amplitudes reach Wollochet Bay 20 min after generation. Smaller wave activity is witnessed throughout the study region for approximately 1.5 hr.

High current speeds (>1.5 m/s) occur at the entrance to Gig Harbor, both ferry terminals, Port of Tacoma waterways, and the recreational area of Dumas Bay.

Inundation Details

Dumas Bay Park is inundated approximately 3 min after tsunami generation with vertical runups reaching 3.5 m (Fig. 5). The waterfront promenade along the north side of Point Defiance Park is struck 5 min after generation with maximum vertical runups reaching 2 m.

Inundation along both ferry terminals occur approximately 7 min after generation with runups reaching 1.5 m and current speeds ranging from 2–3 m/s. Gig Harbor is struck next at 8 min with maximum vertical runups reaching 2 m and inundating the local boat marina. Inundation along the Ruston Way waterfront starts approximately 8 min after generation with the highest runup values of 2.4 m inundating the promenade and roadway.

The tsunami hits the Thea Foss Waterway and Port of Tacoma with an initial 0.6-m wave 10 min after generation. The initial wave front does not overtop port facilities; instead, the wave crest builds up in the waterways and begins overflowing port banks at 15 min. Resonance in the waterways and Puyallup River continue to overflow the channels, and the port and public esplanade are slowly inundated over a period of 3 hr (Fig. 10). The majority of the port has runup values around 1 m, though maximum vertical runups reach 3 m at the termini of Blair and Thea Foss waterways and along Puyallup River banks. The total inundation area extends over 3 km inland.

Current speeds are relatively low in The Narrows, ranging from 0.2–0.4 m/s (Fig. 6). The initial wave crest inundates Titlow Park approximately 12 min after generation with maximum runups reaching 2.5 m and washing over the rail line.

5.3 Rosedale-Dominant Tacoma Fault Scenario

Offshore Dynamics

The Rosedale-dominant Tacoma Fault scenario creates moderate uplift (3.6 m) north of the fault plane. Like the Tacoma Fault scenario, the sharpest dislocation occurs primarily on land and shallow waters along the western edge of the fault. A smaller rupture (1.3 m) on the 33-km fault segment along the Rosedale monocline initiates the primary water displacement within Carr Inlet, Wollochet Bay, Hale Passage, and The Narrows (Fig. 3).

Within the primary rupture zone, high currents (>1.5 m/s) occur within Wollochet Bay and along the shores of Titlow Park. Moderate current speeds (0.5–1.2 m/s) occur within Hale Passage and The Narrows. Most of the initial tsunami energy is directed toward Nisqually Reach traveling into Case Inlet and Dana Passage (Fig. 2) where it dissipates in the shallow waters of southwestern Puget Sound. A strong wave also strikes Burley lagoon at the terminus of Carr Inlet within 10 min of generation (Fig. 11).

Remaining wave energy travels north up The Narrows with the initial wave front diminishing from 0.8 to 0.4 m before reaching the entrance to

