Tsunami

TSUNAMI	Frequency	50+ yrs	10-50 yrs	1-10 yrs	Annually
	People	<1,000	1,000-10,000	10,000-50,000	50,000+
	Economy	1% GDP	1-2% GDP	2-3% GDP	3%+ GDP
	Environment	<10%	10-15%	15%-20%	20%+
	Property	<$100M	$100M-$500M	$500M-$1B	$1B+
	Hazard scale	< Low to High >			

Risk Level[1]

- Frequency – Based on geologic evidence along the coast of Washington State, the Cascadia Subduction Zone (CSZ) has ruptured and created tsunamis at least 7 times in the past 3,500 years. The last CSZ-related earthquake is believed to have occurred in 1700 and researchers predict a 10 - 14% chance that another one could occur in the next 50 years.
- People – The tsunami inundation zone along the coast of Washington State contains more than 42,000 residents that could potentially be affected were a tsunami to occur.
- Economy – The tsunami-inundation zone contains 2,908 businesses representing 31% of the businesses located in the four coastal counties of Washington State most prone to the effects of a Cascadia Subduction Zone generated tsunami. If a tsunami were to occur, the economic impact to these four counties could be severe and the State's economy would also be impacted.
- Environment – The potential impact to the environment due to a tsunami does not meet the minimum threshold of ten percent or more loss of a single species or habitat.
- Property – A USGS study on the vulnerability of Washington communities found that 18,397 households are in the tsunami-inundation zone along the coast of Washington. Property damage to these homes could be between $100 and $500 million dollars depending on the severity of the tsunami.

Hazard Area Map[2]

The tsunami inundation areas indicated on the map (Figure 1) were derived from 25-foot contour lines. This height of 25 feet was determined to be a plausible wave height for a coastal or Puget Sound located tsunami to be able to reach and cause flooding and other types of damage. Current research is beginning to use a 30 foot wave height. The Cascadia Subduction Zone is a region "where an oceanic tectonic plate (the Juan de Fuca plate) is being pulled and driven (i.e. subducted) beneath a continental plate (the North American plate). Earthquakes along the fault that is the contact between the two plates, termed the interpolate thrust or megathrust, may generate significant local tsunamis in the Pacific Northwest".

While tsunamis can occur in the Puget Sound, it is thought only to be a possibility if an earthquake is centered in this region and results in a tsunami. A coastal tsunami is not thought to be able to reach the Puget Sound area as the waves have many obstacles prior to reaching this region.

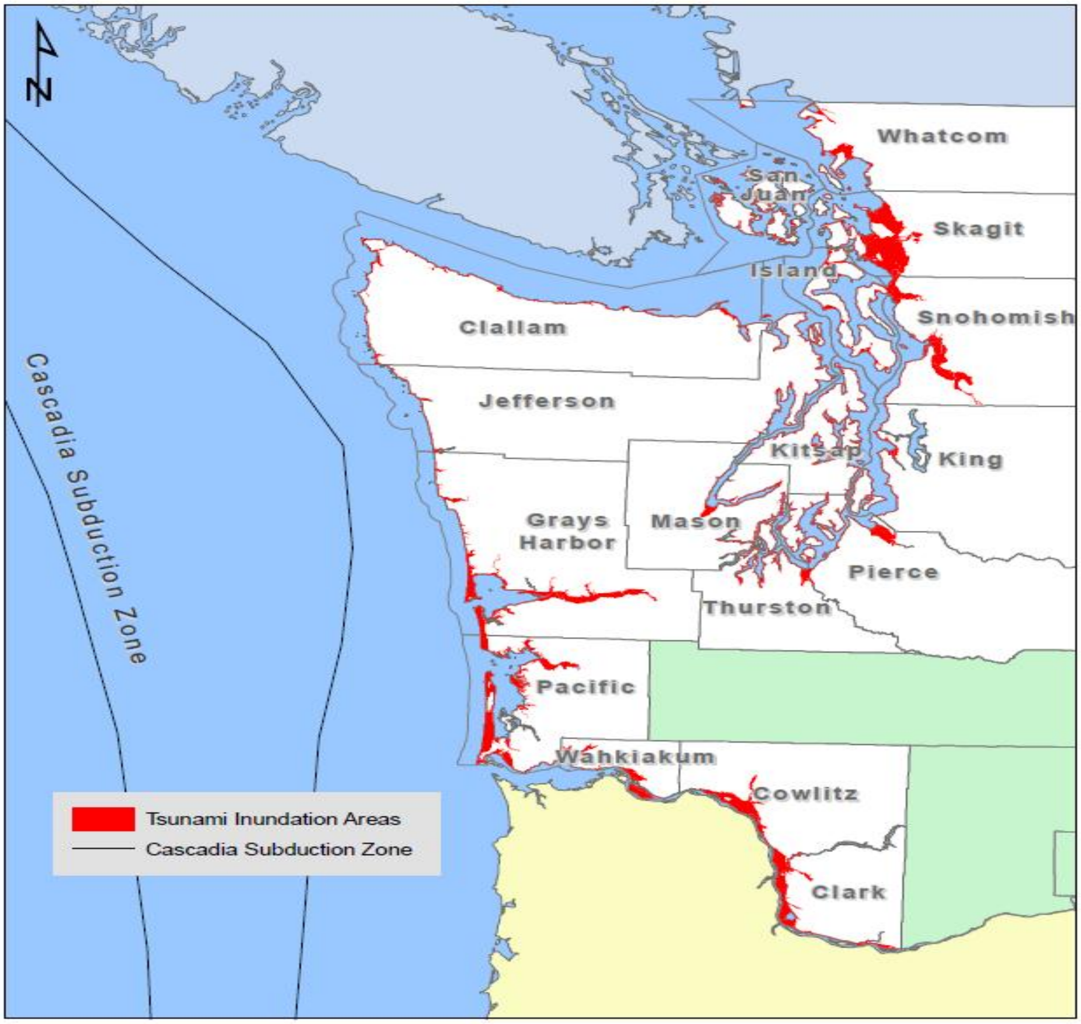


Figure 1 Tsunami Inundation Map for Washington State

Summary[3]

- The hazard – A tsunami is a series of waves typically generated during an earthquake by sudden displacement of the sea floor or lake bed. Tsunamis are particularly dangerous close to their sources, where the first wave in the tsunami series can arrive less than an hour after the tsunami begins and where the earthquake has already created havoc.

- Previous occurrences –Washington State has a long history of tsunamis from sources near and far. The largest of the nearby sources, the Cascadia Subduction Zone, produced its most recent great tsunami in 1700 AD. The State's tsunamis also include a Puget Sound tsunami from the Seattle Fault between 900 AD and 930 AD, a Tacoma Narrows tsunami from a landslide in 1949, a fatal wave from a rockfall into the Columbia River in 1965. The recent State's Pacific Ocean tsunamis include Aleutian Islands in1946, Chile in 1960, and Alaska in 1964. The 2011 Japanese tsunami debris has reached Washington State beaches in 2012.

- Probability of future events –Tsunamis generated elsewhere on the Pacific Rim are the ones that strike Washington most often. The Washington portion of the Cascadia Subduction Zone produces a great earthquake (magnitude 8 or 9) and associated tsunami often enough for the next of these to have a one-in-ten chance, or better, of occurring in the next fifty years. The frequency of tsunamis from inland sources has not been determined.

- Jurisdictions at greatest risk – Communities along the Pacific Coast and Strait of Juan de Fuca, including a number of coastal Indian tribes, are at greatest risk. In a Cascadia Subduction Zone earthquake, the level of the coast could fall or subside six feet, and tsunami waves could reach 30 feet, overtopping several low-lying coastal communities. The at-risk population from a Cascadia-related tsunami is approximately 43,000 residents and 25,000 employees on the outer coast. This analysis excludes tourists and transient populations that could increase the number significantly. In a 2008 study of community exposure on the open-ocean coast of Washington to Cascadia-related tsunamis, the City of Aberdeen had the highest number of residents, employees, dependent-population facilities, public venues, and total parcel value in the tsunami-hazard zone.

Global Perspective – In its earthquake and tsunami potential, the Pacific Northwest rivals the source areas of the greatest tsunamis of the last 100 years: Chile, Alaska, and Sumatra. Like all these areas, Cascadia Subduction Zone has a track record of generating ocean-wide tsunamis from earthquakes as large as magnitude 9.

The Hazard[4, 5, 6]

Tsunamis are a series of waves that threaten people and property along shorelines of the Pacific Coast, Strait of Juan de Fuca, Puget Sound, and large lakes. Sudden raising or lowering of the sea floor or a lake bed during an earthquake typically generates a tsunami, although landslides and underwater volcanic eruptions also can generate them.

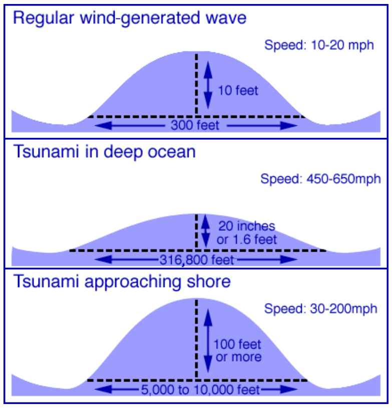


Figure 2 Wind-generated Waves vs. Tsunami Waves

Only as a tsunami approaches land does it become a hazard. In shallow water, it gains height as its waves slow and compress. Tsunamis can resemble a series of quickly rising tides, and they can withdraw with currents much like those of a river; they can also form breaking waves but these are less common than tsunami icons suggest. Swift currents commonly cause most of the damage from tsunamis. A Pacific Ocean tsunami can affect the entire Pacific basin, while a tsunami generated in inland waters can affect many miles of shoreline.

Tsunamis typically cause the most severe damage and casualties near their source. There, waves are highest because they have not yet lost much energy. The nearby coastal population, already reeling from the effects of an earthquake, may have little chance to flee before the tsunami arrives. Persons caught in the path of a tsunami often have little chance to survive; debris may crush them, or they may drown. Children and the elderly are particularly at risk, as they have less mobility, strength, and endurance.

A tsunami crosses the ocean at jetliner speeds, close to 600 miles per hour. The 1964 tsunami from Alaska's Aleutian Islands took less than five hours to reach Hawaii, where it killed 159 people. Computer simulations show that the January 26, 1700 tsunami from the Cascadia Subduction Zone along the Pacific Coast of Washington took about 10 hours to reach Japan, where it caused flooding and damage along 600 miles of the Pacific coast of Honshu.

Tsunami waves in the ocean can continue for hours; later waves can be larger, more deadly, and more damaging. For example, the first wave to strike Crescent City, CA, following the 1964 Alaska earthquake was 9 feet above the tide level; the second was 6 feet above tide; the third was about 11 feet above the tide level; and the fourth, most damaging wave was more than 16 feet above the tide level. The third and fourth waves killed 11 people. Estimates of the damage range from $47 million to $97 million (2004 dollars). The same tsunami destroyed property in many areas along the Pacific coast from Alaska to California. In Washington, the largest wave entered Willapa Bay about 12 hours after the first one; the tsunami caused $640,000 (2004 dollars) in damage (see Table 2, for wave heights along the Washington coast).

Although the 1964 event was the largest 20th-century tsunami on the Washington coast, the state has its own sources of tsunamis, and these have produced great waves recorded geologically in the last few thousand years.

Table 1. Recent Subduction Zone Earthquakes and Tsunamis Worldwide, 1946 – January 2013

Date	Origin	Effects	Casualties
April 1, 1946[7]	Aleutian Islands EQ Magnitude 8.6	Tsunami destroyed the Scotch Cap Lighthouse on Unimak Island, AK. Led to creation of The Pacific Tsunami Warning Center.	165 dead in Alaska and Hawaii
May 22, 1960[8]	South-Central Chile EQ Magnitude 9.5	Largest earthquake in world. Damage to Chile, Hawaii (61 tsunami deaths), and Japan (118 tsunami deaths).	4,000-5,000 dead; 3,000 homeless; 2 million injured.
March 27, 1964[9]	Prince William Sound, Alaska EQ Magnitude 9.2	Second-largest earthquake in 20th century. Shaking lasted 3 minutes. Severe damage to south coast of Alaska. Wave height at Valdez Inlet estimated at 220 feet. Tsunami deaths in AK, OR, Crescent City, CA.	125 dead (tsunami 110, EQ 15)
Aug. 23, 1976[10]	Celebes Sea EQ Magnitude 7.9	Southwest Philippines struck, devastating Alicia, Pagadian, Cotabato and Davao.	8,000 dead
July 17, 1998[11]	Papua New Guinea EQ Magnitude 7.1	Arop, Warapu, Sissano, and Malol, Papua New Guinea devastated. Wave height estimated at 33 feet.	2,200 dead; 200 missing; 9,500 homeless
Dec. 26, 2004[12,13]	Sumatra, Indonesia EQ Magnitude 9.0	Parts of Indonesia, Thailand, Malaysia, India, Sri Lanka, and Maldives devastated. Wave heights reached 100 feet. Tsunami measured around the world.	283,000 dead; 14,100 missing; 1.1 million displaced
March 28, 2005[14]	Sumatra, Indonesia EQ Magnitude 8.7	Parts of Sumatra Island, Indonesia badly damaged. Wave height estimated at 10 feet.	1,400 dead
September 29, 2009[15]	South Pacific Basin, Samoa EQ Magnitude 8.0	Parts of American Samoa, Western Samoa, and Tonga were severely impacted. Run-up of 56 feet was reported.	160 dead, 7 missing
March 11, 2011[16]	Honshu, Japan EQ Magnitude 9.0	Near the East Coast of Honshu, Japan	20,896 dead

Tsunami Threat in Washington[17]

Washington's outer coast faces a dual threat: tsunamis generated by distant sources such as earthquakes in Alaska, Chile and Japan; and tsunamis generated directly offshore during an earthquake from the Cascadia Subduction Zone.

Just off the Washington State Pacific Ocean coast, the Cascadia Subduction Zone has generated magnitude 8 or larger earthquakes at least six times in the past 3,500 years. Each is known or suspected to have set off a tsunami. The most recent occurrence dates to the evening of January 26, 1700. During this earthquake and its predecessors, much of the land on Washington's outer coast subsided, or fell, by about five feet. Such lowering of the land makes coastal communities more susceptible to flooding and damage from the ensuing tsunami.

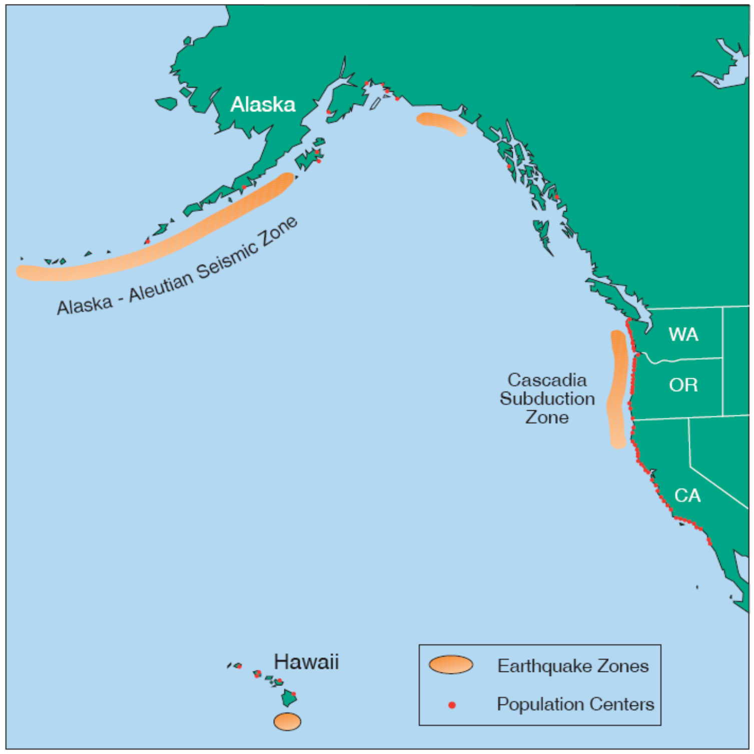


Figure 3 Tsunami Hazards for the West Coast of the United States

Computer models indicate that a Cascadia-generated tsunami could reach nearly 30 feet in height and affect the entire Washington coast. The first wave would reach coastal communities within 30 minutes after the earthquake, and reach communities along the Strait of Juan de Fuca in 90 minutes. Tsunamis from great Cascadia earthquakes probably account for several sand sheets on northwestern Whidbey Island and at Discovery Bay in Puget Sound.

