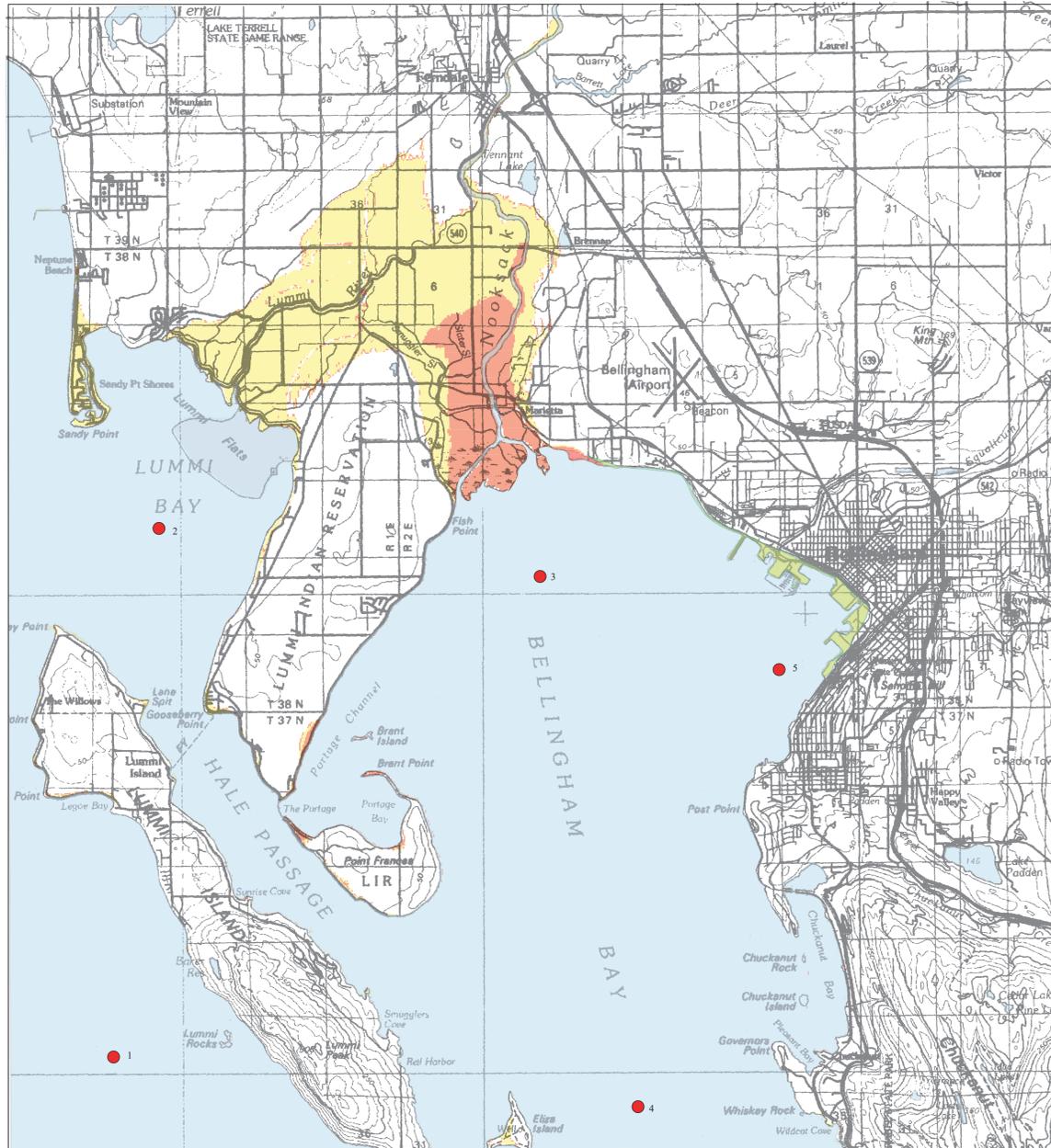


# Tsunami Hazard Map of the Bellingham Area, Washington: Modeled Tsunami Inundation from a Cascadia Subduction Zone Earthquake

by  
**Timothy J. Walsh<sup>1</sup>, Vasily V. Titov<sup>2</sup>, Angie J. Venturato<sup>2</sup>, Harold O. Mofjeld<sup>2</sup>, and Frank I. Gonzalez<sup>2</sup>**  
June 2004