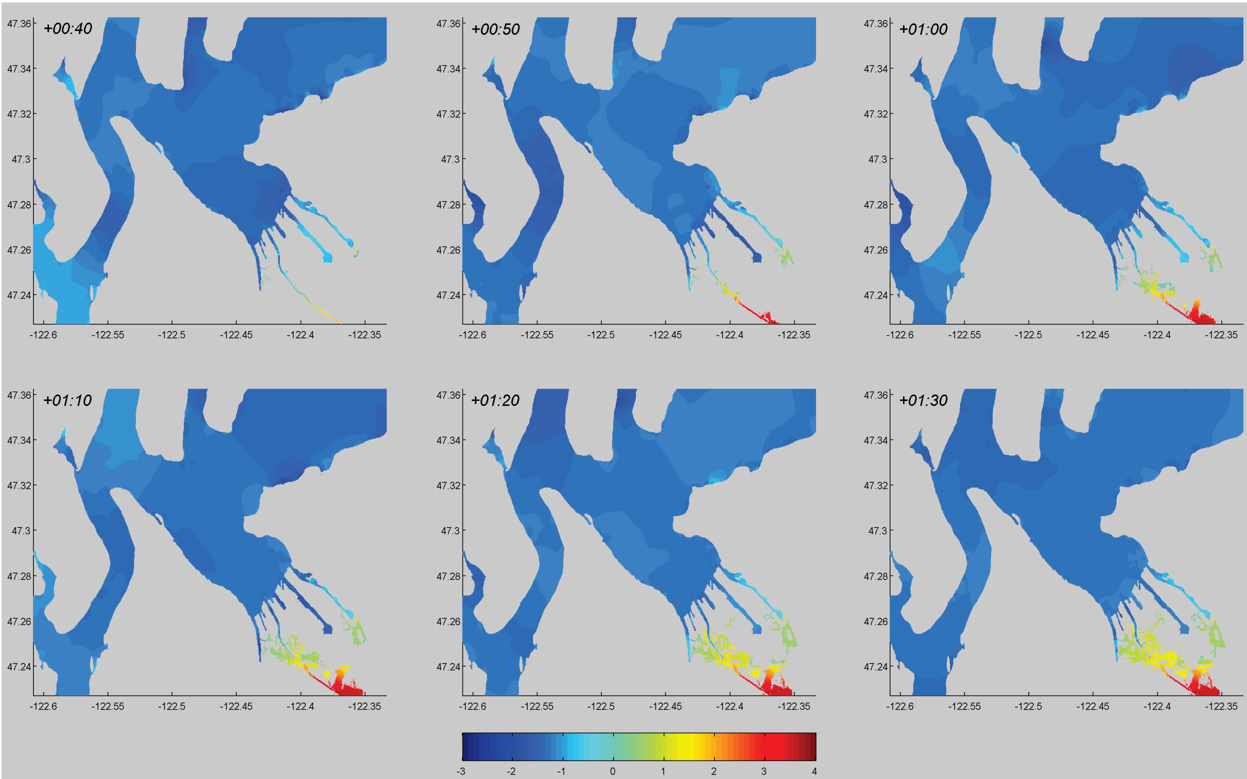

Figure 10: Modeled tsunami inundation in the study region from the Tacoma Fault scenario. Snapshots are in 10-min intervals starting near the time of initial inundation at the Port of Tacoma. Wave heights are in meters.

Gig Harbor 9 min after generation. Part of the wave continues up Colvos Passage and dissipates in central Puget Sound. A 0.2-m wave front reaches Commencement Bay 19 min after generation. This tsunami energy does not dissipate quickly, but sloshes back and forth between the shores of the study region (Fig. 6), starting inundation along the Port of Tacoma 30 min after generation.

A second smaller wave front (0.4 m) travels up The Narrows due to reflected energy from Carr Inlet, Wollochet Bay, and Nisqually Reach approximately 30 min after generation (Fig. 11). This wave combines with the complicated wave activity within Dalco Pass, leading to a second minor wave (0.2 m) striking the Port of Tacoma 40 min after generation. The tsunami continues to dissipate within the region for 4 hr.

Inundation Details

The shores along Wollochet Bay and southern Titlow Park are inundated within 5 min of tsunami generation with maximum runups of 1 m (Fig. 5). Gig Harbor marina is inundated with 1.3 m vertical runups 12 min after generation. The promenade along the north side of Point Defiance Park and Point Defiance ferry terminal are inundated with a 1-m wave at the same

