Tsunamis and Seiches

Key Points

Tsunami

- *Definition*: Tsunamis are waves caused by earthquakes, volcanic eruptions or landslides. In deep water they have long wavelengths and travel very fast. They slow down but can build to great heights as they enter shallow water near shore.
- Damage is caused by the wave's kinetic forces and the flood that follows.
- Tsunamis generated in the open ocean would not have a great effect in Seattle because a tsunami wave has to make a 90 degree turn to reach the city and the complex coastline of Puget Sound acts as a baffle. The most likely effect of a tsunami from the Pacific in Seattle would be strong currents.
- Tsunamis can be generated within Puget Sound by landslides or earthquakes. The most frequent cause of Puget Sound tsunamis is landslides.
- The 1949 Olympia earthquake triggered a landslide into the Tacoma Narrows that caused a 6 – 8 foot tsunami three days after an earthquake. An earthquake on the Seattle Fault about 1,000 years ago produced a 16ft tsunami.
- The Seattle Fault, which runs through Seattle's midsection and through Puget Sound to Bainbridge Island, caused a tsunami around 900 AD.
- If a tsunami like the one in 900 AD happened again it would be devastating. The tsunami would hit immediately after the ground stopped moving. People along the shore would have little time to escape. It would destroy buildings along the shore and flood areas up to a mile inland.
- The 900 AD tsunami was probably a worst case. It is more likely (but not certain) that the next Seattle Fault tsunami will be smaller.

Seiche

- *Definition*: Seiches are standing waves in waterbodies caused by most often by seismic waves or atmospheric pressure. They can occur at great distances (100s or 1000s of miles) from an earthquake epicenter. Because they are *standing* waves they move vertically more than horizontally.
- Lake Union is especially prone to seiches due to its shape. The east and west sides are roughly parallel and the V-shaped northern end focuses waves. There is a historical report of a seiche or tsunami on Lake Washington, but it is not clear how large seiches on Lake Washington could be.
- Seiches have occurred multiple times in Seattle, but they have not caused extensive damage so far. Large seiches are a danger to the I-90 and SR520 bridges. A large seiche could strain cables anchoring the bridges. The new SR 520 bridge is designed to take about 12' of upward motion and 8' of downward motion from a seiche. Based on models the most damaging seiche would probably be caused by a Cascadia subduction zone earthquake.

Context

A tsunami is a sea wave produced by an offshore earthquake, volcanic eruption, landslide, or an impact of an object from space. Any event that suddenly displaces a huge volume of water can generate a tsunami.

Tsunamis generated by four sources have the potential to reach Seattle: 1) distant sources, such as across the Pacific, 2) Cascadia Subduction Zone megathrust earthquakes, 3) local faults, such as the Seattle Fault, and 4) landslides.

Tsunamis are hard to detect in the deep, open ocean. The wavelengths of these tsunamis are very long, between 93 and 155 miles, with amplitudes of one foot or less and travel at speeds of about 500 miles per hour. As a wave approaches the shoreline, its front slows, allowing the rest of the wave to ride up and increasing the wave's height dramatically. Tsunamis nearing the coast can rise to 100 feet in height and move at a speed of 30 miles per hour.

Tsunamis generated in enclosed bodies of water can be especially large. The collapse of a 3,000 foot tall rock wall in a narrow Alaska fjord stripped vegetation over 1,700 feet high on the opposite shore. While the Seattle area does nothave any cliffs nearly that size, it does have steep sea bluffs along enclosed bodies of water.

Most tsunamis have more than one wave, with a distance between crests of 60 or more miles. These waves interact with each other and are why a single tsunami event can last for several hours.

Whether a tsunami is generated by a potential trigger depends on the volume of water displacement and the speed of the displacement. Magnitude 6.5 to 7.5 earthquakes are probably the most common trigger of tsunamis[1].

Some tsunamis break when they reach land. Some just rush ashore as a huge mass of water, like a sudden massive tide. Others break far from land and come ashore as a turbulent cascading mass called a bore. The size and speed of the tsunami as well as the coastal area's form and depth are factors that affect the tsunami's shape. The power of a tsunami comes from the huge amount of water behind the wave's leading edge. Normal waves have a small volume, so they dissipate quickly when they strike the shore. Tsunamis do not. Their huge volume pushes the water far inland. This phenomenon is called "run up" and its size is what often determines a tsunami's destructiveness[2].

Tsunamis rarely crash ashore without warning. Coastal flooding frequently comes first, followed by a recession of the water and numerous waves. This effect is dangerous since many people assume the trouble is over after the first wave breaks. Unaware of the looming danger, they venture too close to shore and are swept away by subsequent waves. During the Indian Ocean Tsunami, a ten-year-old girl who had studied tsunami saved more than 100 people when she recognized this phenomenon.

Three main factors could influence the size, shape, volume and potential destructiveness of a tsunami generated by the Seattle Fault. These are shallow waters, steep seabeds and the contours of Elliott Bay.

- Since Elliott Bay and Puget Sound are shallow, there is less water to displace; therefore, the resulting tsunami would be slower and have less volume than those generated in the deep ocean[3].
- Puget Sound's steeply sloping sea beds tend to increase the chance that a tsunami will break on the shore, thus enhancing the tsunami's destructiveness[4].

- The shape of Elliott Bay could increase damage by funneling waves together, thereby increasing wave height[5]. The net result is unclear, since not much is known about the offsetting relationship between the depth of Elliott Bay on one hand and its shape on the other[6].

Seiches

Seiches are related to tsunamis. A seiche is the sloshing of water in a waterbody like water in a bathtub. Pushes from a seismic wave or air pressure cause the water to rock back and forth. Under the right conditions, resonance builds up wave height just like pumping one's legs to make a swing go higher. Since larger bodies of water usually have longer frequencies, it takes longer frequency waves traveling through the ground to create seiches in them. Due to the mechanics of an earthquake, areas close to the epicenter shake at high frequencies. Therefore, seiches tend to occur far from earthquake epicenters[7]. The biggest danger is from subduction zone or megathrust earthquakes that cause powerful, low frequency ground waves[8].