Washington's Puget Sound waters also are subject to tsunamis. An earthquake around A.D. 900-930 on the Seattle Fault caused uplift that triggered a tsunami in central Puget Sound. A few days after the 1949 Olympia earthquake, a landslide into the Tacoma Narrows set off a tsunami.

As part of the U.S. National Tsunami Hazard Mitigation Program (NTHMP) the National Oceanic and Atmospheric Association (NOAA) set goals to: reduce the loss of life and property in U.S. coastal communities, reduce false alarms and the resulting high economic cost of unnecessary evacuations, lessen the physical risk to the population during evacuations, and reduce the loss of public confidence in the tsunami warning system. To achieve these goals NOAA developed deep-ocean tsunameters for early detection, measurement, and real-time reporting of tsunamis in the open ocean. The tsunameters were developed by Project DART (Deep-ocean Assessment and Reporting of Tsunamis) at NOAA's Pacific Marine Environmental Laboratory (PMEL) located in Seattle. The DART systems (Figure 4) have been deployed near regions with a history of tsunami generation to ensure measurement of the waves as they propagate towards threatened U.S. coastal communities and to acquire data critical to real-time forecasts.

Figure 4 The first DART (Deep-ocean Assessment and Reporting of Tsunami) Detection Buoy

This network now consists of a total of 39 deep-ocean detection and assessment buoys (Figure 5). "When a tsunami event occurs, the first information available about the source of the tsunami is based only on the available seismic information for the earthquake event. As the tsunami wave propagates across the ocean and successively reaches the DART systems (buoys), these systems report sea level information back to the Tsunami Warning Centers, where the information is processed to produce a new and more refined estimate of the tsunami source. The result is an increasingly accurate forecast of the tsunami that can be used to issue watches, advisories, warnings, or evacuations."[18]

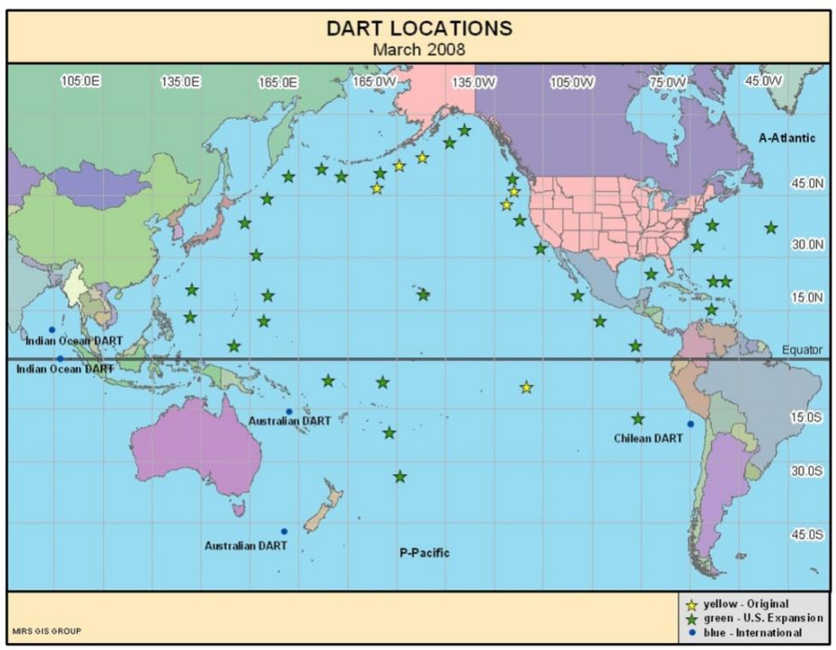


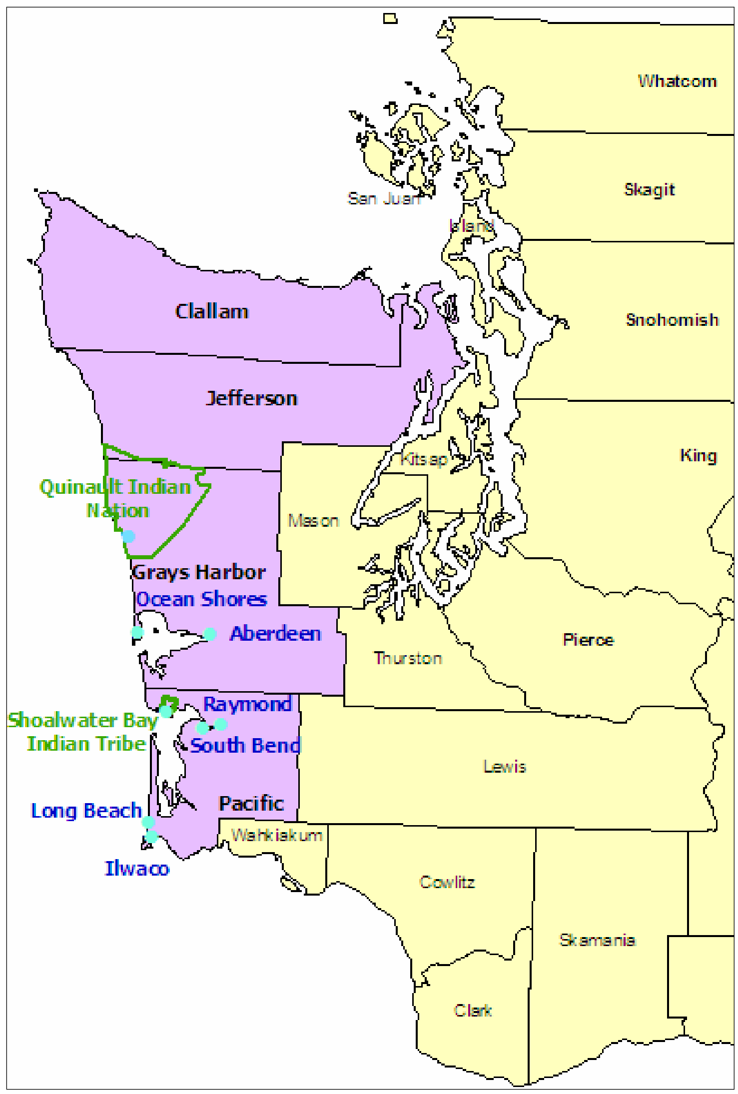
Figure 5 Location of NOAA DART (Deep-Ocean Assessment and Reporting) Tsunami Instruments, as of March 2008

Figure 6 Tsunami Evacuation and Hazard Zone Signs

This initiative toward recognizing tsunamis to issue warnings to affected communities has spread to educating communities on the tsunami potential, signs and signals a tsunami may be approaching, and measures to get out of harm's way should an event occur. Tsunami hazard zone signs are "intended to be posted at Pacific coast access points or other low-lying areas that would clearly be vulnerable to a large, locally generated tsunami." Tsunami evacuation route signs (Figure 6) are used to "designate that evacuation routes established by local jurisdictions in cooperation with emergency management officials."[19]

Figure 7 NOAA's National Weather Service TsunamiReady™ Program

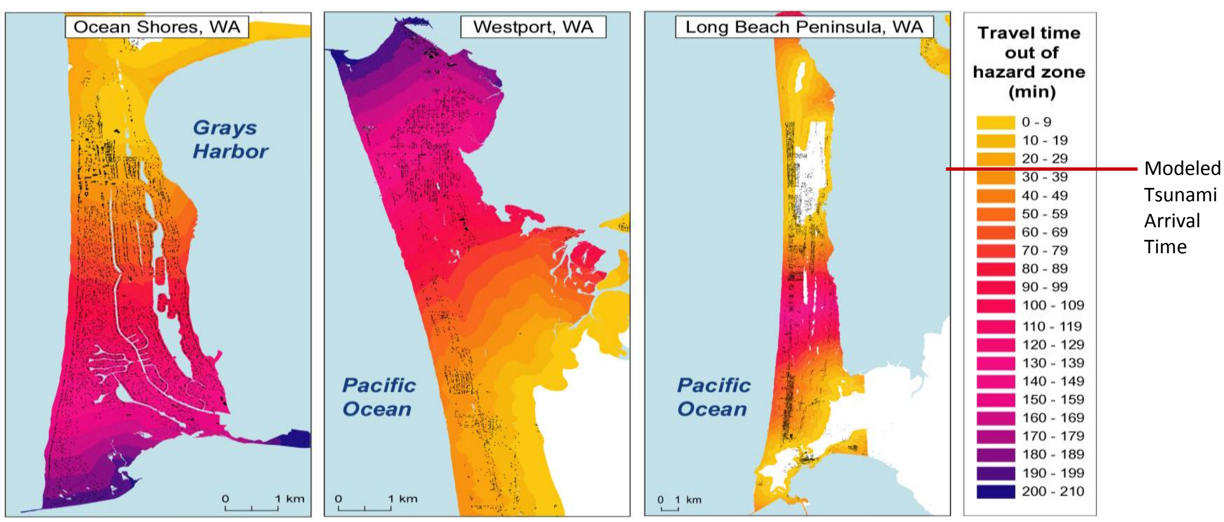
In addition to warning signs, NOAA's National Weather Service (NWS) has established a Tsunami Ready™ (Figure 7) program that "gives communities the skills and education to survive a tsunami before, during and after an event".[20] To meet criteria for this program communities must: establish a 24-hour warning point and emergency operations center, have more than one way to receive tsunami warnings and to alert the public, promote public readiness through community education and the distribution of information, and develop a formal tsunami plan, which include holding emergency exercises.



Currently, Washington State has 6 communities (Aberdeen, Ilwaco, Long Beach, Ocean Shores, Raymond and South Bend), 4 counties (Pacific, Grays Harbor, Jefferson, and Clallam), and 2 Indian Nation (Quinault Indian Nation and Shoalwater Bay Tribe) that have been granted the TsunamiReady™ status (Figure 8).

At least thirteen (13) of Washington State's Pacific Ocean coastal communities and tribal reservations lack natural high ground that is of sufficient elevation to escape a 30+ foot tsunami triggered by a Cascadia Subduction Zone earthquake. The lack of natural high ground coupled with preceding earthquake damage, close proximity to the fault (~50-100 miles), and limited time for evacuation (15-30 minutes) preclude the use of traditional horizontal or vehicular evacuation strategies. These limiting factors make 13 outer coastal communities in Washington extremely vulnerable to significant loss of life from such an incident. This situation is not unique to Washington State, as many low-lying coastal areas within U.S. states, commonwealths, and territories are also constrained by similar geographic factors.

To address this unique challenge, the concept of vertical evacuation was established. This evacuation strategy allows residents and visitors to move upwards to safety in man-made structures (buildings, towers, or berms) and is particularly important on peninsulas where traditional evacuation measures are not viable options for life safety. In 2008, FEMA collaborated with the National Oceanic and Atmospheric Association and published engineering guidance entitled "*Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*" to promote the planning and development of life safety refuges in the United States (FEMA P646). In 2011, the vertical evacuation concept was tested to its fullest extent and successfully saved thousands of lives in Japan during the March 11, 2011 tsunami.



Source: Wood, N.; Schmidtlein, M.; and Schelling, J.; *Preparing for catastrophic tsunamis in the U.S. Pacific Northwest --- the use of pedestrian-evacuation modeling to target mitigation and education*; Paper #NH-38, American Geophysical Union (AGU) Science Policy Conference.

FEMA Post Disaster Mitigation (PDM) grants currently support construction of safe rooms in tornado hazard areas and construction of earthen mounds in floodplains to permit livestock refuge from floodwaters. However, FEMA has not had the opportunity to fully investigate the feasibility of a tsunami mitigation project that provides similar benefits through the PDM program. However, new research indicates that many tsunami mitigation projects are, in fact, more cost-effective with higher benefit-cost ratios than most tornado or earthquake mitigation projects currently authorized by FEMA.[21]

This new line of research clearly indicates that using FEMA's value of life, discount rate, and project useful life, provides ample economic justification for tsunami mitigation projects in high risk locations. Perhaps more importantly, these results also identify that national and local priorities for natural hazard mitigation should be reconsidered, with tsunami mitigation given a very high priority for coastal communities.

To reduce the potential life safety impacts from a Cascadia tsunami, WA EMD initiated Project Safe Haven in order to identify vertical evacuation options for outer coastal and tribal communities. Project Safe Haven is a grassroots, public planning process which empowers coastal residents to develop community-based plans that integrate multi-purpose vertical evacuation refuges into the existing natural and built environments. Subject matter experts facilitate the planning process and final plans have been completed for every tsunami threatened outer coastal and tribal community in Washington State. The final community-developed reports are available at: www.facebook.com/projectsafehaven.

Table 2 – Summary of Proposed Community Strategies and Projected Costs

County	Community Strategy	Population Served	Est. Projected Cost (in millions)
Clallam	2 towers, improving access to some existing high ground	1,755	$1.48
Grays Harbor	3 berms, 18 towers, 8 tower/berm hybrid facilities, 3 buildings	18,450	$40.00
Pacific	13 berms, 5 towers, 2 buildings	6,300	$11.00
TOTAL		26,505	$52.48

While no amount of planning, education and preparedness can make a community tsunami proof, personal and community preparedness can greatly reduce the amount of lives lost and property destroyed in the event that a tsunami strikes Washington's coast.

Previous Occurrences

Tsunamis on Washington's Pacific Coast[22, 23, 24, 25]

While tsunamis have caused significant damage, deaths and injuries elsewhere in the world, only one significant tsunami struck Washington's Pacific coast in recent history. The 1964 Alaska earthquake generated a tsunami that resulted in more than $640,000 (in 2004 dollars) in damage. However, geologic investigations indicate that tsunamis have struck the coast a number of times in the last few hundred years.

1700 Cascadia Tsunami

The most recent Cascadia Subduction Zone earthquake, estimated at magnitude 9, produced a tsunami on Washington's coast in 1700. The tsunami overran Native American fishing camps and left behind telltale sheets of sand on marshes and in lakes along the southern part of the coast. A sand sheet at Discovery Bay in the eastern Strait of Juan de Fuca also probably resulted from the 1700 tsunami.

Japanese written history pinpoints this event to the evening of January 26, 1700. There, the tsunami began in the middle of the night of January 27-28 Japan time and continued until the following afternoon or evening. Its waves drove villagers to high ground, drowned their paddies and crops, damaged their salt kilns and fishing shacks, entered a government storehouse, and ascended a castle moat. It destroyed dozens of buildings, including 20 houses consumed by a fire that the flooding started or spread. It set in motion a nautical accident that sank tons of rice and killed two sailors. It led samurai to give rice to villagers left hungry and to request lumber for those left homeless. The tsunami left a village headman wondering why no earthquake had warned of its coming.