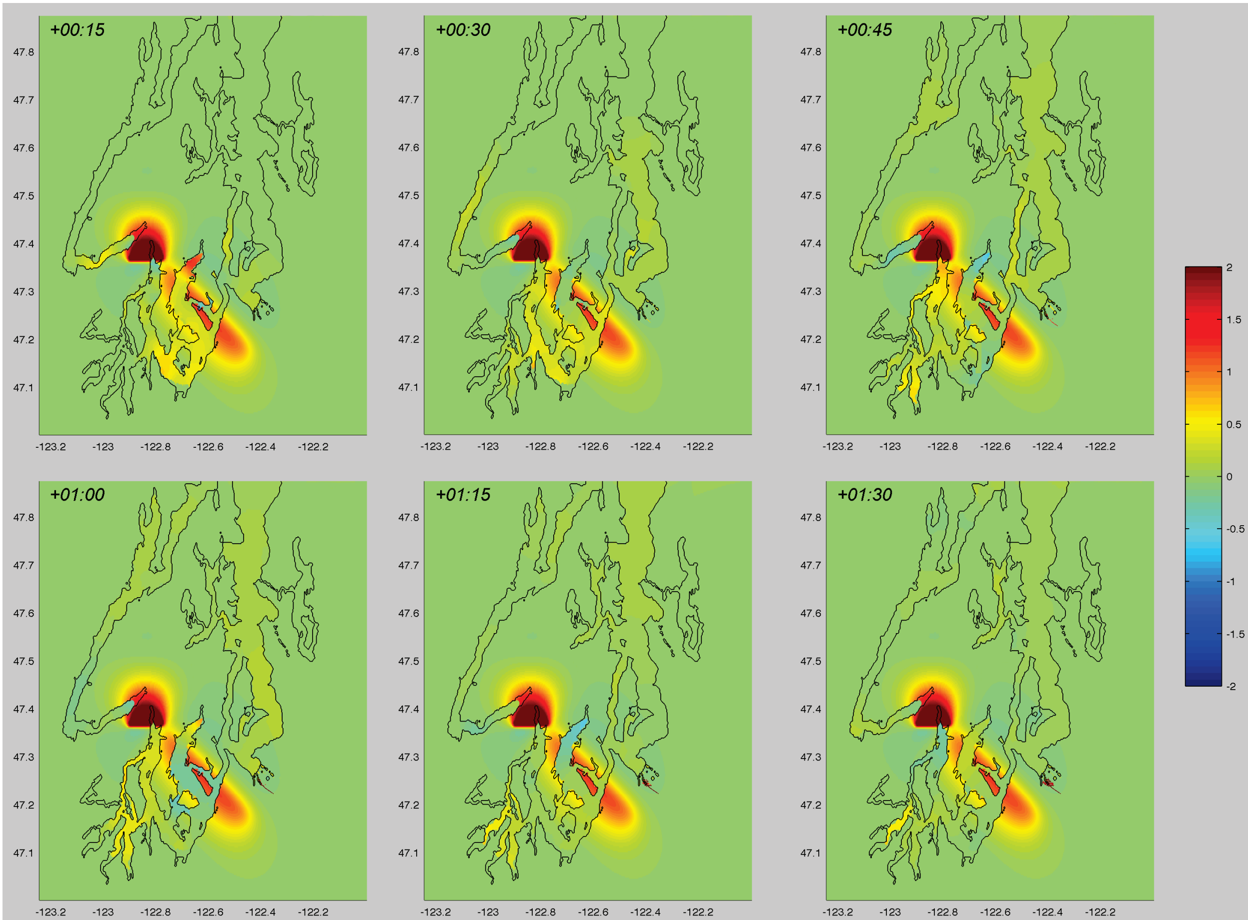

Figure 11: Modeled tsunami propagation in Puget Sound from the Rosedale-dominant Tacoma Fault scenario. Snapshots are in 15-min intervals with wave heights in meters.

time. The Tahlequah ferry terminal receives minor inundation and current speeds at both terminals are small (<0.3 m/s).

Inundation at the Port of Tacoma begins 30 min after generation as tsunami energy builds up in the Puyallup River overtopping its banks. The region around the river is slowly flooded with average vertical runups of 0.5 m (Fig. 12). This flooding starts to spill into Thea Foss Waterway 2 hr after the earthquake, just as another round of minor tsunami waves reaches the waterway. This causes resonant activity within the waterway that builds up, eventually overflowing the channel and causing minor inundation (0.3 m) along the Thea Foss esplanade 3 hr after the earthquake. The remaining waterways do not contribute to the inundation.