History

Both tsunamis and seiches have occurred in the past 1200 years in Central Puget Sound area.

Tsunami deposits have been found in four locations in Puget Sound, including Seattle[9]. It is not known if they are the result of one event or several, but the most likely source in an estimated magnitude 7.3 earthquake on the Seattle Fault around 900 AD.

The 1964 Alaskan Earthquake caused a tsunami that was detected here, causing a sea rise of 0.8 feet. It had more of an impact on the coastal communities of Washington, Oregon and California. Friday Harbor and Neah Bay recorded maximum rises on the order of 2.3 feet and 4.7 feet, respectively. Despite this dramatic change on the coast, the tsunami's effect was negligible in Seattle because the complicated shoreline in Puget Sound acted as a baffle for incoming ocean waves. The protective effects of Puget Sound are probably one reason why the 1700 megathrust earthquake that caused a tsunami in Japan was not detected here.

Landslides have causes localized tsunamis in at least two locations in Puget Sound since the late 1800s. Other records include oral history from the Snohomish Indian people who describe a deadly tsunami in the early 1800s, a small tsunami or seiche in 1891 and a damaging tsunami in 1894 caused by a submarine landslide in Commencement Bay. The most recent was in 1949 when the Tacoma Narrows experienced a landslide that triggered 6 to 8 foot tsunami following that year's magnitude 7.1 earthquake. The 900 AD Seattle Fault earthquake triggered massive landslides into Lake Washington, but no evidence has been found yet that they caused tsunamis.

The 1964 Alaska megathrust earthquake and 2002 Denali earthquake caused seiches in Lake Union[10]. These seiches damaged boats by battering them against docks and moorings in Lake Washington and Lake Union. Interestingly, the seismic waves that caused them could not be directly felt by humans.

Seiches have been more common than tsunamis, but seiches have not caused extensive damage so far. In 1891, an earthquake near Port Angeles caused an eight-foot seiche in Lake Washington, big enough to endanger people along the shore[11]. Both Lake Union and Lake Washington experienced seiches during the 1949 earthquake, but they did no damage[12].

Likelihood of Future Occurrences

Tsunami

Seattle almost certainly experience tsunami and seiches again, but the question in how often the biggest ones occur. Seiches and tsunamis from distant earthquakes are the most common instances but they have produced only minor to moderate damage and, to the best of our knowledge, no casualties so far.

Based on history and the number of landslides in Puget Sound, the most likely source of a tsunami is a large landslide. It is not known how big these waves can be but limited historical evidence suggests at most 6 to 8 feet high.

Tsunamis originating in the Pacific Ocean are a certainty but they will probably have only minor effects on Seattle because they have to travel through the Strait of Juan de Fuca then make a 90 degree turn south into Puget Sound and once in the Sound they are disrupted by the many islands and complex shoreline. A tsunami generated by a magnitude 8.5 Cascadia subduction zone earthquake would lose much of its velocity and be only 1.3 feet high when it arrived in Seattle[13].

The worst tsunami for Seattle would be triggered by a Seattle Fault earthquake[14]. The Seattle Fault runs through Puget Sound, through West Seattle, Sodo, Beacon Hill and then across to Bellevue. (See Figure 18 for a map). The biggest earthquake possible on the Seattle Fault is magnitude 7.3. It is roughly estimated to have a 1 in 5000 chance of occurring each year.

It is more likely that the next Seattle Fault earthquake will be smaller than the one in 900 AD. A team of seismologists and earthquake engineers chose to model a magnitude 6.7 Seattle Fault earthquake that they consider more likely than a magnitude 7.3. A magnitude 6.7 earthquake would probably trigger a much smaller tsunami than the one that happened in 900 AD. The Seattle Fault shows evidence of episodic fault rupture of about 6 feet, enough to produce a tsunami[15].

The size of a tsunami depends on the amount of uplift caused by an earthquake. The earthquake 1,100 years ago caused over 15 feet of uplift. If the fault movement is purely vertical, a magnitude 6.7 earthquake would likely cause about 1 m (3 feet) or less of displacement on the fault plane, which translates to about 0.5 m (1.5 feet) of uplift on a 40 degree thrust fault. A tsunami generated by a 6.7 Seattle Fault earthquake has not been modeled. It would probably cause a fraction of the damage of the NOAA-modeled tsunami following a 7.3 earthquake or the earthquake-generated tsunami of 1,100 years ago.[16]

A two meter wave is not expected to overtop the Elliot Bay Seawall, but a wave could propagate up the Duwamish[17]. The primary impacts are likely to be from the earthquake itself. The impact to bridges is expected to be minimal, since the Washington State Department of Transportation anticipates that storm-generated wave forces would exceed the forces from a small to moderate-sized tsunami. Regarding the possibility of liquefaction impacting bridge support, bridge design assumes seismic effects to govern.

Other faults capable of producing tsunamis run though Puget Sound: the South Whidbey Fault, the Kingston-Edmonds and Tacoma.