1960 Chilean Tsunami

A magnitude 9.5 earthquake along the coast of Chile generated a tsunami that struck the Washington coast at Grays Harbor (small waves), Tokeland (two feet), Ilwaco (two feet), Neah Bay (1.2 feet), and Friday Harbor (0.3 feet). No damage occurred.

1964 Alaskan Tsunami

The tsunami generated by the March 27, 1964 Alaska earthquake was the largest and best-recorded historical tsunami on the Washington coast. Tsunami wave heights generally were greatest on the south coast and smaller on the north coast. Additionally, the tsunami was recorded inland in the Strait of Juan de Fuca (Friday Harbor), Puget Sound (Seattle), and the Columbia River (Vancouver).

Observations were made of the tsunami in Grays Harbor County at Westport, Joe Creek, Pacific Beach, Copalis, Grays Harbor City, and Boone Creek.

Damages included debris deposits throughout the region, minor damage in Ilwaco, damage to two bridges on State Highway 109, a house and smaller buildings being lifted off foundations in Pacific Beach (the house was a total loss), and damage to the Highway 101 bridge over the Bone River near Bay Center when the Moore cannery building washed against its pilings.

Table 2. Recorded Height of Tsunami Waves from 1964 Alaska Earthquake

Wreck Creek	4.5 feet	Neah Bay	0.7 feet
Seaview	3.8 feet	Taholah	0.7 feet
Moclips	3.4 feet	Hoh River Mouth	0.5 feet
Ocean Shores	2.9 feet	Friday Harbor	0.4 feet
La Push	1.6 feet	Vancouver	0.1 feet
Ilwaco	1.4 feet	Seattle	0.1 feet

Additional information concerning observations from the 1964 tsunami on the Washington coast are highlighted below in an excerpt from the Tsunami Hazard Map of the Southern Washington Coast by Timothy Walsh, et al (2000). [26]

Table 1. Observations of the 1964 tsunami on the Washington coast. Height is height of highest wave; MLW, mean low water; MSL, mean sea level. Estimated damage is in 1964 dollars (from Hogan and others, 1964; Wilson and Torum, 1972; and newspaper accounts)

Location	Map no.	Height (ft) above tide	Height (ft) above MLW	Height (ft) above MSL	Estimated damage	Type of damage	Photo
Coast Guard Station, Cape Disappointment	1	5.7	11.9	8.3		None	
Town of Ilwaco	2	4.5	10.7	7.1		Minor damage	
Town of Seaview	3	12.5	19.5	14.8		None	
Ocean Shores	4	9.7	18.1	13.3		Deposition of debris on streets near Central Motel Office. Debris on streets and yards in vicinity of break in sand dune dike about ¾ mile south of motel	
State Highway 109, Copalis River Bridge	5					Loss of one four-pile timber bent and two timber spans near the bridge center and one piling in a four-pile timber bent.	9-1-A; Fig.3
Town of Copalis, Copalis River	6				$5,000	Damage to buildings	
State Hwy 109 at Boone Creek	7				$5,000	Erosion of 80 ft (24 m) of shoulder and deposition of debris on highway.	8-4-A
Iron Springs Resort	7				$500	Foundation and water damage to one house and deposition of debris in yard.	
State Highway 109, Joe Creek Bridge	8				$75,000	Loss of five-pile bent, damage to two pile bents (loss of three pilings), and loss of two 20-ft (6.1-m) reinforced concrete spans.	8-3-A; Fig. 4
Town of Pacific Beach	9	12–14 (est.)			$12,000	Medium-sized house lifted off the foundation and partly torn apart; total loss. Several sheds moved off foundations. A second building partly damaged. Yards eroded and covered with debris.	8-2-A; Fig. 5
Town of Moclips	10	11.1	19.7	14.9	$6,000	Damage to ocean side of buildings by floating logs; one building moved off foundation. Timber pile bulkheads and fills extensively damaged. Water over some floors from 6 in. to several feet. Heavy debris scattered over yards.	8-1-A, B,C; Figs. 6,7,8
State Highway 109, Wreck Creek Bridge	11	14.9	23.5	18.83	$500	Erosion of fill at bridge approach: debris on bridge deck and nearby highway.	7-1-A
Taholah	12	2.4	11.0	6.3	$1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinault River.	
Mouth of Hoh River		1.7	10.1	5.6		None	
La Push		5.3	13.7	9.3		Several boats and a floating dock broke loose from moorings.	
U.S. Highway 101, Bone River Bridge	13					Pilings damaged when the Moore cannery building was lifted off its foundation and washed against the south approach of the Highway 101 bridge over the Bone River	
Raymond docks		3.5–4 (est.)				None	

November 2006 Tsunami

On Nov 15, 2006, a magnitude 8.3 earthquake occurred near the Kuril Islands northeast of Japan. Washington was put into a Tsunami Advisory. A 5 cm tsunami was recorded on the Neah Bay tide gage. However, after the cancellation of the Tsunami Advisory, a train of tsunami waves hit Crescent City, California six hours after the earthquake and destroyed docks, tore about a dozen boats lose from moorings, and sank at least one boat.

Table 3. Recorded Height of Tsunami Waves from 2006 Kuril Island Earthquake

Location	Wave height
La Push	.52 feet
Neah Bay	.01 feet
Port Angeles	.39 feet
Westport	.16 feet

Puget Sound Tsunamis[27, 28, 29, 30, 31]

A.D. 900-930 Tsunami

An earthquake between the years 900 and 930 raised shores of central Puget Sound by 20 feet between the Duwamish River and Bremerton. The uplift, by also including the floor of Puget Sound, created a tsunami. In Seattle, the tsunami washed across West Point, where it deposited a sheet of sand. Farther north, it deposited a sand sheet at Cultus Bay on southern Whidbey Island and along tributaries of the Snohomish River between Everett and Marysville. Computer simulations of the tsunami show it reaching heights of 20 feet or more at the Seattle waterfront.

Early 1800s Camano Head Tsunami

Historical accounts among the Snohomish Indian people describe a landslide at Camano Head that sent a large wave south toward Hat Island. Camano Head is at the south end of Camano Island in Puget Sound. According to tribal accounts, the landslide sounded like thunder, buried a small village and created a large volume of dust. The tsunami washed over the barrier beach at Hat Island, destroying homes or encampments and drowning many people. The accounts make no mention of ground shaking, suggesting that the slide was not associated with a large earthquake.

1891 Puget Sound Tsunami

Water in Lake Washington and Puget Sound surged onto beaches two feet above the high water mark, rocking vessels that had just pulled away from wharves, and causing an elevator in one building to bump against the side of the shaft. The likely cause of this November 29 event was two earthquake shocks and submarine landslides.

1894 Commencement Bay Tsunami

A submarine landslide in the delta of the Puyallup River in Commencement Bay, Tacoma, caused a tsunami. These events carried away a railroad track and roadway, resulting in two deaths.

1949 Puget Sound Tsunami

A small landslide-generated tsunami struck the Point Defiance shoreline in the Tacoma Narrows on April 16, three days after a magnitude 7.1 earthquake weakened the hillside. According to local newspaper reports, an 11 million cubic yard landslide occurred when a 400-foot high cliff gave way and slid into Puget Sound. Water receded 20-25 feet from the normal tide line, and an eight-foot wave rushed back against the beach, smashing boats, docks, a wooden boardwalk, and other waterfront installations in the Salmon Beach area. The slide narrowly missed a row of waterfront homes struck by the tsunami.

Inland Tsunamis[32]

Lake Roosevelt Tsunamis

Landslides into Lake Roosevelt in eastern Washington generated numerous tsunamis from 1944 to 1953 after Grand Coulee Dam created the lake on the Columbia River. Most tsunamis generated large waves (30 to 60 feet in height) that struck the opposite shore of the lake, with some waves observed miles from the source. Two tsunamis caused damage:

- *February 23, 1951* – A 100,000 to 200,000 cubic yard landslide just north of Kettle Falls created a wave that picked up logs at the Harter Lumber Company Mill and flung them through the mill 10 feet above lake level.

- *October 13, 1952* – A landslide 98 miles upstream of Grand Coulee Dam created a wave that broke tugboats and barges loose from their moorings at the Lafferty Transportation Company six miles away. It also swept logs and other debris over a large area above lake level.

- January 16, 2009—Another landslide –induced tsunami reached a height of about 30 feet and damaged docks at Breezy Bay, Moccasin Bay, Sunset Point and Arrowhead Point.

1965 Puget Island Tsunami

This tsunami occurred in 1965. A landslide-triggered tsunami overran Puget Island in the Columbia River near Cathlamet. The landslide originated from Bradwood Point on the Oregon side of the River. The wave killed one person.

1980 Spirit Lake Tsunami

The May 18, 1980 eruption of Mount St. Helens caused a massive tsunami in Spirit Lake. The sliding north face of the volcano slammed into the west arm of the lake, raising its surface an estimated 207 feet and sending a tsunami surging around the lake basin as high as 820 feet above the previous lake level. Displaced water rinsed the valley sides clean of timber and sediment, jamming logs and boulders against the landslide debris. In the east arm of Spirit Lake, the tsunami wave reached nearly 740 feet above the old level of the lake, also washing trees off the sides of the valley and into the lake.

Seiche[33, 34, 35]

Seiches are water waves generated in enclosed or partly enclosed bodies of water such as reservoirs, lakes, bays and rivers by the passage of seismic waves (ground shaking) caused by earthquakes. Sedimentary basins beneath the body of water can amplify a seiche. Seismic waves also can amplify water waves by exciting the natural sloshing action in a body of water or focusing water waves onto a section of shoreline.

In a 2003 paper, researchers at the University of Washington and the National Oceanic and Atmospheric Administration indicate that the geology of the sedimentary basin beneath Seattle amplifies seismic waves from large and distant earthquakes, contributing to the damaging effects of water waves in local enclosed bodies of water.

The November 2002 magnitude 7.9 Denali earthquake in Alaska produced water waves damaging about 20 houseboats in Seattle's Lake Union, buckling moorings, and breaking sewer and water lines. Sloshing action was reported in swimming pools, ponds and lakes around Seattle. Newspaper reports indicate water waves from the 1964 magnitude 9.2 Alaska earthquake caused similar damage on the lake as well as overtopping the Fairview Hill reservoir and washing gravel into an Aberdeen neighborhood. Sloshing wave action also was reported following the 1949 magnitude 7.1 Olympia earthquake and the 1965 magnitude 6.5 Seattle earthquake.

Researchers believe local amplification of seismic waves could make other urban areas above sedimentary basins in the region particularly vulnerable to seiches or water waves during large earthquakes on the Seattle Fault or the Cascadia Subduction Zone.

Probability of Future Events[36]

Great earthquakes in the Pacific Ocean generate tsunamis that sweep through the entire Pacific basin at a rate of about six every 100 years. In the Cascadia Subduction Zone, scientists currently estimate there is a 10 to 14 percent chance a magnitude 9.0 earthquake and associated tsunami will occur in the next 50 years.

A specific rate of occurrence has not been calculated for local earthquakes and landslides that generate tsunamis.

Jurisdictions Most Threatened and Vulnerable to Tsunami [37, 38, 39]

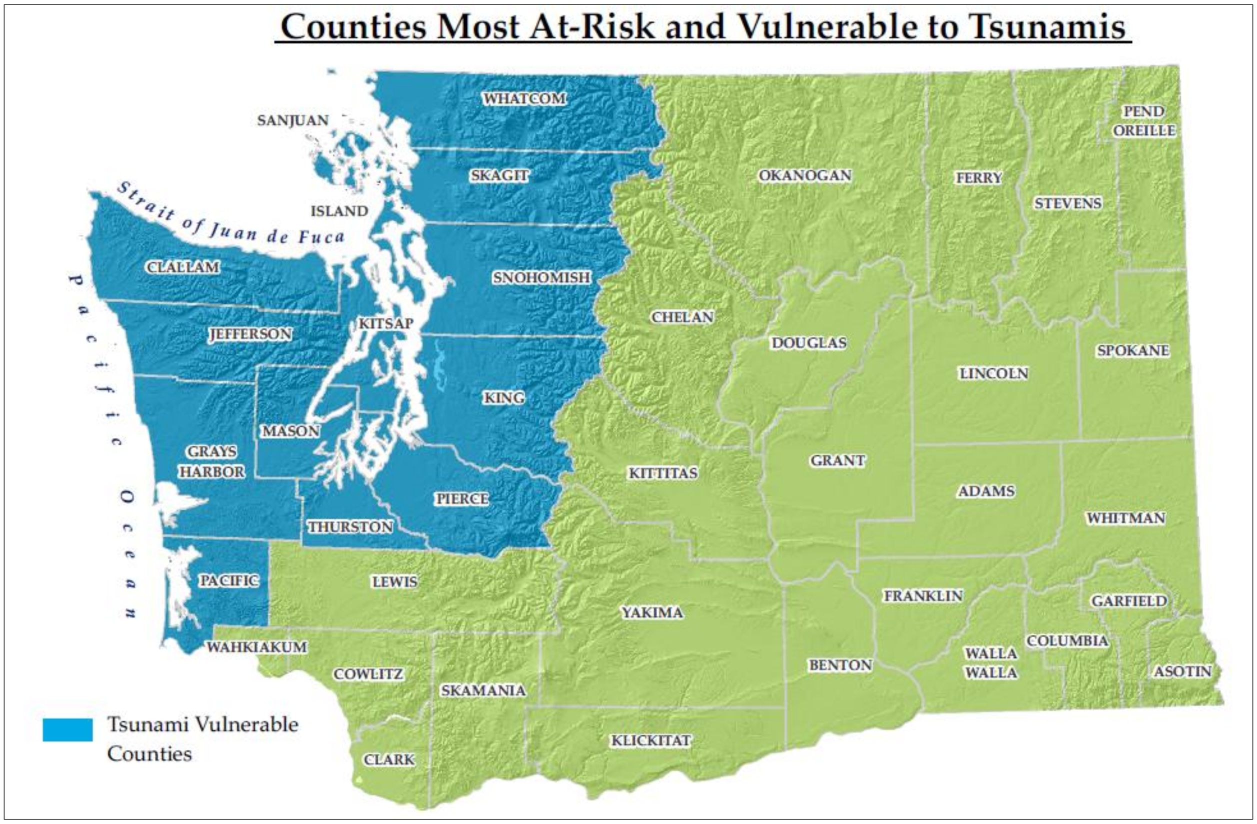
Areas vulnerable to tsunamis in Washington State include ocean beaches, bay entrances, tidal flats, the banks of tidal rivers, and some inland waters.

Washington began creating tsunami inundation models and maps for its Pacific Coast shoreline in the late 1990s using funds from the National Tsunami Hazard Mitigation Program. To date, tsunami inundation mapping for a Cascadia Subduction Zone earthquake is complete for most shorelines of the Pacific Coast and Strait of Juan de Fuca. Modeling and mapping is complete for an earthquake on the Seattle Fault for Seattle and Tacoma, and on the Tacoma Fault for Tacoma. Modeling for tsunamis caused by surface faults in the Everett area and in Lake Washington is underway or scheduled.

The Washington Department of Natural Resources Division of Geology and Earth Resources prepares tsunami inundation maps from the modeling. Local governments then use inundation maps to develop evacuation maps for their communities.