6. Summary and Conclusions

This project studied local tsunami inundation and regional propagation effects in the greater Tacoma and Gig Harbor region based on three modeling scenarios simulating tsunamigenic earthquakes along the Seattle and

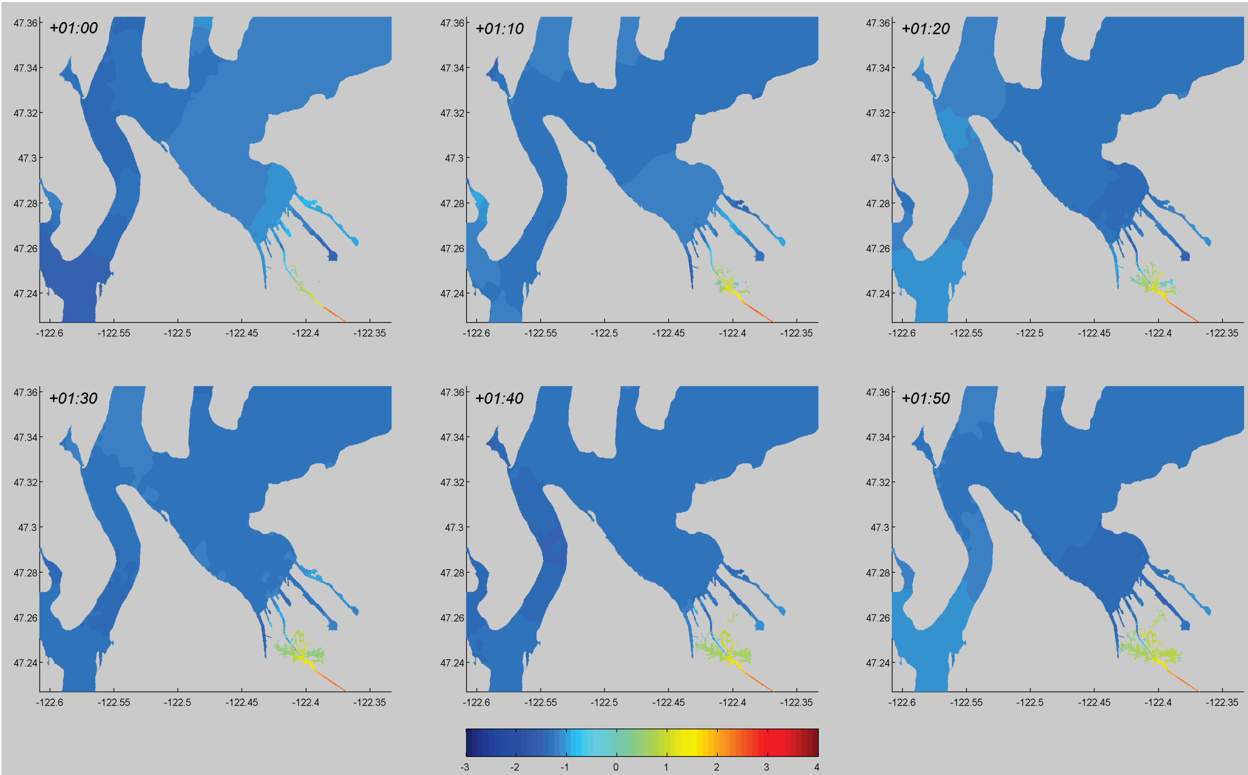

Figure 12: Modeled tsunami inundation in the study region from the Rosedale-dominant Tacoma Fault scenario. Snapshots are in 10-min intervals starting near the time of initial inundation at the Port of Tacoma. Wave heights are in meters.

Tacoma faults. The results of this study (Appendix A) are being used to develop tsunami hazard maps for the area.

The results show that a Mw 7.3 earthquake along the Seattle Fault would generate the most inundation at Tacoma and Gig Harbor. This conclusion is credible given that the Seattle Fault displaces a significantly greater volume of water than either Tacoma Fault model. Additionally, the deep East Passage acts like a one-dimensional channel allowing significant wave energy to reach the lower Puget Sound region. Both Tacoma Fault scenarios displace less water and the wave series must travel through several shallower channels, causing significant energy dissipation before reaching the shores of Tacoma or Gig Harbor.