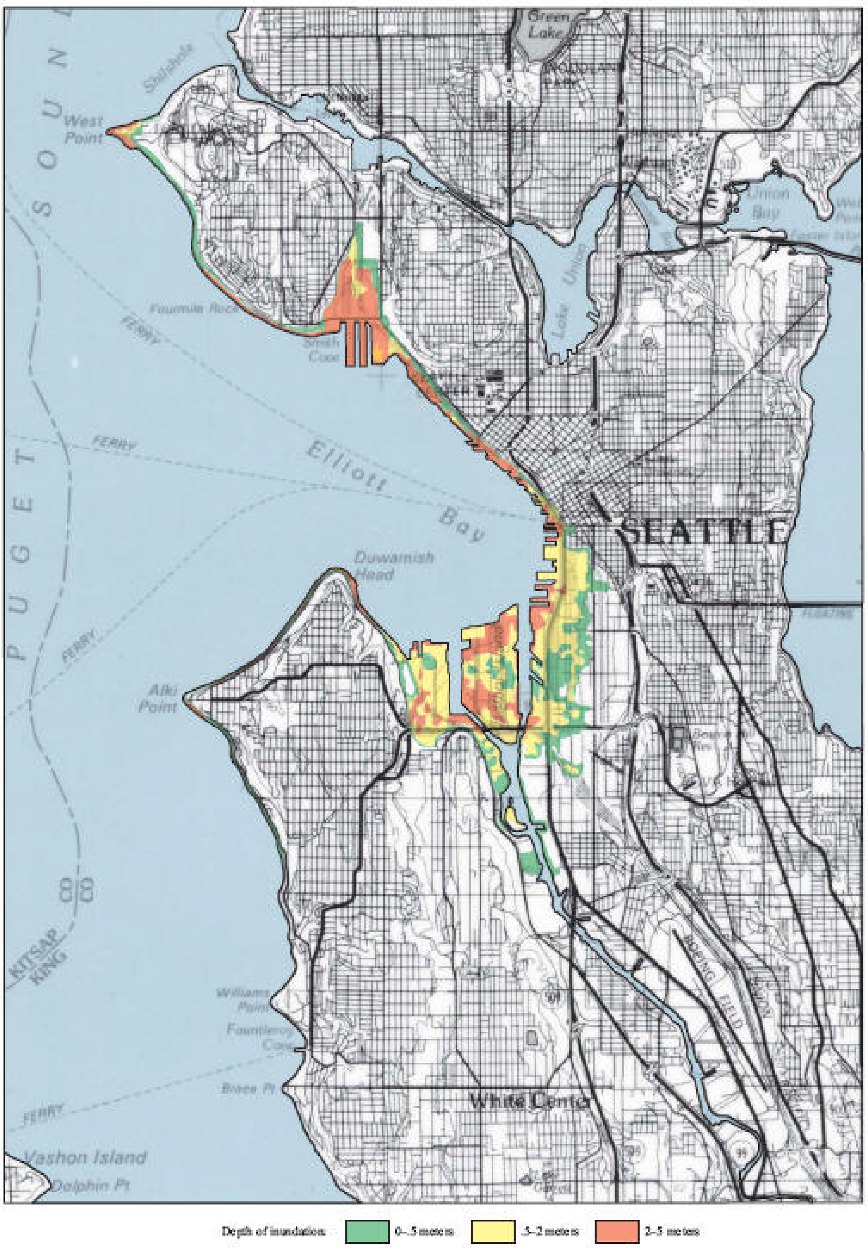
Seiches

Seiches are more common than tsunamis. Both Puget Sound and Lake Washington experienced them in 1891, 1949 and 1964. These events caused light to moderate damage. It is very likely similar seiches will happen again. A Cascadia megathrust earthquake would probably cause a much more dangerous seiche in Lake Union and possibly Lake Washington[18]. Washington megathrust earthquakes happen every 400-600 years. See the chapter on earthquakes for more details.

Vulnerability

Seattle has a long and highly developed shoreline that makes it highly exposed to tsunami and seiche damage. Large numbers of people work, play and live near the water. Major port facilities, tourist attractions and housing ring Elliott Bay. Lake Union's shoreline is home to houseboats, businesses, parks and museums.

Figure 1. Worst Case Tsunami Inundation Area. Source: Washington State Dept. of Natural Resources.



The exposure is enhanced because the short time between a triggering event (earthquake, landslide) and arrival of the wave train (30 seconds to 5 minutes) would not permit many people to escape[19]. The only possible escape is running upstairs in multi-story buildings. These buildings are likely to be severely damaged if the trigger is a Seattle Fault earthquake. Most engineered structures performed fairly well in

Table 1. Land Use in Worst Case Tsunami Inundation Area

Area	Acres	% Seattle	% Area
Seattle	53178.37	100%	
Worst Case Tsunami Inundation Area	2234.58	4%	100%
Parcel area in Area	**1710.63**	**3%**	77%
Commercial/Mixed-Use	218.48	0%	10%
Easement	0.70	0%	0%
Industrial	362.80	1%	16%
Major Institutions	835.34	2%	37%
Multi-Family	15.36	0%	1%
Parks/Open Space/Cemeteries	47.21	0%	2%
Reservoirs/Water Bodies	3.02	0%	0%
Single Family	21.03	0%	1%
Unknown	5.58	0%	0%
Vacant	201.12	0%	9%
Right of Way in Area	**523.95**	**1%**	23%

Figure 2. Summary of Land Use in Worst Case Tsunami Inundation Area.

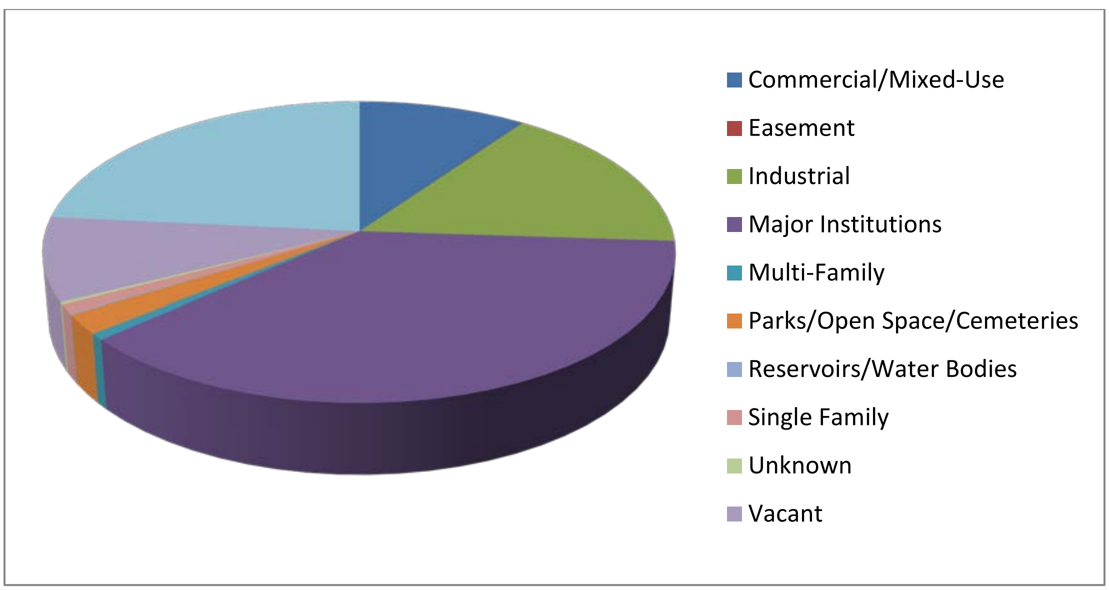


Table 2. Estimated Pop., Structures and Assessed Value in Worst Case Tsunami Inundation Area.