<sup>1</sup> Washington Division of Geology and Earth Resources, PO Box 47007, Olympia, WA 98504-7007, tim.walsh@wadnr.gov  
<sup>2</sup> National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115-6349  
Vasily.Titov@noaa.gov, Angie.J.Venturato@noaa.gov, Harold.Mofjeld@noaa.gov, Frank.I.Gonzalez@noaa.gov



## INTRODUCTION

In 1995, Congress directed the National Oceanic and Atmospheric Administration (NOAA) to develop a plan to protect the West Coast from locally generated tsunamis. 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. Since 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.

This map is one of a series of tsunami inundation maps produced by the Washington Department of Natural Resources, Division of Geology and Earth Resources, in cooperation with the Washington Emergency Management Division as a contribution of the National Tsunami Hazard Mitigation Program (Walsh and others, 2003a,b,c; 2002a,b; 2000). These maps are produced using computer models of earthquake-generated tsunamis from nearby seismic sources. The modeling for this map was done by the Center for the Tsunami Inundation Mapping Efforts (TIME) at NOAA's Pacific Marine Environmental Laboratory in Seattle for a scenario earthquake on the Cascadia subduction zone.

## CASCADIA SUBDUCTION ZONE

Recent research about the occurrence of great earthquakes off the 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 Cascadia subduction zone (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 tsunami deposits have been identified as far east as Discovery Bay, just west of Port Townsend (Williams and others, 2002), and on the west shore of Whidbey Island (Williams and Hutchinson, 2000). Heaton and Savelly (1985) report that Malak stories may reflect a tsunami washing through Watch Fraire 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 caused a shipwreck about 100 km north of Tokyo on A.D. 1700 (Atwater and Satake, 2003). The frequency of occurrence of Cascadia subduction zone earthquakes ranges from a few centuries to a millennium, averaging about 600 years (Atwater and Hemphill-Haley, 1997). It is believed that the last earthquake on the Cascadia subduction zone was about magnitude ( $M_w$ ) 9 (Satake and others, 1996, 2003). It is not known, however, if that is a characteristic magnitude for this fault.

## INUNDATION MODELING

The tsunami inundation is based on a computer model of waves generated by a scenario earthquake. The earthquake scenario adopted for this study was developed by Priest and others (1997) and designated Scenario 1A (also see Myers and others, 1999). It was one of a number of scenarios they compared to paleoseismic data and was found to be the best fit for the A.D. 1700 event. This scenario has been the basis for tsunami inundation modeling for the other maps produced by the NTHMP in both Oregon and Washington, based on a CSZ event. The land surface along the coast is modeled to subside during ground shaking by about 1 to 2 meters (Fig. 1), which is consistent with some paleoseismic investigations and also matches thermal constraints of Hyndman and Wang (1993). This earthquake is a magnitude ( $M_w$ ) 9.1 event with a rupture length of 1050 km and a rupture width of 70 km. Satake and others (2003) have recently calculated a very similar magnitude and rupture dimension from an inversion of tsunami wave data from the A.D. 1700 event.

The model used is the finite difference model of Titov and Synolakis (1998), also known as the Method of Splitting Tsunami (MOST) model (Titov and Gonzalez, 1997). It uses a grid of topographic and bathymetric elevations and calculates a wave elevation and velocity at each grid point at specified time intervals to simulate the generation, propagation, and inundation of tsunamis down the Strait of Juan de Fuca and into the Bellingham Bay area.