The state map below highlights the counties considered most at-risk and vulnerable to tsunamis; the latest inundation maps, population estimates and communities considered most at risk are on the pages that follow. A study co-sponsored by the State Emergency Management Division and the U.S. Geological Survey completed in 2008 provides more detailed estimates on population, infrastructure and local economic assets in the Cascadia-related tsunami-hazard zones of Clallam, Jefferson, Grays Harbor and Pacific counties).

Estimates for state agency facilities located in the tsunami hazard zone were developed using the inundation maps on the following pages.

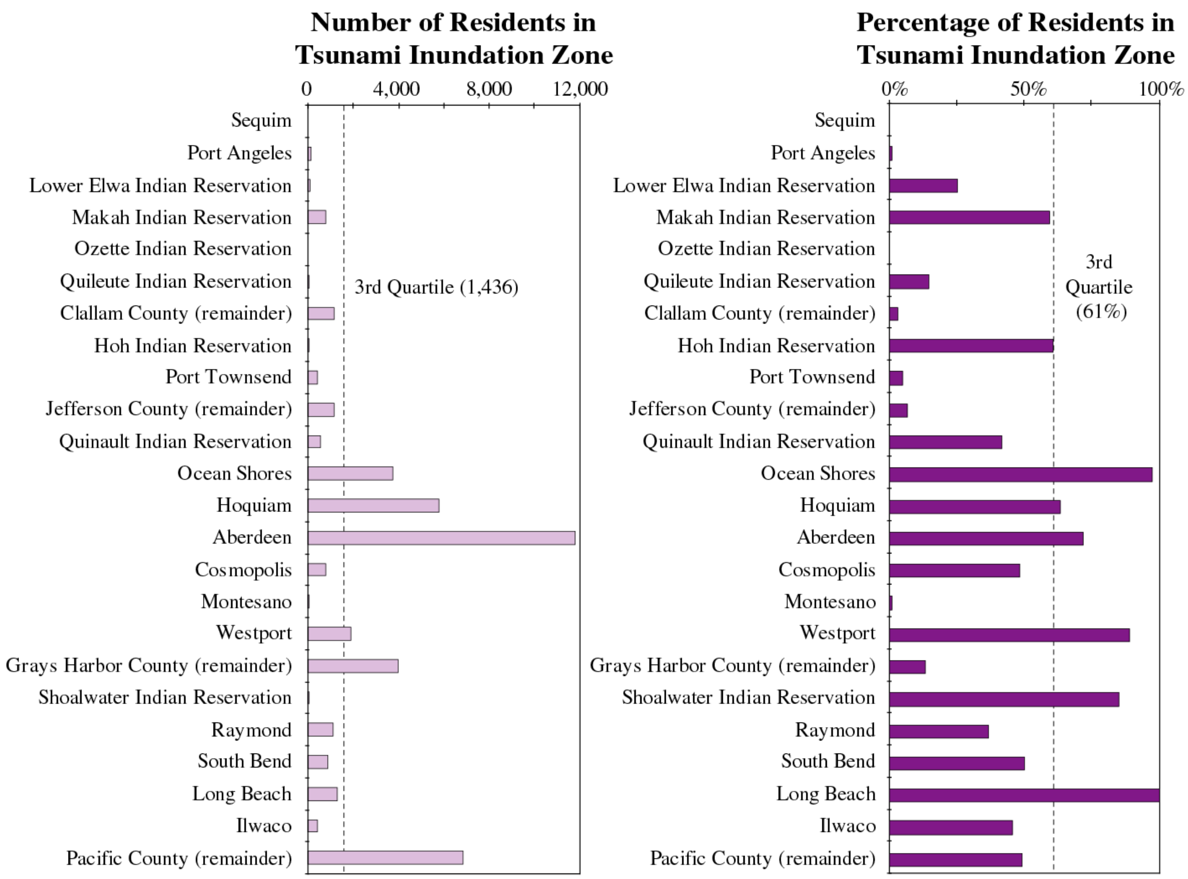


Pacific Coast, Strait of Juan de Fuca[40, 41, 42, 43]

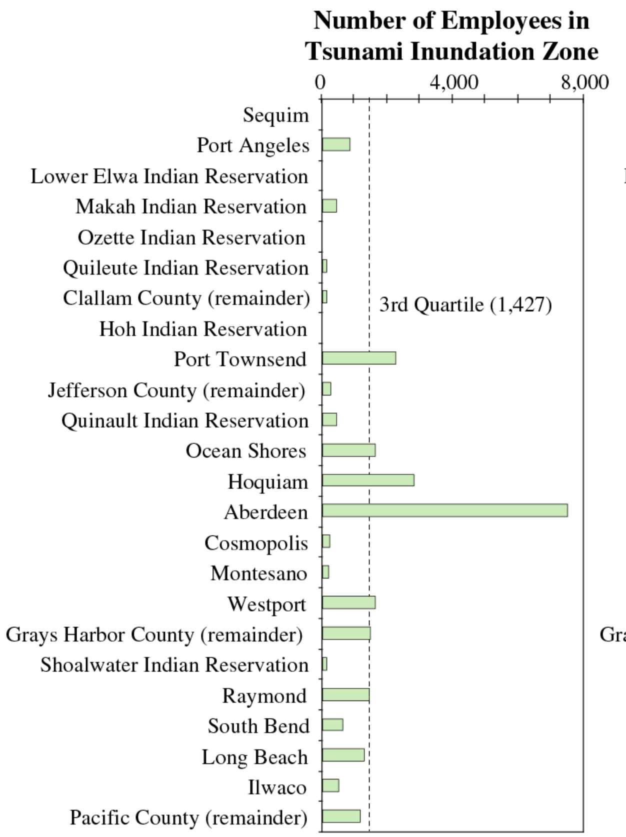
The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts models uses a magnitude 9.1 earthquake on the Cascadia Subduction Zone off the Washington coast as the generator of the tsunami.

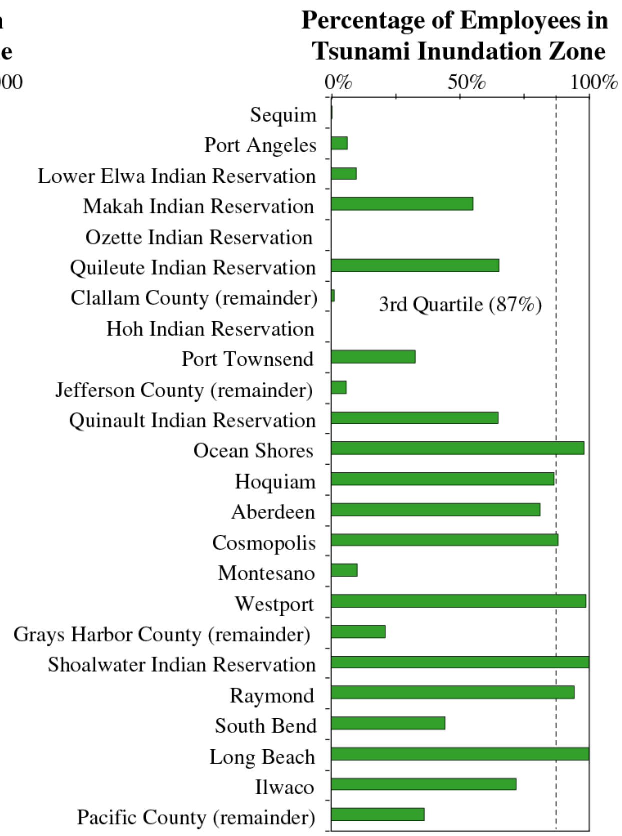
The estimated at-risk population in the four counties bordering the outer Pacific Coast is 42,972 residents (based on the 2000 U.S. Census), representing 24% of the total people in these counties (Wood and Soulard, 2008). It does not include at-risk communities on the east end of the Strait of Juan de Fuca such as Bellingham, Anacortes and Mount Vernon, and Island and San Juan counties; their at-risk populations have not been calculated.

Within the four counties bordering the Pacific Ocean, the City of Aberdeen has the highest number of residents (11,781) in the tsunami-inundation zone. Approximately 13,096 residents in tsunami-prone areas are outside of the 13 incorporated cities and 7 Indian reservations and are primarily in the unincorporated portions of Pacific County (6,823) and Grays Harbor County (3,957). Many communities have low numbers but high percentages of residents in the tsunami-inundation zone, including the Makah Indian Reservation (802 residents, representing 59 percent of the community), the Hoh Indian Reservation (62 residents, 61 percent), South Bend (900 residents, 50 percent), and Long Beach (1,281 residents, 100 percent).



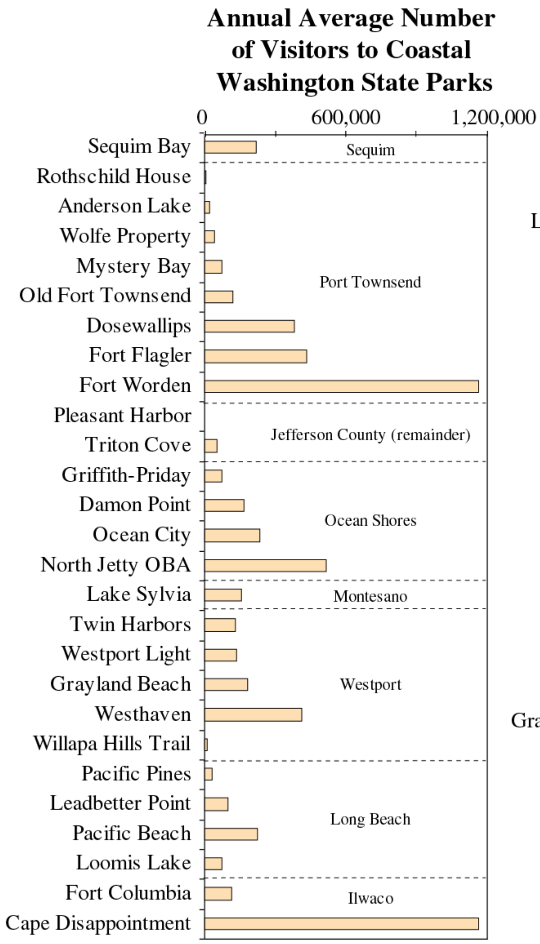
The tsunami-inundation zone contains 24,934 employees (based on 2007 economic data), representing 33 percent of the employees in the four coastal counties (Wood and Soulard, 2008). Certain communities such as Hoquiam and Aberdeen have high numbers of employees in the tsunami-inundation zone (2,792 and 7,488, respectively) that represents high percentages of their community workforce (86 percent and 81 percent, respectively). Other communities have much lower numbers of employees in the tsunami-inundation zone, including Shoalwater Indian Reservation (138), but these employees represent the entire community workforce.

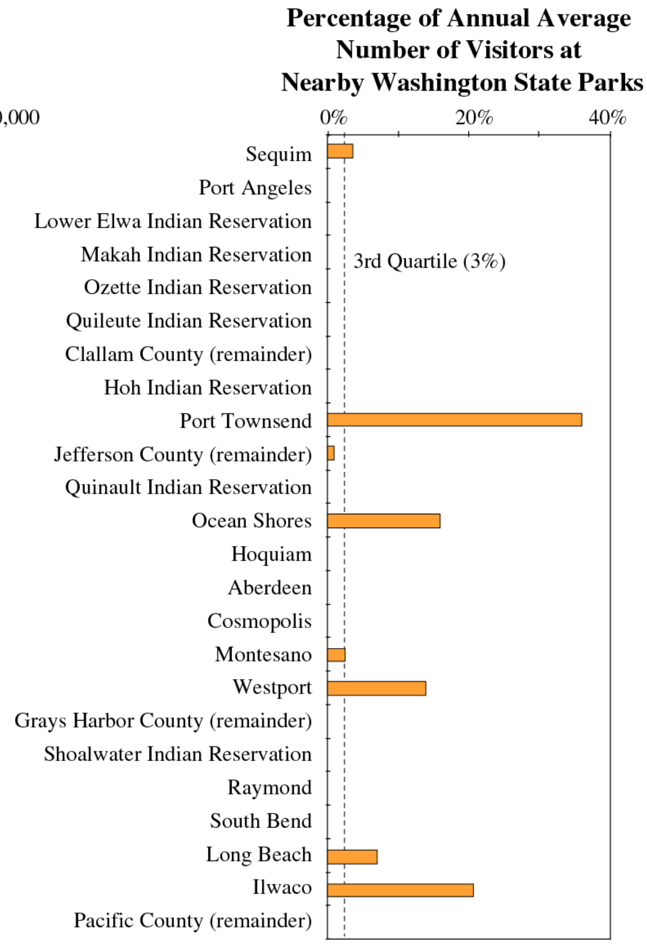




These at-risk population estimates exclude the thousands of tourists that populate at-risk beach areas at various times of the year. Analysis of visitor data from Washington State Parks in Wood and Soulard (2008) suggests that 27 parks in the tsunami-inundation zone of the study area receive a significant amount of day tourists. The highest annual average of day-use visitors for the 27 parks are for Fort Worden (1,164,125 visitors near Port Townsend) and Cape Disappointment (1,162,447 visitors near Ilwaco). The sum of annual average visitors to the 27 coastal parks of the Washington State parks selected in Wood and Soulard (2008) is 6,215,569 people (2007 estimates).

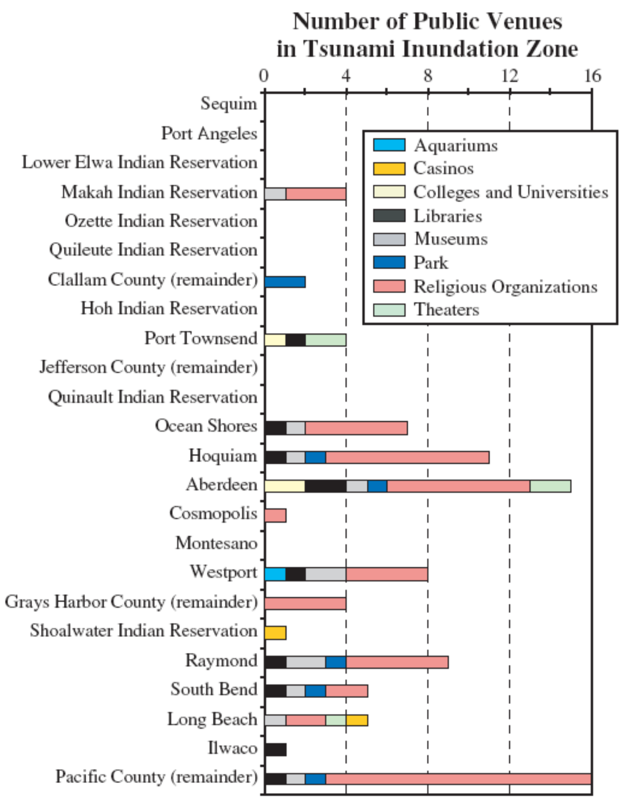
Assuming an equal distribution of visitors on every day of the year, this equates to 17,029 day-use visitors to these coastal State parks on average every day. In reality, this number is low because attendance is not equally distributed throughout the year; there will be seasonal peaks in park attendance (for example, summer months and holidays). Clustering the number of visitors of coastal parks to nearby towns, it is clear that the majority of visitors are going to parks near Port Townsend (36 percent) on the Strait of Juan de Fuca and Hood Canal coasts, followed by parks near Ilwaco (21 percent), Ocean Shores (16 percent), and Westport (14 percent). Therefore, in addition to dealing with residents and employees within the tsunami-inundation zones of their communities, cities like Port Townsend may have significant numbers of tourists that are visiting nearby State Parks when a tsunami occurs.