All three scenarios cause inundation along the Port of Tacoma and Puyallup River. However, the wave action causing the inundation is significantly different for the Seattle Fault scenario in that the initial wave overtops the port due to a high amplitude. The Tacoma scenarios cause inundation by overflowing the harbor waterways over time.

Model results also show significantly high currents in the major marine transit channels and ports for all three scenarios. Tidal currents were not included in the tsunami simulations but may add to the tsunami hazard. Mean

High Water is used as a background level for the inundation model, with the assumption that tides interact linearly with the propagating tsunami wave.

This study provides a good first step toward analyzing the impact of tsunamigenic earthquakes within Puget Sound on Tacoma and Gig Harbor. However, this study does not consider tsunamigenic landslides that occur due to earthquakes or other mechanisms. Lower Puget Sound has a history of tsunamigenic subaerial and submarine landslides along the Puyallup delta and The Narrows (Fig. 1, Table 1). Slope stability maps also suggest a high probability of subaerial or submarine landslides within the study region. González *et al.* (2003) suggest that a deltaic submarine landslide associated with a major earthquake would produce a credible "worst-case" scenario for the study region.

The results of this study led to recommendations for future research in tsunamigenic hazards within lower Puget Sound:

- Research the inclusion of dynamic tidal interaction with the model.
- Characterize the geometry of potential deltaic and non-deltaic landslides within the study region.
- Review the tsunamigenic sources for the hazard every few years as new research adds to the understanding of the Seattle-Tacoma fault structures and their possible relationship.

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8. References

Atwater, B.F. (1999): Radiocarbon dating of a Seattle earthquake to A.D. 900–930. *Seis. Res. Lett., 70*, 232.

Brocher, T.M., R.J. Blakely, and R.E. Wells (2004): Interpretation of the Seattle Uplift, Washington, as a Passive-Roof Duplex. *Bull. Seis. Soc. Am., 94*(4), 1379–1401.

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*, 1611–1614.

Chleborad, A.F. (1994): Modeling and analysis of the 1949 Narrows landslide, Tacoma, Washington. *Bull. Assoc. Eng. Geol., 31*, 305–327.

Gardner, J.V., E.J. van den Ameele, G. Gelfenbaum, W. Barnhardt, H. Lee, and S. Palmer (2001): Mapping southern Puget Sound delta fronts after 2001 earthquake. *Eos Trans., Am. Geophys. Union, 82*(42), 485, 488–489.

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 Special Report, 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. NOAA Tech. Memo. NOS CS 4, 27 pp.

Johnson, S.Y., R.J. Blakely, W.J. Stephenson, S.V. Dadisman, and M.A. Fiser (2004): Active shortening of the Cascadia forearc and implications for seismic hazards of the Puget Lowland. *Tectonics, 23*, TC1011.

Johnson, S.Y., S.V. Dadisman, J.R. Childs, and W.D. Stanley (1999): Active tectonics of the Seattle fault and central Puget Sound, Washington—Implications for earthquake hazards. *Geol. Soc. Am. Bull., 111*, 1042–1053.

Lander, J.F., P.A. Lockridge, and M.J. Kozuch (1993): Tsunamis affecting the west coast of the United States 1806–1992. NGDC Key to Geophysical Record Documentation 29, NOAA, 242 pp.

National Ocean Service (2006): Predicted Tidal Currents for The Narrows. `http://tidesandcurrents.noaa.gov/`

Pierce County (2004): Pierce County Hazard Mitigation Plan. Pierce County Department of Emergency Management, Section 4.

Port of Tacoma (2005): Economic Impact of the Port of Tacoma. Port of Tacoma Commission, 42 pp.

Pratt, T.L., S. Johnson, C. Potter, W. Stephenson, and C. Finn (1997): Seismic reflection images beneath Puget Sound, western Washington State: The Puget Lowland thrust sheet hypothesis. *J. Geophys. Res., 102*(B12), 27,469–27,489.