Number of Buildings	1,339	Est. Pop
Number of Single Family Units	256	527
Number of Multi-Family Units	2,846	5863
Gross Sq. Footage	41,209,932	
Residential Gross Sq. Footage	5,283,843	
Commercial Gross Sq. Footage	26,323,583	
Total Assessed Value	$ 8,790,180,758	
Estimated Residential Population		6390

Table 3. Critical Facilities in Worst Case Tsunami Inundation Area.

Medical and Health Services	1
Government Function	0
Protective Function	2
Schools	0
Hazardous Materials Storage Sites	11
Bridges	37
Major Tunnels	1
Water	0
Waste Water	0
Communications	0
Energy	2
Human Services	1
High Population	4
Total	***59***

Table 4. Facilities with Concentrated Vulnerable Pop. in Worst Case Tsunami Inundation Area.

Adult Family Homes	0
Boarding House	0
Child Care Centers	2
Nursing Home	0
Intermediate Care Facility	0
Total	***2***

Table 5. Zoning in Worst Case Tsunami Inundation Area.

Zoning Area	Acres	% of Seattle	% of Area
Seattle	53178.37	100%	
Worst Case Tsunami Inundation Area	2234.58	4%	100%
Parcel area	**1710.63**	**3%**	77%
Unzoned	0.11	0.00%	0.01%
Commercial - C1	7.83	0.01%	0.35%
Commercial - C2	13.59	0.03%	0.61%
Downtown Harborfront - DH1	32.60	0.06%	1.46%
Downtown Harborfront - DH2	10.73	0.02%	0.48%
Downtown Mixed Commercial - DMC	8.93	0.02%	0.40%
Downtown Mixed Residential/Commercial - DMR	4.15	0.01%	0.19%
Industrial Buffer - IB	3.83	0.01%	0.17%
Industrial Commercial - IC	177.93	0.33%	7.96%
Downtown, International District Mixed - IDM	0.73	0.00%	0.03%
Downtown, International District Residential - IDR	0.00	0.00%	0.00%
General Industrial - IG1	1111.92	2.09%	49.76%
General Industrial - IG2	200.17	0.38%	8.96%
Lowrise - LR1	1.57	0.00%	0.07%
Lowrise - LR2	4.37	0.01%	0.20%
Lowrise - LR3	1.11	0.00%	0.05%
Major Institution - MIO	0.00	0.00%	0.00%
Multi-Family, Midrise - MR	3.64	0.01%	0.16%
Neighborhood Commercial - NC1	25.25	0.05%	1.13%
Neighborhood Commercial - NC2	4.60	0.01%	0.21%
Neighborhood Commercial - NC3	1.22	0.00%	0.05%
Downtown, Pike Place Market - PMM	0.14	0.00%	0.01%
Downtown, Pioneer Square - PSM	26.83	0.05%	1.20%
Single Family - SF 5000	8.92	0.02%	0.40%
Single Family - SF 7200	60.21	0.11%	2.69%
Single Family - SF 9600	0.25	0.00%	0.01%
Neighborhood Commercial, Seattle Mixed- SM	0.00	0.00%	0.00%
Neighborhood Commercial, Seattle Mixed - SMI	0.00	0.00%	0.00%
Neighborhood Commercial, Seattle Mixed Residential - SMR	0.00	0.00%	0.00%
Right of Way in area	**523.95**	**0.99%**	23.45%

Table 6. Growth Centers in Worst Case Tsunami Inundation Area.

Urban Centers / Villages and Manufacturing Centers	Acres	% Seattle	% Area	% Center
Seattle	53178	100%		
All Hub and Residential Urban Villages	*5714.5*	*10.75%*		
All Urban Centers	*5715.5*	*6.98%*		
All Manufacturing / Industrial Center	*5716.5*	*11.10%*		
Worst Case Tsunami Inundation Area	2234.58	4%	100%	
Hub and Residential Urban Villages in Zone	0.00	0.00%	0.00%	0.00%
Urban Centers in Zone	186.29	0.35%	8.34%	5.02%
Manufacturing / Industrial Center in Zone	1825.89	3.43%	81.71%	30.94%

Table 7. Wildlife Areas in Worst Case Tsunami Inundation Area.

	Acres	% Seattle
Seattle	53178	100%
Worst Case Tsunami Inundation Area	2234.58	4%
Wildlife Habitat Areas	3749.89	7.05%
Wildlife Habitat in Worst Case Tsunami Inundation Area	391.52	0.74%

recent tsunamis, structures already damaged by a landslide or earthquake would be especially susceptible to more damage from a tsunami.

In any event involving incidents on Puget Sound, the tide is very important. A tsunami or seiche riding on a high tide is more dangerous than one occurring at low tide.

The effect of the built environment is also important. Sea walls line most of Elliot Bay and the Duwamish Waterway. They provide some protection against waves whether they are storm wave, seiche waves or tsunami waves. Buildings also affect the propagation of waves inland. The first layer of buildings acts as a barrier and tends to decrease wave velocity, but they can add debris into storm water. The tsunami modeled for Seattle does not include the effects of the built environment. Seattle's downtown seawall is very weak and will be replaced by 2017. There is a high probability that the existing sea wall would not survive a Seattle fault earthquake.

Tsunami Lifeline Exposures:

- None of Seattle's water supply lines travel through the worst case tsunami inundation area, but feeder and distribution mains run along the shore from Interbay to Sodo, under 1st Ave South and along the West Seattle Bridge.
- The BP Olympic pipeline which carries fuel runs through the area from Harbor Island and along the West Seattle Bridge and the Spokane Street Viaduct.
- City Light power transmission lines enter the area near Port of Seattle. 30 transmission towers are in the area.
- Sewer mains run through the area in the Interbay area to Myrtle Edwards Park and in the south from downtown through the rail corridor serving the Port and along the West Seattle Bridge. In West Seattle a sewer main runs along Harbor Ave SW to Duwamish Head.