## RESULTS

The computed tsunami inundation is shown on the map in three color-coded depth ranges: 0-0.5 m, 0.5-2 m, and greater than 2 m. These depth ranges were chosen because they are approximately knee-high or less, knee-high to head-high, and more than head-high and so approximately represent the degree of hazard for life safety. The greatest amount of tsunami flooding is expected to occur in the valleys of the Lummi (red) and Nooksack Rivers up to their confluence near Ferndale and then to be confined to the relatively narrow valley of the Nooksack. Sandy Point Shores is expected to be flooded to a depth of a few feet. Elsewhere, tsunami flooding is expected only in the immediate vicinity of the shoreline, where evacuation to higher ground would be an easy matter.

Current velocities (Fig. 2) are shown in three zones—less than 1.5 m/s (<3 mph), which is the current speed at which it would be difficult to stand, 1.5-5 m/s, and greater than 5 m/s, which is a modest running pace. Within this zone, computed velocities locally exceed 20 m/s (>40 mph) in confined channels.

Figure 3 shows simulated tide gage records at five locations. These records show fluctuations of water surface elevation and also the time history of the waves. The initial water disturbance is a trough of about a meter at 2 hours after the earthquake, followed by a crest at between 2½ and 3 hours after the earthquake. At about 4 hours after the earthquake, a deeper trough occurs and reaches about 3 m near the Port of Bellingham. A trough this large, if it occurred at low tide, could be a significant grounding hazard for ships in the harbor. This is visually displayed in Figure 4, which shows screen shots of an animation of the tsunami troughs and crests in and around Bellingham Bay.

These models do 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, 2002); in the Snohomish delta near Everett (Bourgeois and Johnson, 2001); and in 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 THE MAP

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 for consistency with the paleoseismic and historical constraints, but the best CSZ earthquake may be substantially different. Another significant limitation is that the resolution of the modeling is no greater or more accurate than the bathymetric and topographic data used. Topographic mapping with a 5-ft contour was available from the city of Bellingham, but elsewhere 10-m DEMs, which are interpolated from 20-ft contour data, were used.

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. In Bellingham Bay, the mean spring tide range is about 8½ ft and can be as much as about 13 ft (NOAA, accessed at <http://co-op.noaa.gov/co-op.html>, May 6, 2004). This means that, while the modeling can be a useful tool to guide evacuation planning, it is not of sufficient resolution to be useful for land-use planning.

## ACKNOWLEDGMENTS

This project was supported by the National Tsunami Hazard Mitigation Program (NTHMP) in cooperation with Whatcom County, Lummi Nation, and the Washington Emergency Management Division. Information about NTHMP is available at <http://www.pmel.noaa.gov/tsunami-hazard/>. Karl Wegmann and Steve Palmer, both Washington Division of Geology and Earth Resources, provided helpful reviews.