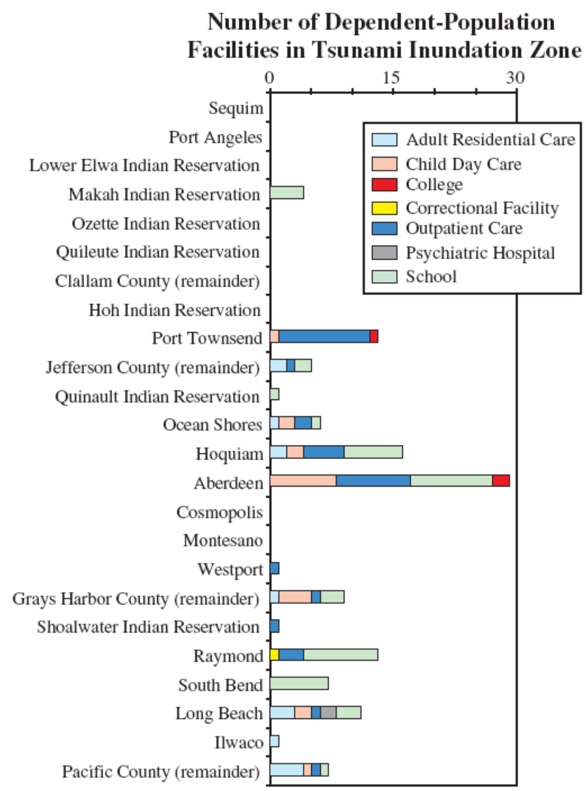

Annual Average Number of Visitors to Coastal Washington State Parks
0
600,000
1,200,000
Sequim Bay
Rothschild House
Anderson Lake
Wolfe Property
Mystery Bay
Old Fort Townsend
Dosewallips
Fort Flagler
Fort Worden
Pleasant Harbor
Triton Cove
Griffith-Priday
Damon Point
Ocean City
North Jetty OBA
Lake Sylvia
Twin Harbors
Westport Light
Grayland Beach
Westhaven
Willapa Hills Trail
Pacific Pines
Leadbetter Point
Pacific Beach
Loomis Lake
Fort Columbia
Cape Disappointment
Sequim
Port Townsend
Jefferson County (remainder)
Ocean Shores
Montesano
Westport
Long Beach
Ilwaco


Percentage of Annual Average Number of Visitors at Nearby Washington State Parks
0%
20%
40%
Sequim
Port Angeles
Lower Elwa Indian Reservation
Makah Indian Reservation
Ozette Indian Reservation
Quileute Indian Reservation
Clallam County (remainder)
Hoh Indian Reservation
Port Townsend
Jefferson County (remainder)
Quinault Indian Reservation
Ocean Shores
Hoquiam
Aberdeen
Cosmopolis
Montesano
Westport
Grays Harbor County (remainder)
Shoalwater Indian Reservation
Raymond
South Bend
Long Beach
Ilwaco
Pacific County (remainder)
3rd Quartile (3%)

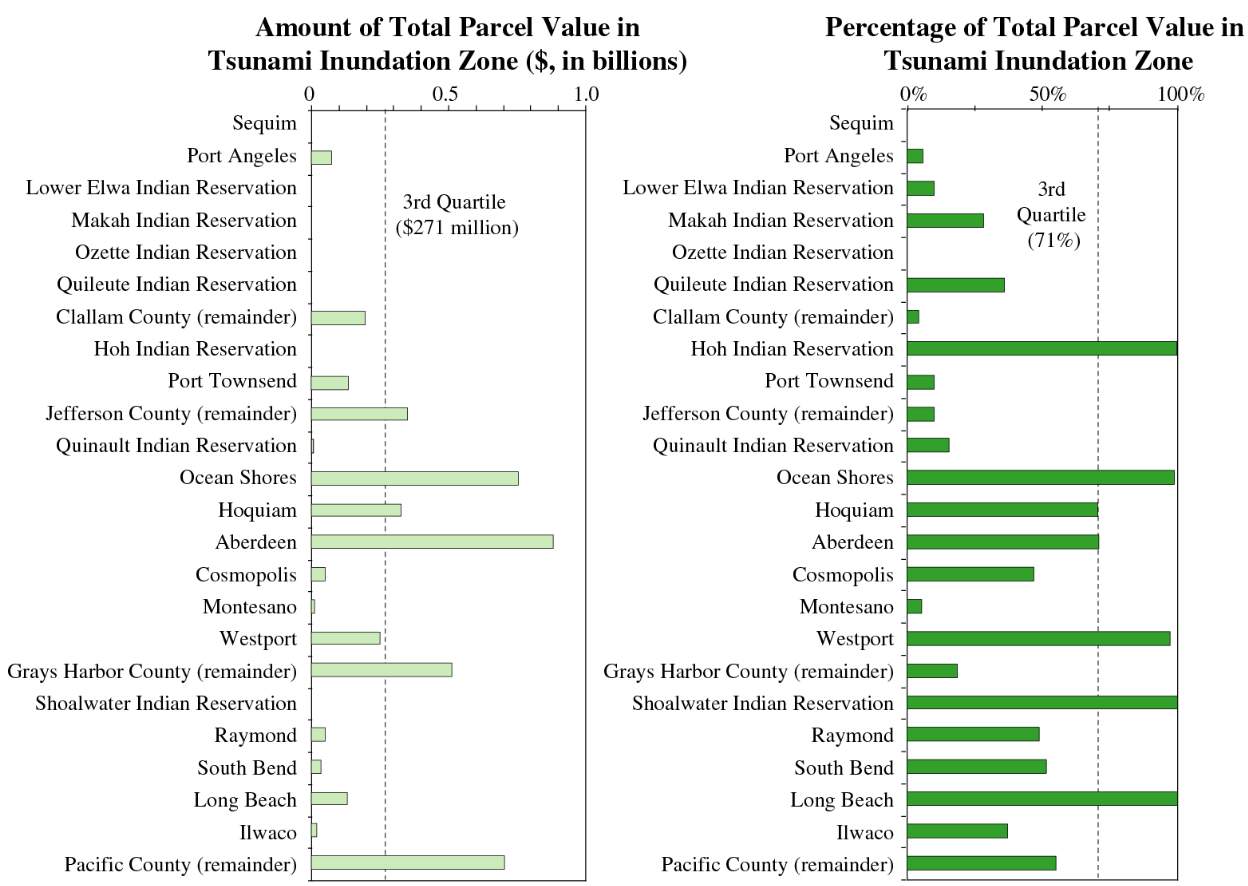
The tsunami-hazard zone of the four counties bordering the Pacific Ocean also contains several public venues that likely attract high numbers of local populations (Wood and Soulard, 2008). The highest number of public venues in the tsunami-inundation zone are in the unincorporated areas of Pacific County (16 facilities) and the majority of them are religious facilities (for example, churches). The next highest numbers of public venues in the tsunami-inundation zone are in the coastal communities of Grays Harbor County (for example, Aberdeen, Ocean Shores, Hoquiam, and Westport).

This tsunami-hazard zone also contains several dependent-population facilities that house individuals that would require evacuation assistance in the event of a tsunami warning (Wood and Soulard, 2008). Many of these facilities are in central-coast communities, specifically the cities of Aberdeen and Hoquiam





The tsunami-inundation zone of the four counties bordering the Pacific Ocean contains parcel values assessed at approximately $4.5 billion (2007 U.S. dollars), representing 25 percent of the total parcel values in the four coastal counties (Wood and Soulard, 2008). The highest total exposed tax parcel values for the 20 communities are in Aberdeen ($887 million) and Ocean Shores ($759 million), representing 71 percent and 99 percent, respectively, of the total tax base in the communities. The third highest total parcel values is in the unincorporated portion of Pacific County, primarily reflecting the unincorporated town of Ocean Park. Although many communities have relatively low amounts of total parcel value in the tsunami-inundation zones, the exposed parcels represent a high percentage of a community's total assets. Building damages due to CSZ-related tsunamis, as well as from the preceding earthquake, could significantly lower the content value of individual properties, thereby lowering the tax base of a community after a tsunami disaster, and reducing the funds available for long-term recovery.



A Cascadia tsunami would overtop several at-risk coastal communities including Bay Center, Long Beach, Ocean Park, Ocean Shores, Raymond, and Westport. Many of these communities are popular with tourists year-round.

At-risk tribal communities include the Makah, Hoh, Quinault, Shoalwater, Quileute, and Lower Elwha Indian nations, each with small reservations in low-lying coastal areas. Most coastal Tribes need assistance as they have little to no infrastructure to support emergency planning and response.

The first tsunami wave will arrive in at-risk communities on the outer coast 30 to 60 minutes after a great Cascadia earthquake, and about 90 minutes later in at-risk communities along the Strait of Juan de Fuca. Significant flooding is expected before the first wave because the earthquake will lower the elevation of the coast about five feet.[50] Maximum flood depth and extent of flooding will depend on tide height at the time of tsunami arrival.

Table 4. Projected Cascadia Tsunami Wave Heights For At-Risk Coastal Communities

Ocean Park	29 Feet
Sunset Beach	20 Feet
Grayland	19 Feet
Long Beach	18 Feet
Westport, Ocean Shores	15 Feet
Quileute	13 Feet
Port Angeles	11 Feet
Neah Bay	10 Feet
Port Townsend	10 Feet
Aberdeen, Hoquiam	4 Feet

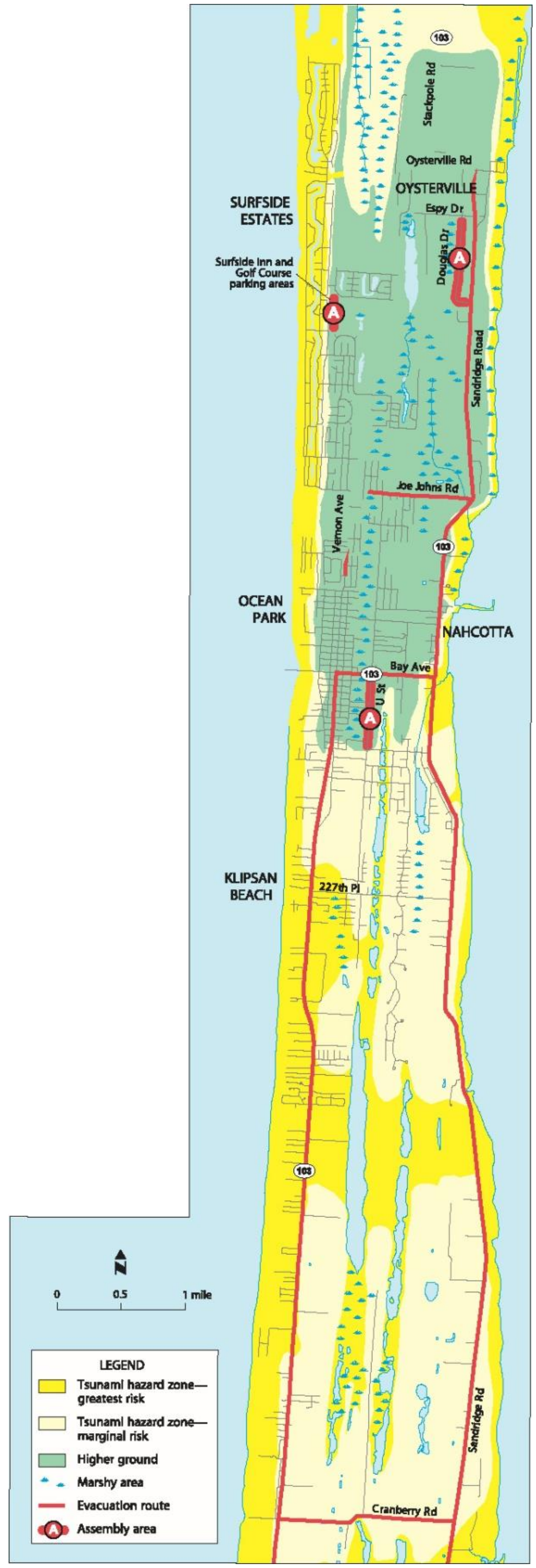
Note: Tsunami wave height may be larger depending upon local tide conditions. [44, 45, 46, 47, 48, 49]

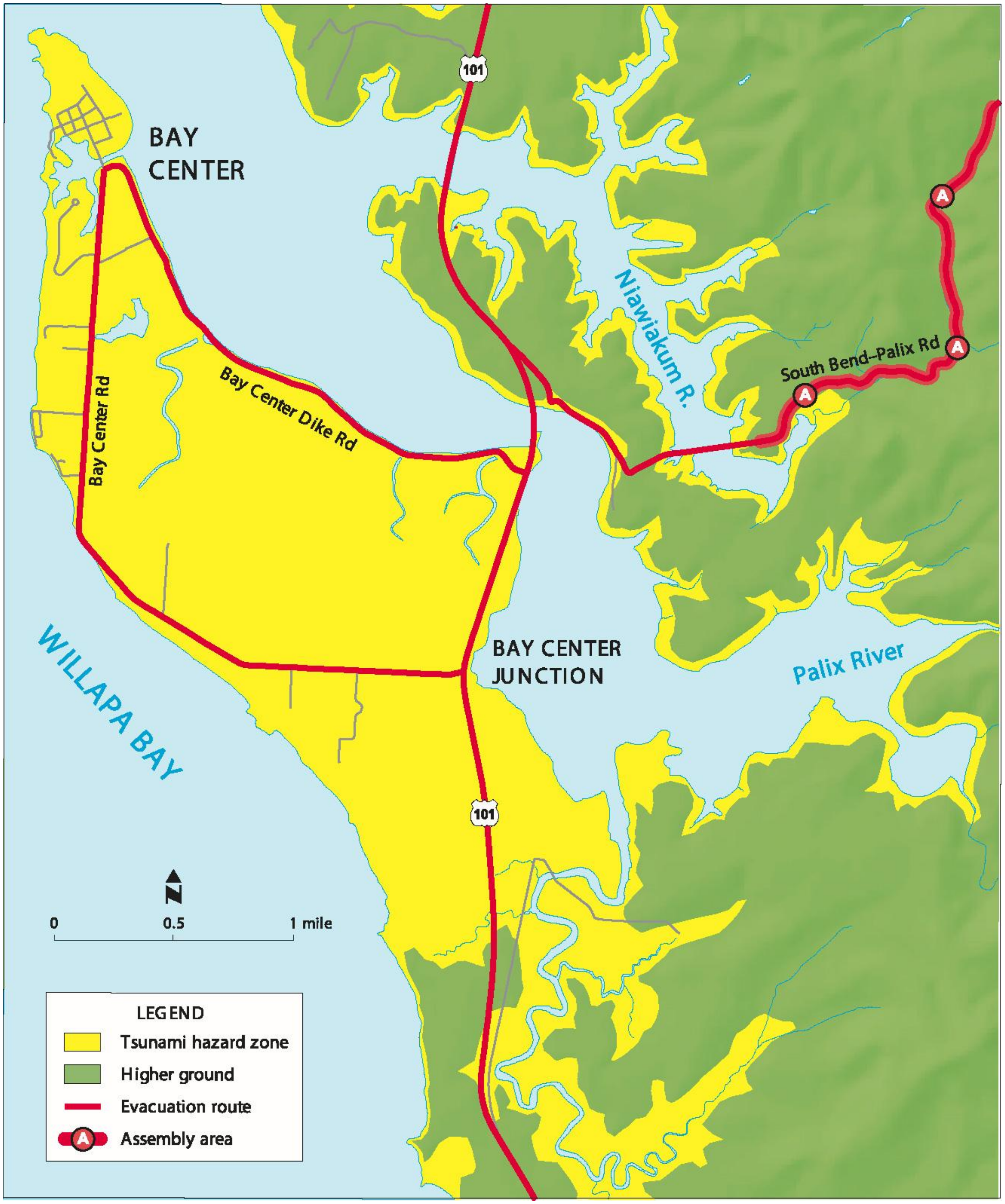
Pacific County – Estimated at-risk residential population: 10,595 (50% of total)
– Estimated at-risk employee population: 5,096 (57% of total)

Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Shoalwater Indian Reservation	59	85%	138	100%
Raymond	1,098	37%	1,417	94%
South Bend	900	50%	630	44%
Long Beach	1,281	100%	1,259	100%
Ilwaco	433	46%	503	72%
Pacific County (remainder)	6,823	49%	1,149	36%

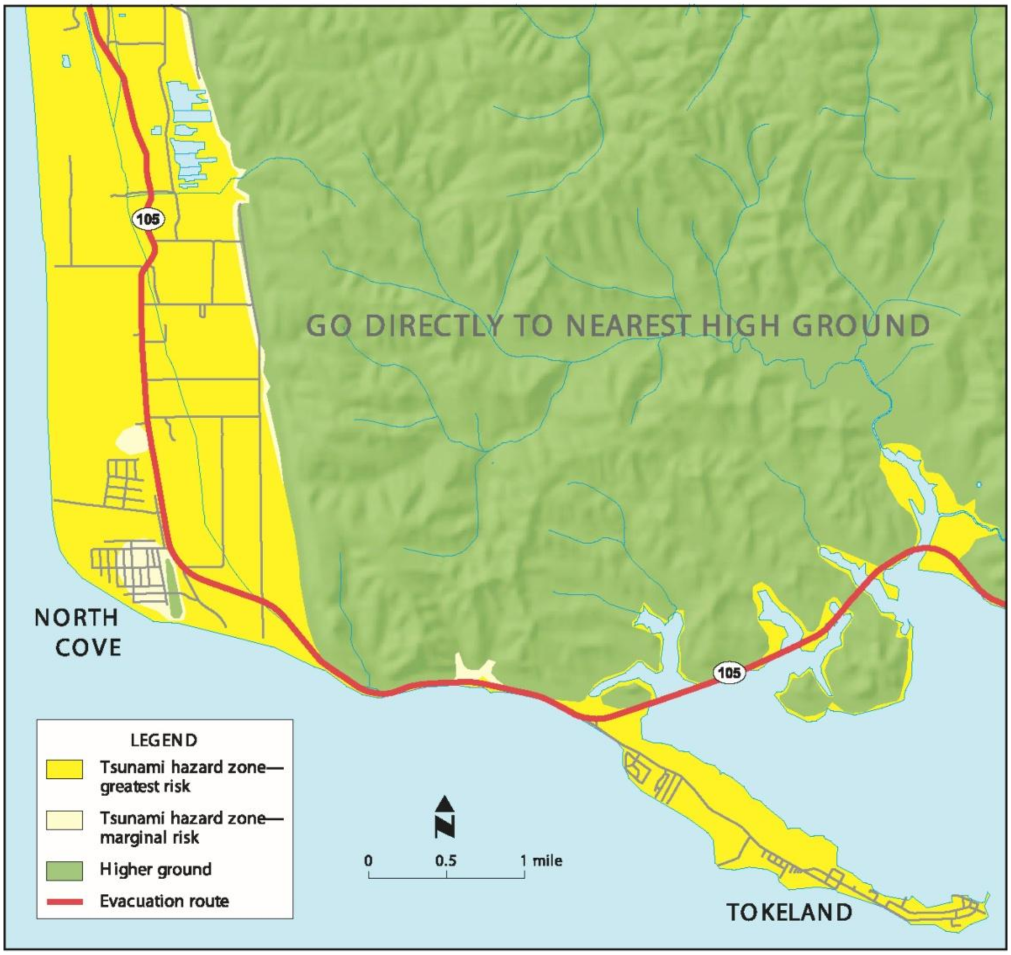
Communities with population at risk: Bay Center, Ilwaco, Long Beach, Ocean Park, Raymond, South Bend, Tokeland.

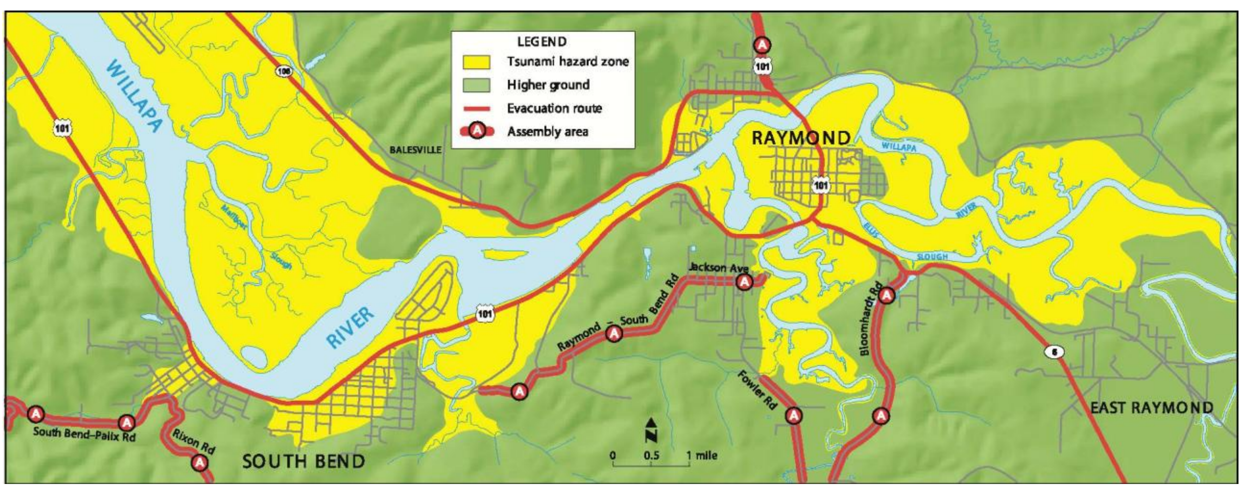

Cranberry Road
PACIFIC PARK
LONG BEACH
SEAVIEW
Sandridge Road
67th Place
School Hill
Loop 100
ILWACO
LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Evacuation route
Assembly area
0
0.5
1 mile


Stackpole Rd
Oysterville Rd
OYSTERVILLE
Espy Dr
Douglas Dr
SURFSIDE ESTATES
Surfside Inn and Golf Course parking areas
Sandridge Road
Joe Johns Rd
Vernon Ave
OCEAN PARK
NAHCOTTA
Bay Ave
U St
KLIPSAN BEACH
227th Pl
Sandridge Rd
Cranberry Rd
0
0.5
1 mile
LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Marshy area
Evacuation route
Assembly area



BAY CENTER
101
Niawiakum R.
South Bend–Palix Rd
Bay Center Rd
Bay Center Dike Rd
BAY CENTER JUNCTION
Palix River
WILLAPA BAY
101
0
0.5
1 mile
LEGEND
Tsunami hazard zone
Higher ground
Evacuation route
Assembly area

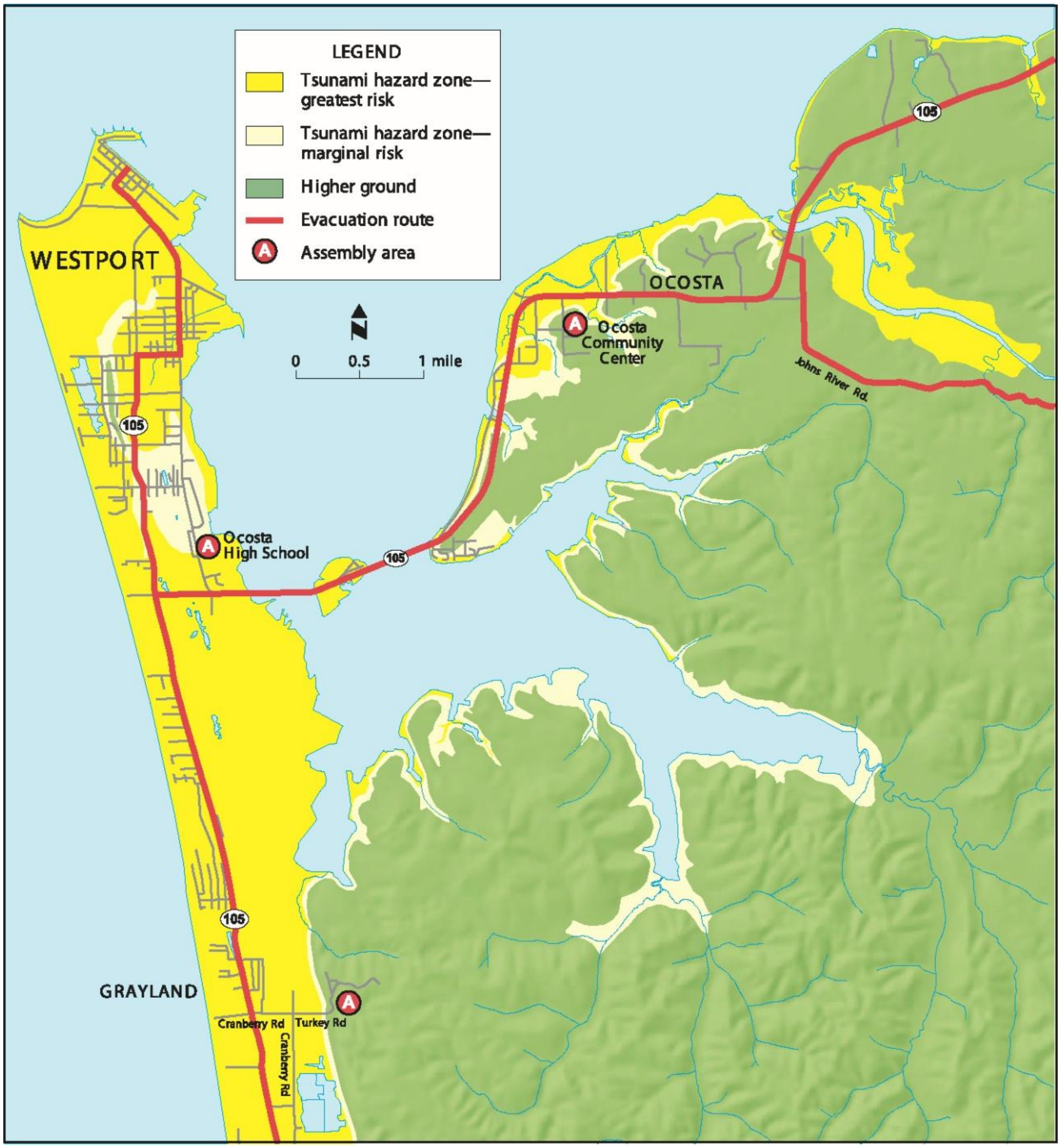

GO DIRECTLY TO NEAREST HIGH GROUND
NORTH COVE
TOKELAND
105
LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Evacuation route
0
0.5
1 mile


LEGEND
Tsunami hazard zone
Higher ground
Evacuation route
Assembly area
WILLAPA
RIVER
BALESVILLE
RAYMOND
SOUTH BEND
EAST RAYMOND
101
105
6
Jackson Ave
Raymond – South Bend Rd
Fowler Rd
Bloomhardt Rd
South Bend–Palix Rd
Rixon Rd
0
0.5
1 mile

Grays Harbor County – Estimated at-risk population: 28,447 (42% of total)
– Estimated at-risk employee population: 15,816 (62% of total)

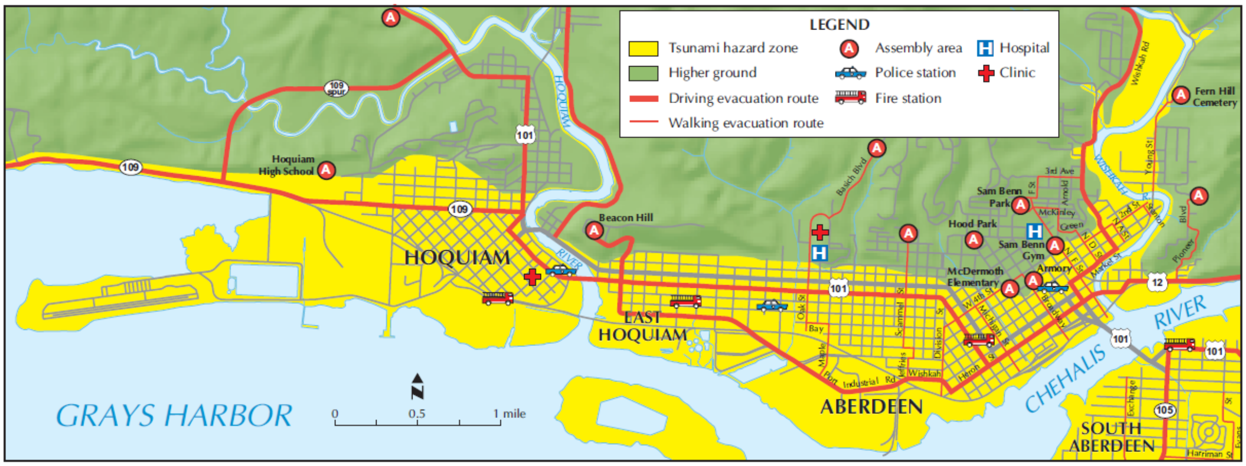
Communities with population at risk: Aberdeen, Cohassett Beach, Copalis Beach, Grayland, Hoquiam, Markham, Moclips, Ocean City, Ocean Shores, Oyhut-Hogans Corner, Taholah, Westport.