Tsunami Transportation Exposures:

- Most of Seattle's marine terminals sit in the tsunami inundation area.
- BSNF's Sodo railyards and about half of its Interbay yard are in the area; all Seattle's north-south rail corridors touch the area.
- The southern entrance to the new SR99 tunnel is in the area. See the paragraph below for more on its exposure.
- SR99, 1st Ave S and the West Seattle Bridge cross the area.
- The King County International Airport is *not* in the inundation area.

Consequences

Seiches would cause moderate to severe damage to structures on or adjacent to the shore of Seattle's lakes and Puget Sound. Lake Union is likely to experience the most severe consequences. According to Barberopoulou's 2009 modelling, Lake Union would experience waveheights up to 6 feet (measured trough to crest) for minutes following the earthquake. Ships, boats, floating docks and houseboats would pound violently against each other. Power, water, sewer, gas and communications lines would be severed. People standing on vessels or near the shore could easily fall into the violently sloshing water. Wave motion would be more up and down than side to side because seiches are standing waves. This effect means that major flooding would probably not occur.

The likelihood of a seiche on other local waterbodies is not as well understood, but a seiche's magnitude on them would probably be smaller than those on Lake Union. The consequences of a seiche on Lake Washington could include casualties resulting from people near the shore being knocked into the water, residential and commercial property damage and damage to the floating bridges. A seiche on Elliot Bay could include damage to port and industrial facilities.

Seiches could precipitate landslides, fires and hazardous materials releases. Seiches can erode the base of steep slopes causing them to fail. The northeastern side of Lake Union, the south side of Magnolia, and four locations along Lake Washington have landslide prone hillsides near the shoreline (See Figure 20).

Tsunamis have the potential to cause extreme damage and high casualties. The worst tsunami for Seattle would be a repeat of the one that occurred in 900 AD and modelled by the National Oceanic and Atmospheric Administration (NOAA). The model is a worst case scenario. It assumes a maximum of 7 meters of uplift on the Seattle Fault's south side (on Bainbridge), 4 meters uplift at Alki Point and 1 meter subsidence on the north side at West Point (Magnolia). The model assumes the earthquake happens at high tide. It does not account for the effects of sea walls or buildings. It adjusts for their absence by using a greater bottom friction parameter. Doing so has the effect of decreasing the amount of flooding in flat areas.

The largest part of the wave would be in Puget Sound between Seattle and Bainbridge Island. Most of this part would miss Seattle. Inside Elliott Bay the first wave crest would form a bore with an amplitude of 6 meters (i.e., 6 meters above the still water line). The biggest wave would form on the northern edge of the fault. It would move north, striking Magnolia, Interbay, Myrtle Edwards Park and the Downtown Waterfront in two minutes and 20 seconds. It would reflect off the steep bluffs of Magnolia and move south reaching Harbor Island about 5 minutes after the earthquake.

The wave would flood an area up to 1 mile inland around the Duwamish River's mouth. Figure 28 shows the extent and depth of the inundation. The highest vertical run-ups are about 10 meters along Magnolia, Alki Beach and east of Alki Point[20].