Sherrod, B.L., T.M. Brocher, C.S. Weaver, R.C. Bucknam, R.J. Blakely, H.M. Kelsey, A.R. Nelson, R. Haugerud (2004): Holocene fault scarps near Tacoma, Washington. *Geology, 32*(1), 9–12.

Snyder, J.P. (1987): Map Projections—A working manual. USGS Professional Paper 1395, 383 pp.

Titov, V.V., F.I. González, E.N. Bernard, M.C. Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato (2004): Real-time tsunami forecasting: Challenges and solutions. *Nat. Haz., 35*(1), 41–58.

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, 21 pp.

Titov, V.V. and F.I. González (1997): Implementation and testing of the Method of Splitting Tsunami (MOST) model. NOAA Tech. Memo. ERL PMEL-112, 11 pp.

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., and C.E. Synolakis (1995): Modeling of breaking and non-breaking long wave evolution and runup using VTCS-2. *J. Waterw. Port Coast. Ocean. Eng., 121*(6), 306–316.

Venturato, A.J. (2005): A digital elevation model for Seaside, Oregon: Procedures, data sources, and analyses. NOAA Tech. Memo. OAR PMEL-129, 17 pp.

Washington State Department of Transportation (2006): Point Defiance and Tahlequah Ferry Terminal Feasibility Study. http://www.wsdot.wa.gov/Projects/

Washington State Department of Transportation (2005): The Tacoma Narrows Bridge Project Folio. http://www.tacomanarrowsbridge.com/

Appendix A: Modeling Products

Model results, metadata, and documentation were provided to the Washington State Division of Geology and Earth Resources and the Washington State Military Department Emergency Management Division, which are responsible for redistribution of these products. A list of the data series is provided in Table A1. All geospatial data are in ESRI ArcGIS© format with the following parameters:

- Projection: State Plane Coordinate System Zone 5626 (Washington South)
- XY Units: feet
- Z Units: meters or meters/second
- Horizontal Datum: North American Datum of 1983
- Vertical Datum: Mean High Water

Table A1: Product summary.

Item	Name	Type
0	Presentations, Product Report, Grid Report	Documentation
1	sea_animation, tac_animation, tacrd_animation	Animations of tsunami propagation and inundation
2	DEMs, Legends, Shoreline, Timeseries_sites, Model Grids, Source Scenarios	Geospatial data in ESRI ArcGIS© shapefile or ASCII Raster format
3	hi_res_images, low_res_images	Images for use in maps or general distribution
4	wa_tacoma	FGDC-compliant metadata
5	tac_timeseries	Tsunami time series at selected points of interest

Appendix B: Data Credit

NOAA National Geodetic Survey (2004): Vertical Geodetic Control Data. Silver Spring, Maryland. http://www.ngs.noaa.gov/

NOAA National Geophysical Data Center (2002): NOS Hydrographic Database, GEODAS Version 4.1.18. Boulder, Colorado. http://ngdc.noaa.gov/

NOAA National Ocean Service (2004): Regional Water-Level Station Benchmarks. Silver Spring, Maryland. http://tidesandcurrents.noaa.gov/benchmarks/

NOAA National Ocean Service Coastal Survey Development Laboratory (2004): VDatum Transformation Tool Version 1.06. Silver Spring, Maryland. http://nauticalcharts.noaa.gov/csdl/vdatum.htm

Port of Tacoma: 2002 Topographic contours. http://www.portoftacoma.com/

U.S. Army Corps of Engineers (2001): Tacoma Harbor, Blair Waterway, and Hylebos Waterway Condition Surveys. Seattle, Washington. http://www.nws.usace.army.mil/

U.S. Geological Survey EROS Data Center (1999): Seamless Data Distribution System National Elevation Dataset. Boulder, Colorado. http://seamless.usgs.gov/

U.S. Geological Survey (2001): Multibeam Mapping of the Major Deltas of Southern Puget Sound, Washington, Open-File Report OF01-266. Menlo Park, California. http://geopubs.wr.usgs.gov/open-file/of01-266/

Washington State Department of Ecology (2001): Washington State Marine Shorelines. Olympia, Washington. http://www.ecy.wa.gov/services/gis/