## REFERENCES CITED

Atwater, B. F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington: *Journal of Geophysical Research*, v. 97, no. B2, p. 1901-1919.  
Atwater, B. F.; Hemphill-Haley, Eileen, 1997, Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington: *U.S. Geological Survey Professional Paper* 1576, 108 p.  
Atwater, B. F.; Moore, A. L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: *Science*, v. 258, no. 5088, p. 1614-1617.  
Atwater, B. F.; Nelson, A. R.; Clague, J. J.; Carver, G. A.; Yamaguchi, D. K.; Bobrowsky, P. T.; Bourgeois, Joanne; Darienzo, M. E.; Grant, W. C.; Hemphill-Haley, Eileen; Kelsey, H. M.; Jacoby, G. C.; Nishenko, S. P.; Palmer, S. P.; Peterson, C. D.; Reinhart, Mary Ann, 1995, Summary of coastal geologic evidence for great past earthquakes at the Cascadia subduction zone: *Earthquake Spectra*, v. 11, no. 1, p. 1-17.  
Atwater, B. F.; Satake, Kenji, 2003, The 1700 Cascadia tsunami initiated a fatal shipwreck in Japan [abstract]: *Geological Society of America Abstracts with Programs*, v. 35, no. 6, p. 478.  
Bourgeois, Joanne; Johnson, S. Y., 2001, Geologic evidence of earthquakes at the Snohomish delta, Washington, in the past 1200 yr: *Geological Society of America Bulletin*, v. 113, no. 4, p. 482-494.  
Gonzalez, F. I., compiler, 2003, Puget Sound tsunami sources—2002 workshop report: NOAA/Pacific Marine Environmental Laboratory Contribution No. 2526, 36 p.  
Heaton, T. H.; Snavely, P. D., Jr., 1985, Possible tsunami along the northwestern coast of the United States inferred from Indian traditions: *Seismological Society of America Bulletin*, v. 75, no. 5, p. 1455-1460.  
Hyndman, R. D.; Wang, Kelvin, 1993, Thermal constraints on the zone of major thrust earthquake failure—The Cascadia subduction zone: *Journal of Geophysical Research*, v. 98, no. B2, p. 2039-2060.  
Jacoby, G. C.; Bunker, D. E.; Benson, B. E., 1997, Tree-ring evidence for an A.D. 1700 Cascadia earthquake in Washington and northern Oregon: *Geology*, v. 25, no. 11, p. 999-1002.  
Ludwin, R. S., 2002, Cascadia megathrust earthquakes in Pacific Northwest Indian myths and legends: *Tsunami Alert*, v. 4, no. 2, p. 6-10.  
Myers, E. P.; Baptista, A. M.; Priest, G. R., 1999, Finite element modeling of potential Cascadia subduction zone tsunamis: *Science of Tsunami Hazards*, v. 17, no. 1, p. 3-18.  
Peters, Robert; Jaffe, B. E.; Gelfenbaum, Guy; Peterson, C. D., 2003, Cascadia tsunami deposit database: U.S. Geological Survey Open-File Report 03-13, 25 p. [accessed May 6, 2004 at <http://geopubs.wr.usgs.gov/open-file/of03-13/>].  
Priest, G. R.; Myers, E. P.; Baptista, A. M.; Fleuk, Paul; Wang, Kelvin; Kamphaus, R. A.; Peterson, C. D., 1997, Cascadia subduction zone tsunamis—Hazard mapping at Yaquina Bay, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-97-34, 144 p.

Satake, Kenji; Shimozaki, Kimihiko; Tsuji, Yoshinori; Ueda, Kazuo, 1996, Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700: *Nature*, v. 379, no. 6562, p. 246-249.

Satake, Kenji; Wang, Kelvin; Atwater, B. F., 2003, Fault slip and seismic moment of the 1700 Cascadia earthquake inferred from Japanese tsunami description: *Journal of Geophysical Research*, v. 108, no. B11, 2535, DOI:10.1029/2003JB002521, p. ESE 7-1 - 7-17.

Titov, V. V.; Gonzalez, F. I., 1997, Implementation and testing of the Method of Splitting Tsunami (MOST) model: NOAA Technical Memorandum ERL PMEL-112 (P98-122773), 11 p.

Titov, V. V.; Synolakis, C. E., 1998, Numerical modeling of tidal wave runup: *Journal of Waterway, Port, Coastal and Ocean Engineering*, v. 124, no. 4, p. 157-171.

Walsh, T. J.; Caruthers, C. G.; Heiniz, A. C.; Myers, E. P.; III; Baptista, A. M.; Erdakos, G. B.; Kamphaus, R. A., 2000, Tsunami hazard map of the southern Washington coast—Modeled tsunami inundation from a Cascadia subduction zone earthquake: Washington Division of Geology and Earth Resources Geologic Map GM-49, 1 sheet, scale 1:100,000, with 12 p. text.