Figure 3. Area Exposed to Lake Union Seiche

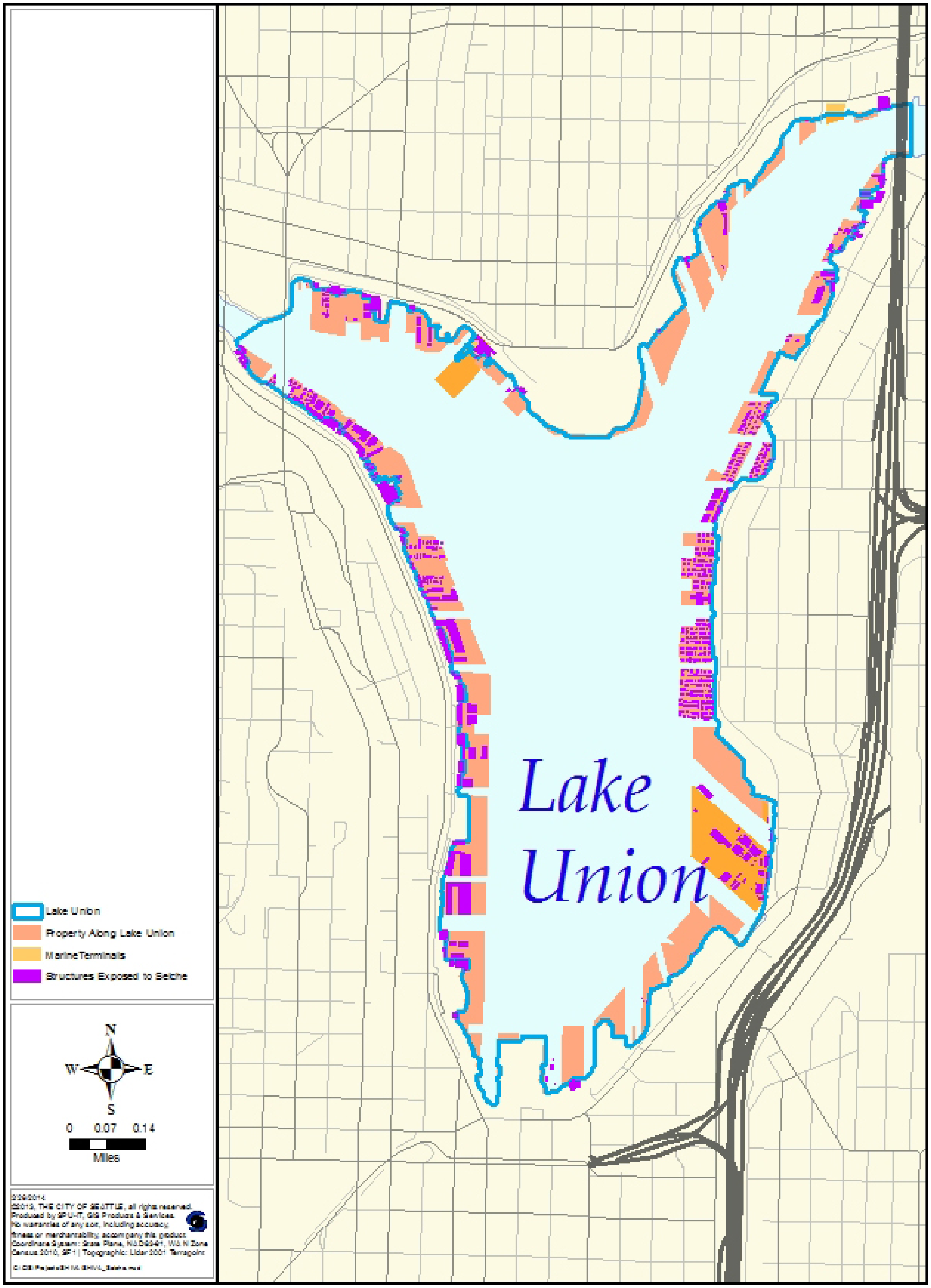


Table 8. Land Use in Lake Union Seiche Area

Area	Acres	% Seattle	% Area
Seattle	53178.37	100%	
Lk. Union Seiche Area	144.11	0%	100%
Property in area	**144.11**	**0%**	100%
Commercial/Mixed-Use	84.89	0%	59%
Easement	0.00	0%	0%
Industrial	2.46	0%	2%
Major Institutions	17.29	0%	12%
Multi-Family	0.89	0%	1%
Parks/Open Space/Cemeteries	4.74	0%	3%
Reservoirs/Water Bodies	0.01	0%	0%
Single Family	19.24	0%	13%
Unknown	1.26	0%	1%
Vacant	6.30	0%	4%
Right of Way in area	**0.00**	**0%**	0%

Figure 4. Summary of Land Use in Lake Union Seiche Area.

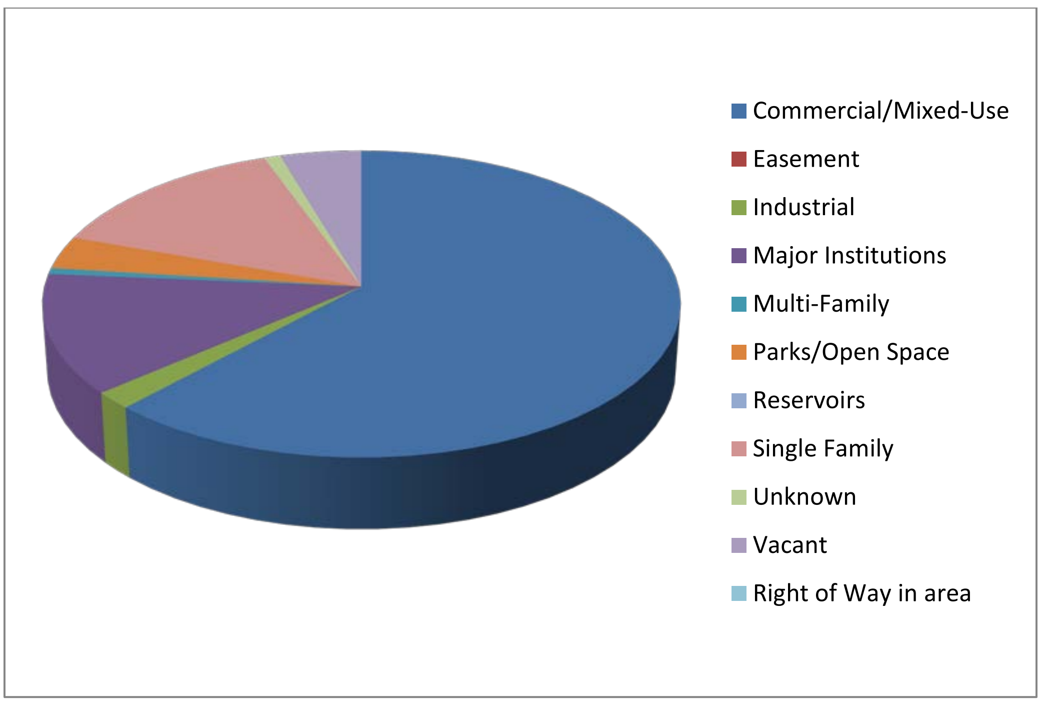


Table 9. Estimated Population, Structures and Assessed Value in Lake Union Seiche Area

Number of Buildings	530	Est. Pop
Number of Single Family Units	77	159
Number of Multi-Family Units	100	206
Gross Sq. Footage	2,113,176	
Residential Gross Sq. Footage	281,073	
Commercial Gross Sq. Footage	1,445,938	
Total Assessed Value	$ 702,618,934	
Estimated Residential Population		365

Table 10. Critical Facilities in Lake Union Seiche Area

Medical and Health Services	0
Government Function	1
Protective Function	0
Schools	0
Hazardous Materials Storage Sites	0
Bridges	1
Major Tunnels	0
Water	0
Waste Water	0
Communications	0
Energy	0
Human Services	0
High Population	0
Total	***2***

Table 11. Facilities with Concentrated Vulnerable Populations in Lake Union Seiche Area.

Adult Family Homes	0
Boarding House	0
Child Care Centers	0
Nursing Home	0
Intermediate Care Facility	0
Total	***0***

Table 12. Zoning in Lake Union Seiche Area.