Walsh, T. J.; Myers, E. P.; III; Baptista, A. M., 2002a, Tsunami inundation map of the Port Angeles, Washington area: Washington Division of Geology and Earth Resources Open File Report 2002-1, 1 sheet, scale 1:24,000.

Walsh, T. J.; Myers, E. P.; III; Baptista, A. M., 2002b, Tsunami inundation map of the Port Townsend, Washington area: Washington Division of Geology and Earth Resources Open File Report 2002-2, 1 sheet, scale 1:24,000.

Walsh, T. J.; Myers, E. P.; III; Baptista, A. M., 2003a, Tsunami inundation map of the Neah Bay, Washington, area: Washington Division of Geology and Earth Resources Open File Report 2003-1, 1 sheet, scale 1:24,000.

Walsh, T. J.; Myers, E. P.; III; Baptista, A. M., 2003b, Tsunami inundation map of the Quileute, Washington, area: Washington Division of Geology and Earth Resources Open File Report 2003-1, 1 sheet, scale 1:24,000.

Walsh, T. J.; Titov, V. V.; Venturato, A. J.; Mofjeld, H. O.; Gonzalez, F. I., 2003c, Tsunami hazard map of the Elliott Bay area, Seattle, Washington—Modeled tsunami inundation from a Seattle fault earthquake: Washington Division of Geology and Earth Resources Open File Report 2003-1A, 1 sheet, scale 1:50,000.

Williams, H. F. L.; Hutchinson, Ian, 2000, Stratigraphic and microfossil evidence for late Holocene tsunamis at Swatnow Marsh, Whidbey Island, Washington: *Quaternary Research*, v. 54, no. 2, p. 218-227.

Williams, H. F. L.; Hutchinson, Ian; Nelson, A. R., 2002, Multiple sources for late Holocene tsunamis at Discovery Bay, Washington State [abstract]: *Eos (American Geophysical Union Transactions)*, v. 83, no. 47, Supplement, p. F1082.

Yamaguchi, D. K.; Atwater, B. F.; Bunker, D. E.; Benson, B. E.; Reid, M. S., 1997, Tree-ring dating the 1700 Cascadia earthquake: *Nature*, v. 389, no. 6654, p. 922-923.

The phenomenon we call "tsunami" (soo-NAH-mee) is a series of traveling ocean waves of extremely long length generated by disturbances associated primarily with earthquakes occurring below or near the ocean floor. Underwater volcanic eruptions and landslides can also generate tsunamis. In the deep ocean, their length from wave crest to wave crest may be a hundred miles or more but with a wave height of only a few feet or less. They cannot be felt aboard ships nor can they be seen from the air in the open ocean. In deep water, the waves may reach speeds exceeding 500 miles per hour.

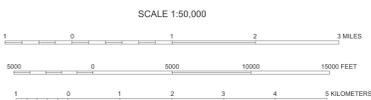
Tsunamis are a threat to life and property to anyone living near the ocean. For example, in 1992 and 1993 over 2,000 people were killed by tsunamis occurring in Nicaragua, Indonesia and Japan. Property damage was nearly one billion dollars. The 1960 Chile Earthquake generated a Pacific-wide tsunami that caused widespread death and destruction in Chile, Hawaii, Japan and other areas in the Pacific. Large tsunamis have been known to rise over 100 feet, while tsunamis 10 to 20 feet high can be very destructive and cause many deaths and injuries.

From *Tsunami—The Great Waves* by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Intergovernmental Oceanographic Commission, and International Tsunami Information Center  
Accessed at <http://www.nws.noaa.gov/cm/brochures/tsunami.htm> on 6/27/03



Depth of inundation: 0-5 meters 5-2 meters 2-5 meters

3 Location of simulated tide gage record shown in Figure 3.



TIMOTHY J. WALSH  
6/30/04

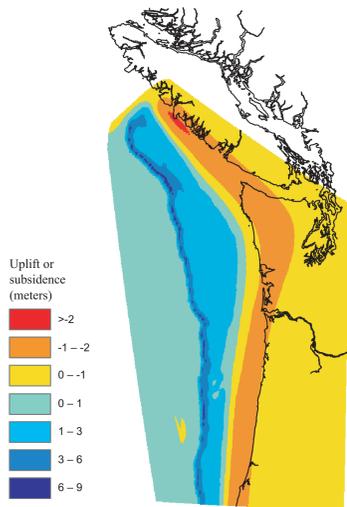


Figure 1. Map of uplift and subsidence for earthquake scenario (1A) used to model the initial condition for the tsunami simulation.

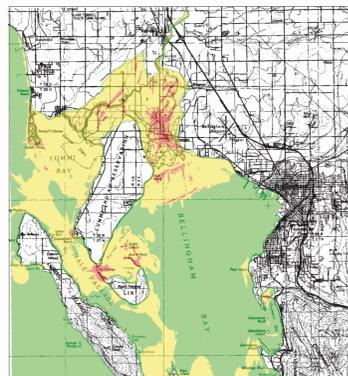


Figure 2. Computed current velocity zones. Note that velocities are highest along the shoreline and in narrow channels. One meter/second is about 2.2 mph.

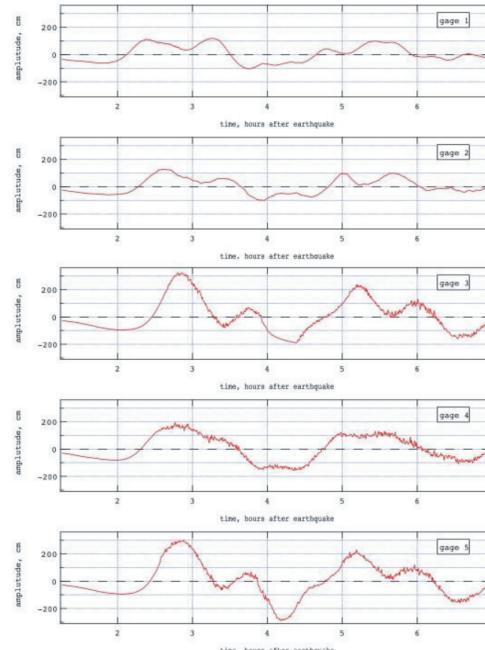


Figure 3. Time histories (simulated tide gages) at five locations noted on map. Note that the first wave crest is not projected to reach the area until about 2½ hours after the earthquake.

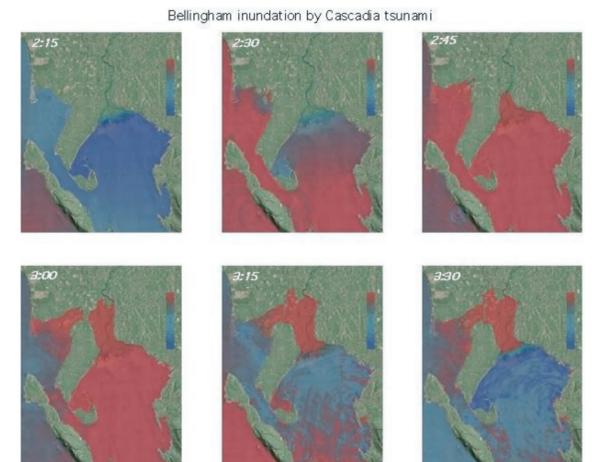


Figure 4. Screen shots of animation of tsunami arriving in Bellingham area. Red areas are crests, blue are troughs. From left to right and top to bottom, frames shown are taken at 15-minute intervals from the time the tsunami arrives in the area at about 2 hours and 15 minutes after the scenario earthquake until the first crest has receded at about 3½ hours after the earthquake.