	Acres	% of Seattle	% of Area
Seattle	53178.37	100%	
Lk. Union Seiche Area	144.11	0.27%	100%
Property in area	144.11	0.27%	100%
Unzoned	0.01	0.00%	0.01%
Commercial - C1	1.86	0.00%	1.29%
Commercial - C2	73.91	0.14%	51.29%
Downtown Harborfront - DH1	32.60	0.06%	22.62%
Downtown Harborfront - DH2	0.00	0.00%	0.00%
Downtown Mixed Commercial - DMC	0.00	0.00%	0.00%
Downtown Mixed Residential/Commercial - DMR	0.00	0.00%	0.00%
Industrial Buffer - IB	20.67	0.04%	14.34%
Industrial Commercial - IC	8.86	0.02%	6.15%
Downtown, International District Mixed - IDM	0.73	0.00%	0.51%
Downtown, International District Residential - IDR	0.00	0.00%	0.00%
General Industrial - IG1	20.40	0.04%	14.16%
General Industrial - IG2	0.00	0.00%	0.00%
Lowrise - LR1	0.00	0.00%	0.00%
Lowrise - LR2	3.74	0.01%	2.59%
Lowrise - LR3	0.62	0.00%	0.43%
Major Institution - MIO	0.00	0.00%	0.00%
Multi-Family, Midrise - MR	0.00	0.00%	0.00%
Neighborhood Commercial - NC1	0.00	0.00%	0.00%
Neighborhood Commercial - NC2	0.00	0.00%	0.00%
Neighborhood Commercial - NC3	0.00	0.00%	0.00%
Downtown, Pike Place Market - PMM	0.00	0.00%	0.00%
Downtown, Pioneer Square - PSM	0.00	0.00%	0.00%
Single Family - SF 5000	14.03	0.03%	9.73%
Single Family - SF 7200	0.00	0.00%	0.00%
Single Family - SF 9600	0.00	0.00%	0.00%
Neighborhood Commercial, Seattle Mixed- SM	0.01	0.00%	0.01%
Neighborhood Commercial, Seattle Mixed - SMI	0.00	0.00%	0.00%
Neighborhood Commercial, Seattle Mixed Residential - SMR	0.00	0.00%	0.00%
Right of Way	**0.00**	**0.00%**	0.00%

Table 13. Growth Centers in Lake Union Seiche Area

Urban Centers / Villages and Manufacturing Centers	Acres	% Seattle	% Area	% Center
Seattle	53178	100%		
All Hub and Residential Urban Villages	*5714.5*	*10.75%*		
All Urban Centers	*5715.5*	*6.98%*		
All Manufacturing / Industrial Center	*5716.5*	*11.10%*		
Seiche Area	2234.58	4%	1551%	
Hub and Residential Urban Villages in Zone	5.79	0.01%	0.26%	0.10%
Urban Centers in Zone	3.02	0.01%	0.14%	0.08%
Manufacturing / Industrial Center in Zone	0.00	0.00%	0.00%	0.00%

Table 14. Wildlife Areas in Lake Union Seiche Area.

	Acres	% Seattle
Seattle	53178	100%
Worst Case Tsunami Inundation Area	2234.58	4%
Wildlife Habitat Areas	3749.89	7.05%
Wildlife Habitat in Seiche Area	0	0.00%

The consequences of this tsunami would be catastrophic. Depending on the time of year and day, the shores ringing Elliott Bay are some of the most densely populated parts of Seattle. Survivors of the triggering earthquake would have minutes to reach higher ground. Many people would be trapped in collapsed or damaged buildings. Roads would be blocked by debris. The best evacuation strategy would be to seek shelter in the upper stories of buildings. Normally, it would be inadvisable to enter potentially severely damaged buildings but doing so it safer than facing a tsunami in the open.

The tsunami would impact most of Seattle's port facilities including critical fuel terminals. It would also inundate major roadways (SR 99, Elliott Avenue and the area under the West Seattle Bridge) and railways. If the tsunami occurs before the replacement of the downtown seawall and viaduct, it is likely that both would fail.

(Disclaimer: the information in the following paragraph is out of date. The next update to this document will have new information. The update is scheduled for December 2018).

The SR99 tunnel is scheduled to open to traffic in late 2015. The effects of this tsunami on the tunnel have not been studied, but the area around the south entrance is shown to have six feet of inundation. The extent of flooding depends not only on the flood depth, but also the total volume of water, the flow rate, the direction of flow and the grade of the entrance, the wavelength of the tsunami, and the coseismic subsidence. If the tunnel were to flood the consequences would be severe. People would be trapped underground; flooding would make escape harder and hamper rescue efforts. The tunnel will automatically close when strong earthquakes occur, but because the tsunami would arrive within minutes after the earthquake, it is unlikely that everyone inside during the earthquake would get out before it floods.

The tsunami would probably cause many landslides on the south side of Magnolia and the area each of Alki point. It would likely also trigger fires and hazardous materials spills in the port and industrial areas around Harbor Island. Inundation could affect Seattle Steam. If Seattle Steam loses generating capacity Seattle's major hospitals would lose their ability to sterilize medical instruments.

Most Likely Scenario: Seiche following Cascadia Megathrust Earthquake

During a Cascadia Subduction Zone earthquake (see the Alternate Earthquake Scenario) the water in Lake Union begins to oscillate. Waves that move more up and down begin to appear in the Lake. Soon ships, boats, houseboats and floating docks move up and down 6 feet (from wave crest to trough). Vessels and houseboats smash violently together. Power, water, sewer, gas and communications lines are severed. Lake Washington, Elliott Bay and Greenlake also have seiches, but they are not as extreme. Cables on the I-90 Bridge over Lake Washington are damaged.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	**2**	Seiches have occurred on multiple occasions in the Seattle area since the late 19th century, most recently in 2002. Lake Union seems especially prone to seiches, probably because of its Y-like shape. Previous events have caused damage but have not been disastrous. Modelling results published in 2008 indicate that a Cascadia Subduction Zone earthquake would produce the most damaging seiche for Lake Union. Effects on Lake Washington and other water bodies are still not well understood.
Geographic Scope	3	The seiche effects Lake Union and its shoreline
Duration	2	The seiche continues for 10 minutes after the end of the ground shaking gradually becoming less and less violent. Amidst the overall earthquake response it takes three days to stabilize response to the seiche and transition to short term recovery.
Health Effects, Deaths and Injuries	2	1 person falls in the water and drowns and 13 are injured in falls and by debris. Most of the injuries occur to people inside ships or houseboats.
Displaced Households and Suffering	3	Due to extreme battering and the severing of most utilities 159 people living aboard boats and houseboats need to find temporary shelter.
Economy	3	The damage from the seiches blends with that of the earthquake. Maritime businesses, especially those on Lake Union suffer significant damage.
Environment	2	The seiche resuspends and redistributes pollutants from the sediments in local water bodies.
Structures	3	15 houseboats are red tagged and another 45 are yellow tagged. Many ships, boats and seawalls docks are heavily damaged.
Transportation	2	The I-90 and SR 520 floating bridges must be closed for inspection and repair. They are closed for one week. Lake Washington Blvd is damaged in two locations.
Critical Services and Utilities	1	The seiche damages utility connections to individual properties but no major lifelines are damaged.
Confidence in Government	1	Local government is able to respond to the seiche in a timely and comprehensive manner. The public retains confidence in government.
Cascading Effects	2	The seiche undermines slopes in 12 locations causing landslides.

Maximum Credible Scenario: Tsunami following Magnitude 7.2 Seattle Fault Earthquake

A Seattle fault earthquake triggers a tsunami like the one that occurred here in 900 AD. This tsunami occurred at high tide and sends waves up to 16 feet high into the area around Elliott Bay minutes after the most powerful earthquake Seattle has ever experienced. The waves cover all Harbor Island, large parts of Sodo and Interbay, and the crowded downtown waterfront. Because the source of the earthquake is so close there is no chance for many people to escape. The waves destroy many buildings weakened by the earthquake.

Category	Impacts 1 = low 5 = high	Narrative
Frequency	2	Tsunami deposits have been found in Seattle and Whidbey Island. They are from the Seattle Fault earthquake that occurred around 900 AD. Earthquake of this magnitude on the Seattle Fault are rare events. Currently seismologists estimate they have a 1 in 1000 chance of occurring each year.
Geographic Scope	4	The tsunami would affect the area surrounding Elliott Bay and the shoreline of West Seattle.
Duration	2	The tsunami would strike the Seattle shoreline seconds to minutes after the earthquake stops. Active response to the tsunami would take days as urban search and rescue looked for survivors in debris. Recovery would take years and would be part of the larger earthquake recovery project.
Health Effects, Deaths and Injuries	4	175 people near the waterfront perish. The majority of deaths occur along Alki and the Downtown Waterfront. Cool rainy weather has limited the number of people out doors.
Displaced Households and Suffering	5	743 people are displaced by the tsunami. Their residences along Alki, West Seattle and Magnolia have been destroyed or severely damaged. This number added to those displaced by the earthquake itself.
Economy	4	The tsunami devastates the critical Seattle port and manufacturing sectors. Fuel depots on Harbor Island are knocked offline. This damage has enormous multiplier effects on the rest of the Seattle economy.
Environment	3	The tsunami ruptures many tanks containing hazardous materials. The biggest is a tank rupture on Harbor Island. Response to the fuel spill is complicated by the damage to Port infrastructure and the need to concentrate resources on life safety.
Structures	3	245 structures are destroyed and 1200 are yellow tagged. They are a mix of residential, commercial and industrial buildings.
Transportation	4	The tsunami severely damages roads along the waterfront and along the Duwamish waterway. The tsunami floods the SR99 tunnel as it is under construction. The tsunami further damages the downtown seawall and viaduct with have partially collapse due to the earthquake that preceded the tsunami.
Critical Services and Utilities	3	The tsunami occurs before the downtown seawall is replaced. This collapse breaks utility lifelines: water, wastewater, communications, electrical, steam and gas lines. The outage causes a near lack of service in the downtown waterfront areas.

Confidence in Government	3	Response to the tsunami is complex and slow, especially when combined with the earthquake. The public wonders why more was not done to mitigate tsunami risk.
Cascading Effects	4	The tsunami causes a large hazardous material spill, fires and numerous landslides

Conclusions

Seattle has an extensive and well developed coastline. Many recreational and economic activities occur near the shoreline. Both tsunami and seiches would occur with little or no warning. These factors give Seattle an inherent vulnerability to tsunami and seiche hazards. Despite this vulnerability, Seattle's risk is mitigated due to the infrequency of incidents that generate truly powerful tsunami and seiches.

Because of their greater frequency in Puget Sound, landslide-caused tsunami are the greatest overall risk to Seattle. Landslide-caused tsunami can be very large and can be triggered by many relatively common events like moderate earthquakes and storms.

The worst case, modeled by the National Oceanic and Aeronautic Administration (NOAA), would be a devastating blow on top of the worst earthquake Seattle has ever faced. This type of event happens only about once every 5,000 years; the last such event occurred 1,100 years ago.

[1] Bryant, 1991 and Noson, 1988
[2] Myles, 1985
[3] Bryant, 1991
[4] Myles, 1985; Shuto, 1991
[5] Myles, 1985
[6] Because the nature of the tsunami depends on the initial deformation of the earthquake, which is poorly understood, the largest source of uncertainty is the input earthquake. The earthquake scenario used in this modeling was selected to honor the paleoseismic constraints, but the next Seattle fault earthquake may be substantially different from these. Sherrod and others (2000) show that an uplift event at Restoration Point predating the A.D.900–930 event was smaller. Trenching of subsidiary structures to the Seattle fault that are thought to be coseimic with the main fault trace (Nelson and others, 2002) indicate that there were at least two earthquakes in the 1500 years before the A.D. 900–930 event. These, however, did not produce prominent uplifted wavecut platforms similar to the one made by the A.D. 900–930 event, suggesting that significant earthquakes have occurred on the fault that had different and smaller uplifts in central Puget Sound.
[7] Myles, 1985
[8]
[9] Atwater and Moore, 1992
[10] National Academy of Sciences, 1972
[11] USGS, 1975
[12] Noson et al, 1988.
[13] Whitmore, 1993
[14] EERI scenario working papers 2003
[15] Weaver, 2003; Sherrod, 2000
[16] (Pratt; Wells and Coppersmith)
[17] EERI Seattle Fault Scenario 2003 working papers
[18] Barberopoulou, 2009
[19] Titov et al, 2003
[20] Titov et al, 2003