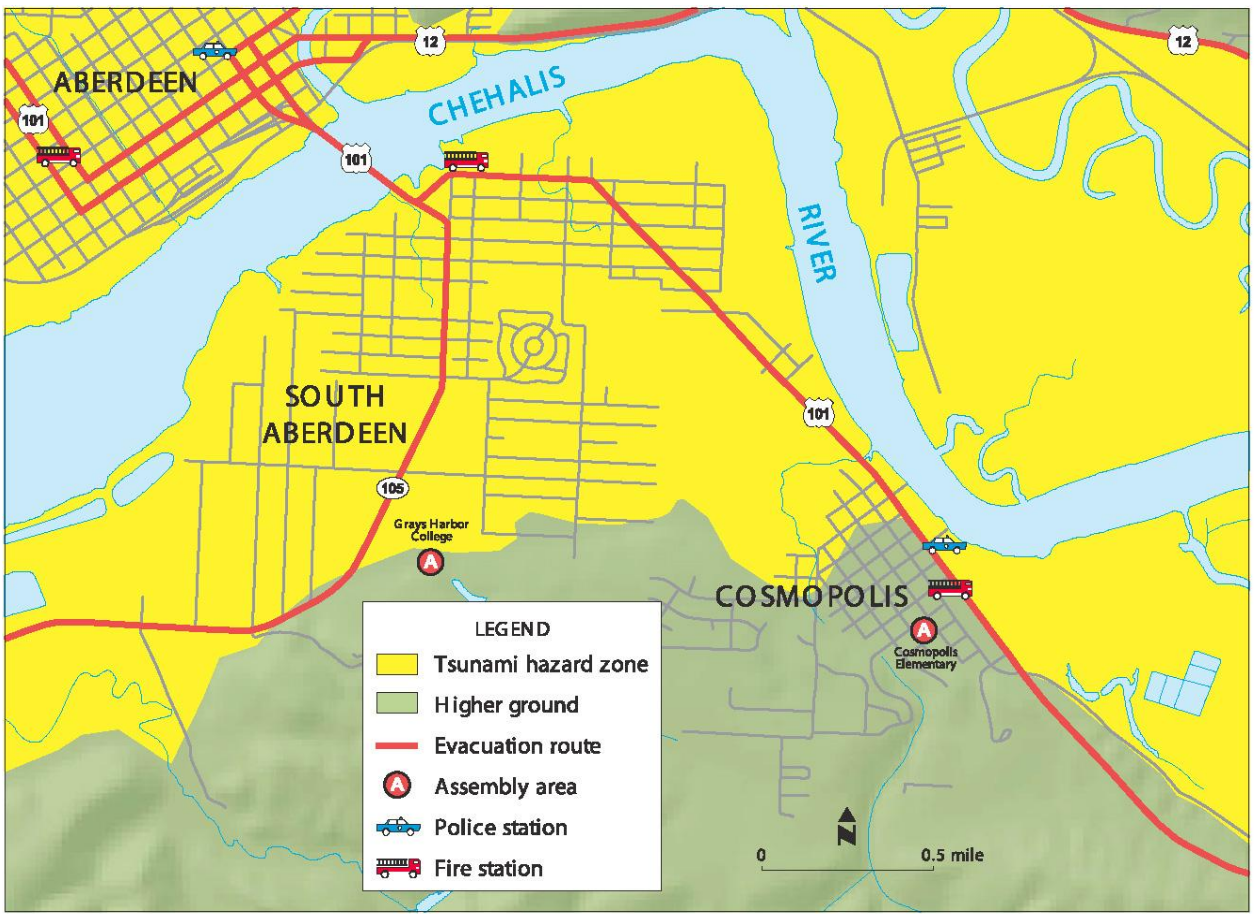
Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Quinault Indian Reservation	572	42%	449	65%
Ocean Shores	3,733	97%	1,603	98%
Hoquiam	5,756	63%	2,792	86%
Aberdeen	11,781	72%	7,488	81%
Cosmopolis	768	48%	229	88%
Montesano	28	1%	178	10%
Westport	1,900	89%	1,619	99%
Grays Harbor County (remainder)	3,957	13%	1,458	21%


LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Evacuation route
Assembly area
0
0.5
1 mile
WESTPORT
OCOSTA
Ocosta Community Center
Ocosta High School
Johns River Rd.
105
GRAYLAND
Cranberry Rd
Turkey Rd
Cranberry Rd


Saddle Mountain Housing Development
109
115
OYHUT
OCEAN SHORES
LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Evacuation route
Assembly area
Police station
Fire station
0
0.5
1 mile


LEGEND
Tsunami hazard zone—greatest risk
Tsunami hazard zone—marginal risk
Higher ground
Evacuation route
Assembly area
Fire station
Clinic
Pacific Beach Naval Facility
PACIFIC BEACH
Ocean Beach Rd
109
COPALIS BEACH
Copalis Beach Rd
COPALIS STATION
OCEAN CITY
North Beach School District
Saddle Mountain Housing Development
115


LEGEND
Tsunami hazard zone
Higher ground
Driving evacuation route
Walking evacuation route
Assembly area
Police station
Fire station
Hospital
Clinic
GRAYS HARBOR
0
0.5
1 mile
HOQUIAM
EAST HOQUIAM
ABERDEEN
SOUTH ABERDEEN
CHEHALIS RIVER
HOQUIAM RIVER
WISHKAH R.
Hoquiam High School
Beacon Hill
Hood Park
Sam Benn Park
Sam Benn Gym
Armory
McDermoth Elementary
Fern Hill Cemetery
109
109 spur
101
12
105


ABERDEEN
CHEHALIS
RIVER
SOUTH ABERDEEN
COSMOPOLIS
Grays Harbor College
Cosmopolis Elementary
12
101
105
LEGEND
Tsunami hazard zone
Higher ground
Evacuation route
Assembly area
Police station
Fire station
0
0.5 mile

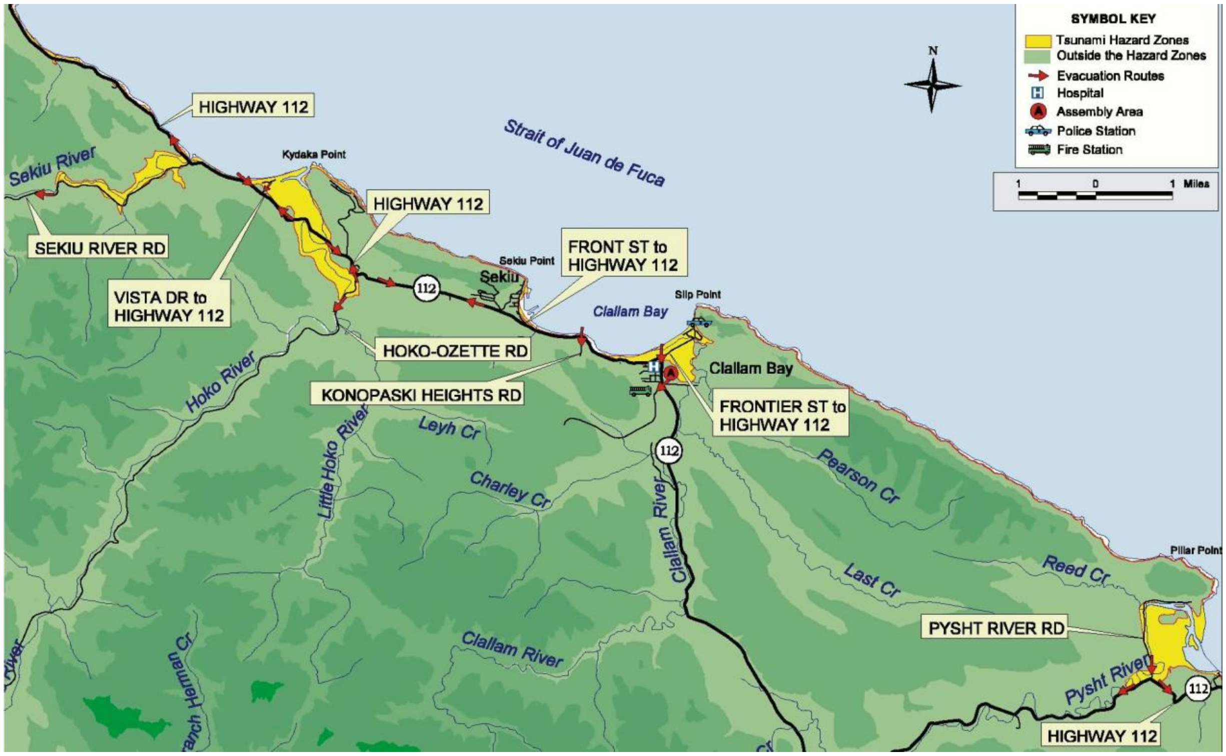
<u>Clallam County</u> – Estimated at-risk residential population: 2,239 (3% of total)
– Estimated at-risk employee population: 1,550 (5% of total)

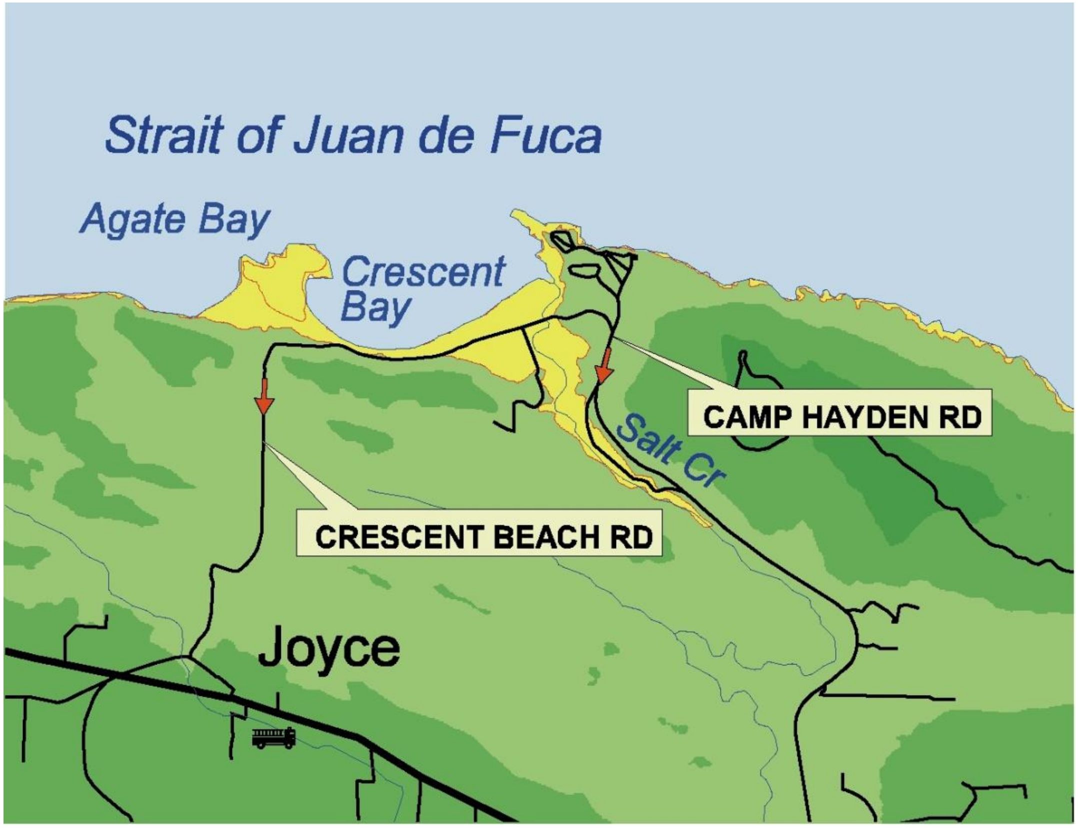
Communities with population at risk: Clallam Bay, La Push, Neah Bay, Port Angeles, Sequim

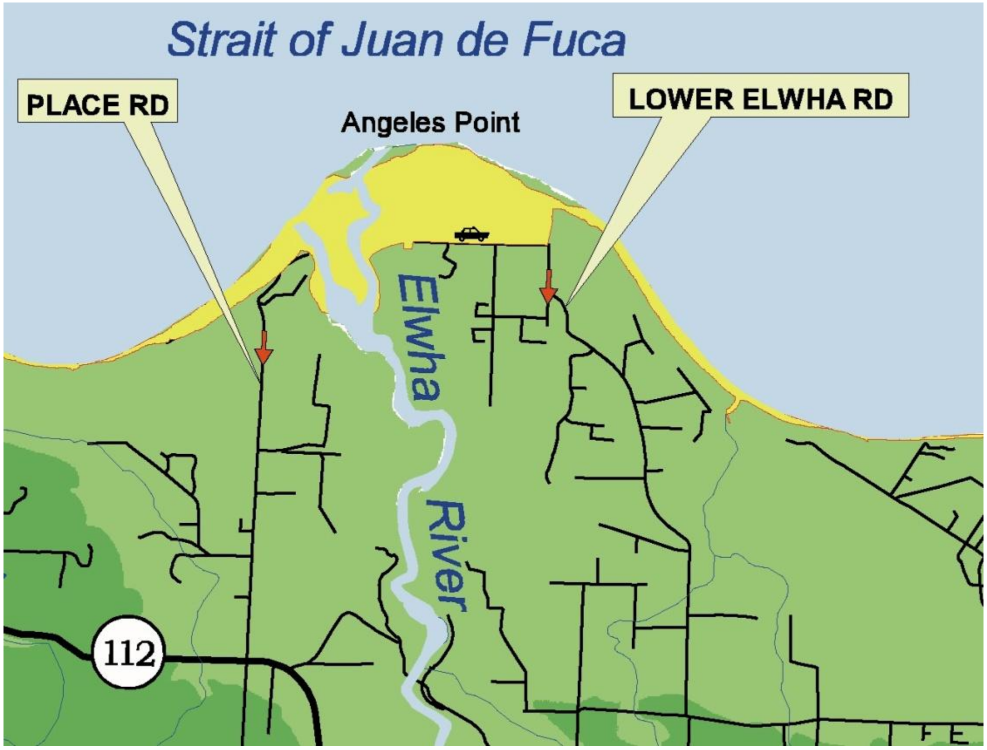
Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Sequim	0	0%	15	0%
Port Angeles	143	1%	849	6%
Lower Elwa Indian Reservation	80	25%	4	10%
Makah Indian Reservation	802	59%	434	55%
Quileute Indian Reservation	54	15%	138	65%
Clallam County (remainder)	1,159	3%	110	1%


Johnson Cr
Olympic
Ellen Cr
National
Park
River
Dickey
Pacific Ocean
Rialto
Beach
MORA RD
La Push
Quillayute River
Quileute
Reservation
James Island
Olympic
National
Park
Quateata
OCEAN DR
LA PUSH RD
SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Community Center
Assembly Area
Medical Clinic
Police Station
Fire Station
0
0.5
1 Miles

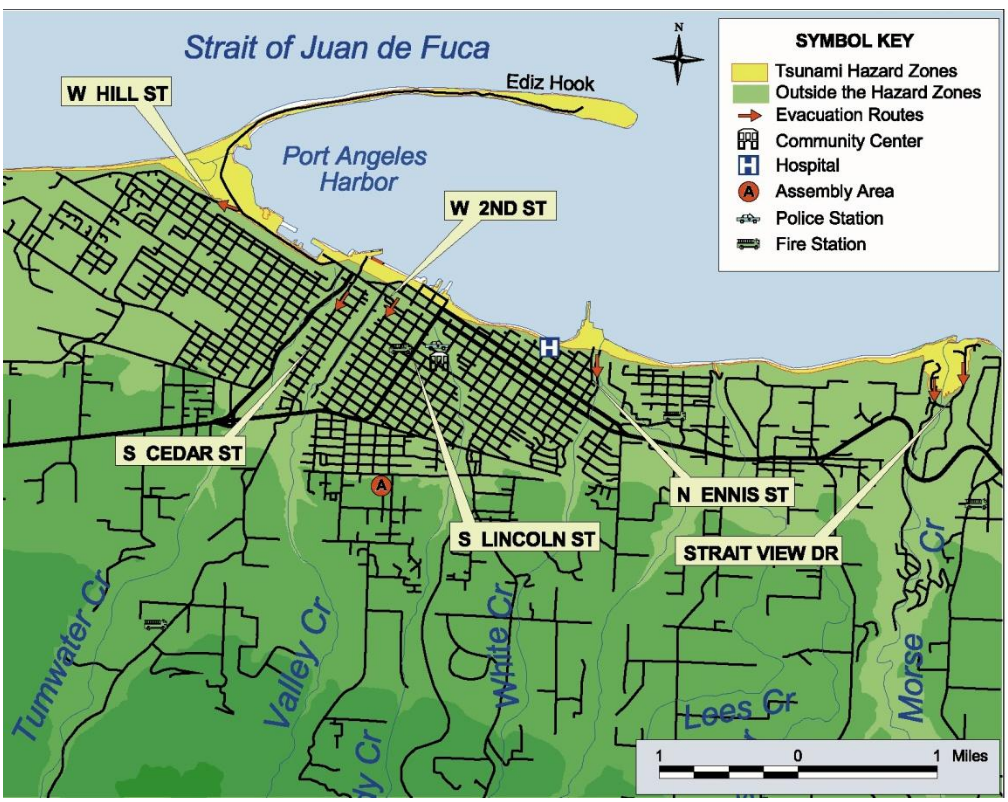
Tatoosh Island
Strait of Juan de Fuca
N
Koitlah Point
Waadah Island
Neah Bay
BAY VIEW AVE
3rd AVE to KOITLAH POINT RD
CAPE FLATTERY RD
BAHOKUS PEAK RD.
200 LINE RD
QUARRY RD.
Waatch
Waatch Point
Makah
WAATCH PEAK RD.
Sail River
Pacific Ocean
Bohobohosh Point
River
Reservation
Makah Bay
200 LINE LOOP
Anderson Point
Portage Head
Gate
HATCHERY RD
SPUR-7
Sooes River
SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Community Center
Medical Clinic
Police Station
Fire Station
1 0 1 Miles


SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Hospital
Assembly Area
Police Station
Fire Station
1 0 1 Miles
N
Strait of Juan de Fuca
HIGHWAY 112
Sekiu River
Kydaka Point
SEKIU RIVER RD
VISTA DR to HIGHWAY 112
FRONT ST to HIGHWAY 112
Sekiu Point
Sekiu
Slip Point
Clallam Bay
HOKO-OZETTE RD
KONOPASKI HEIGHTS RD
Hoko River
Little Hoko River
Leyh Cr
Charley Cr
FRONTIER ST to HIGHWAY 112
Pearson Cr
Clallam River
Last Cr
Reed Cr
Pillar Point
PYSHT RIVER RD
Pysht River
Herman Cr

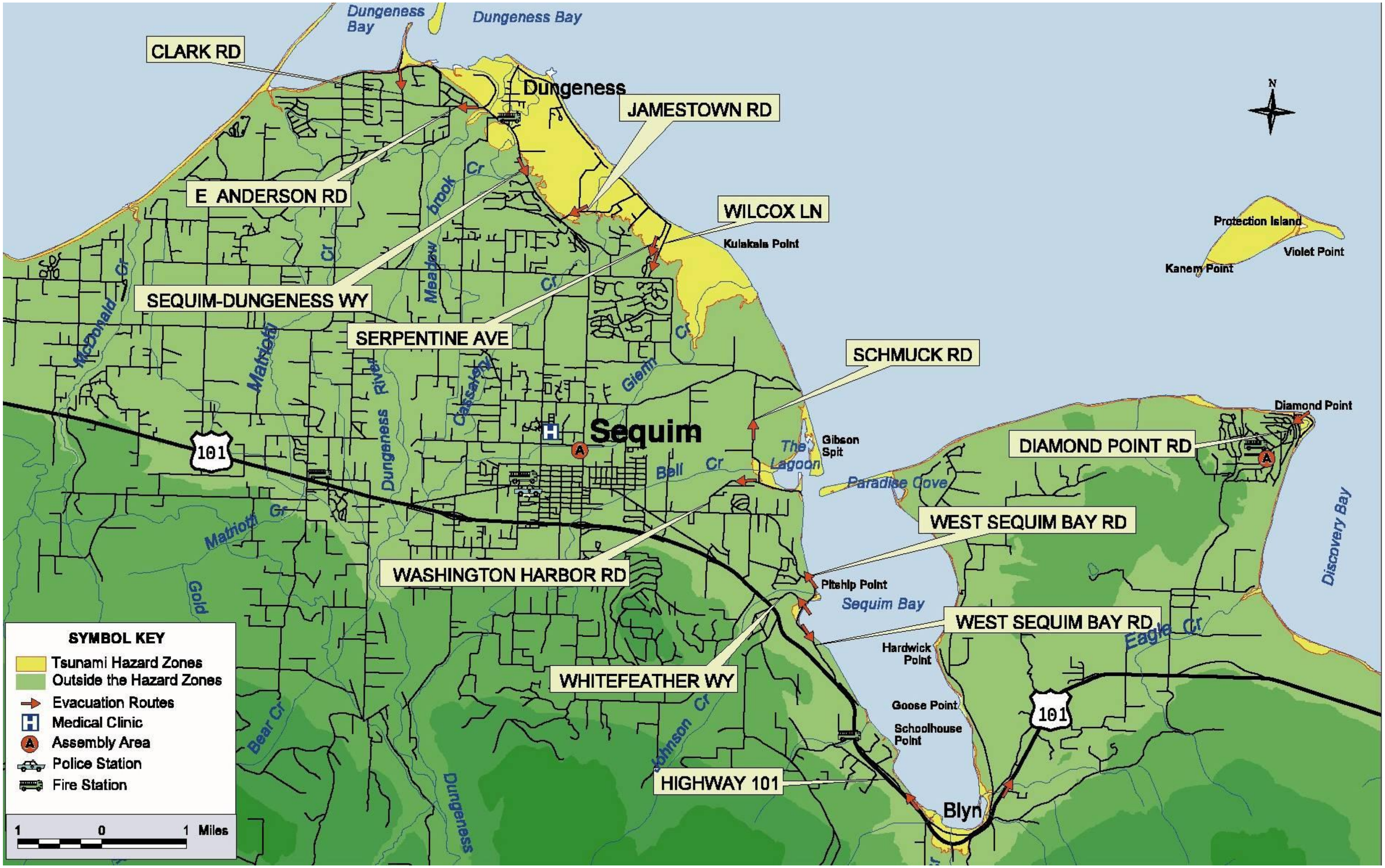

Strait of Juan de Fuca
Agate Bay
Crescent Bay
CAMP HAYDEN RD
Salt Cr
CRESCENT BEACH RD
Joyce



Strait of Juan de Fuca
PLACE RD
LOWER ELWHA RD
Angeles Point
Elwha River
112



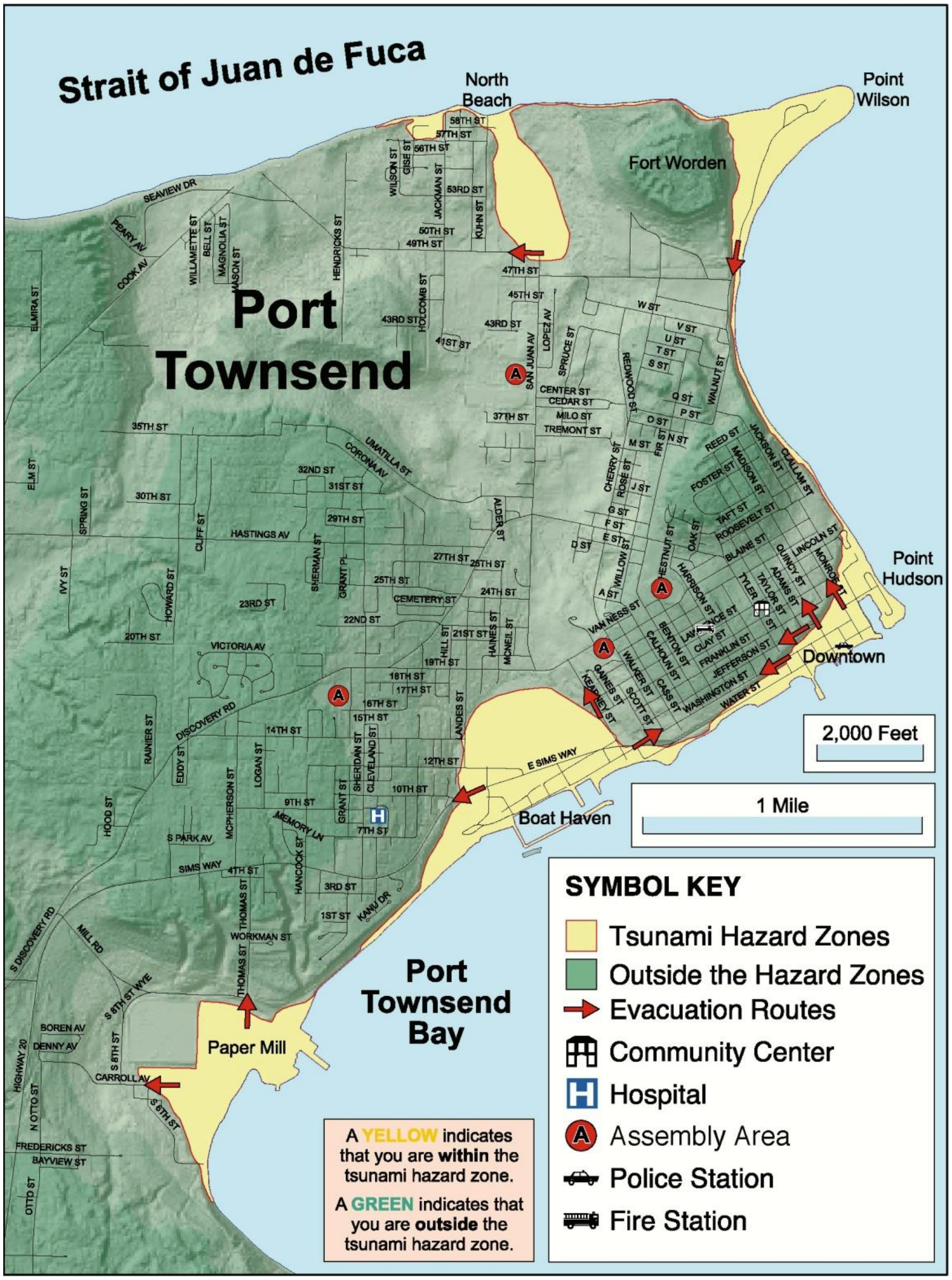
Strait of Juan de Fuca
Ediz Hook
W HILL ST
Port Angeles Harbor
W 2ND ST
SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Community Center
Hospital
Assembly Area
Police Station
Fire Station
S CEDAR ST
N ENNIS ST
S LINCOLN ST
STRAIT VIEW DR
Tumwater Cr
Valley Cr
White Cr
Lees Cr
Morse Cr
1 0 1 Miles


Dungeness Bay
Dungeness Bay
CLARK RD
Dungeness
JAMESTOWN RD
E ANDERSON RD
WILCOX LN
Kulakala Point
Protection Island
Violet Point
Kanem Point
SEQUIM-DUNGENESS WY
SERPENTINE AVE
SCHMUCK RD
Sequim
101
The Lagoon
Gibson Spit
Paradise Cove
Diamond Point
DIAMOND POINT RD
WEST SEQUIM BAY RD
Discovery Bay
WASHINGTON HARBOR RD
Pitship Point
Sequim Bay
WEST SEQUIM BAY RD
Hardwick Point
WHITEFEATHER WY
Goose Point
Schoolhouse Point
101
HIGHWAY 101
Blyn
SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Medical Clinic
Assembly Area
Police Station
Fire Station
1 0 1 Miles

Jefferson County – Estimated at-risk residential population: 1,692 (7% of total)
– Estimated at-risk employee population: 2,472 (23% of total)

Communities with population at risk: Marrowstone Island, Port Hadlock-Irondale, and Port Townsend.

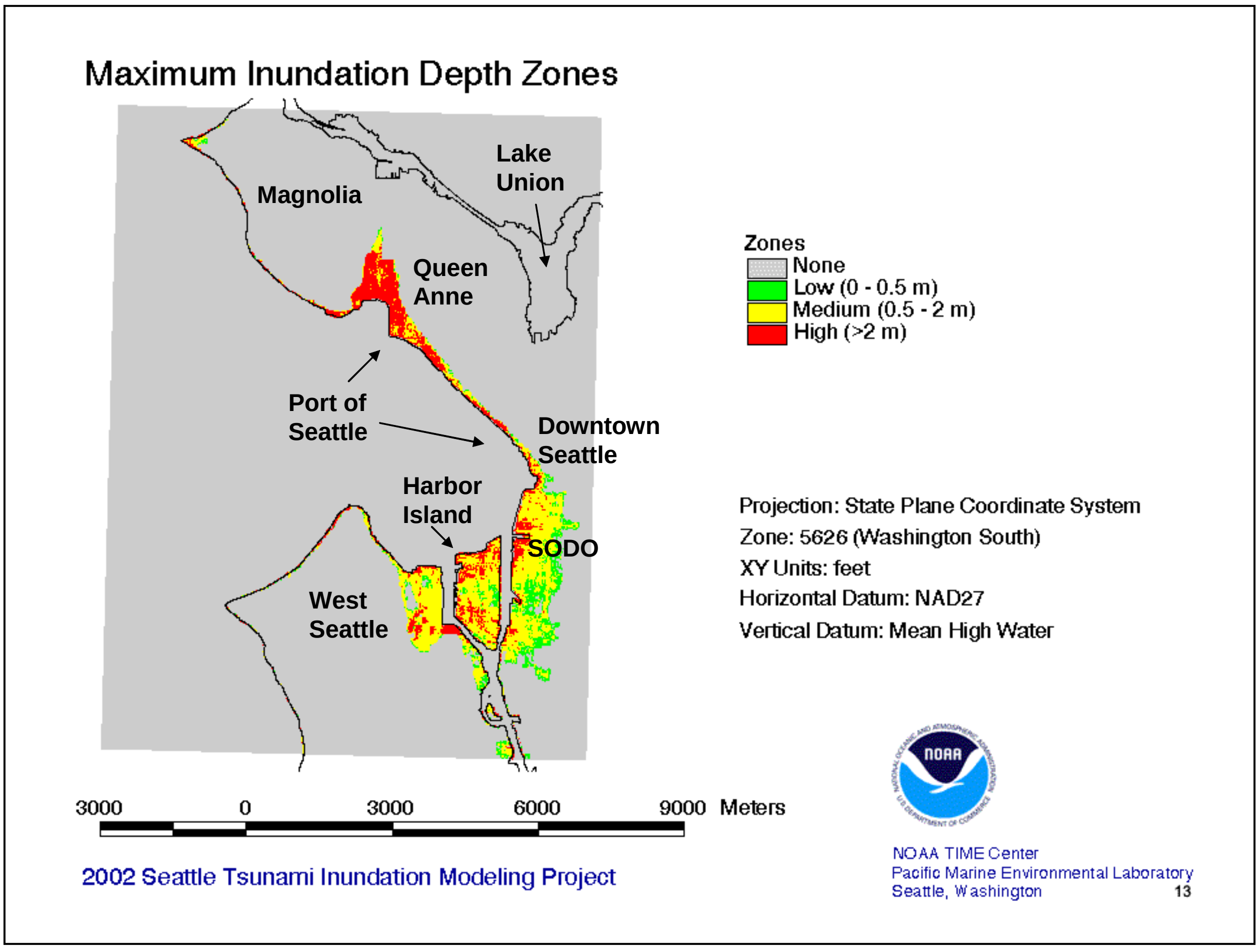
Incorporated City or Tribal Community	Number of Residents in Tsunami-Hazard Zone	Percentage of Community Residents	Number of Employees in Tsunami-Hazard Zone	Percentage of Community Employees
Hoh Indian Reservation	62	61%	0	0%
Port Townsend	424	5%	2,228	33%
Jefferson County (remainder)	1,157	7%	244	6%


Strait of Juan de Fuca
North Beach
Point Wilson
Fort Worden
Port Townsend
Point Hudson
Downtown
Boat Haven
Port Townsend Bay
Paper Mill
2,000 Feet
1 Mile
SYMBOL KEY
Tsunami Hazard Zones
Outside the Hazard Zones
Evacuation Routes
Community Center
Hospital
Assembly Area
Police Station
Fire Station
A YELLOW indicates that you are within the tsunami hazard zone.
A GREEN indicates that you are outside the tsunami hazard zone.

Seattle[51, 52]

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for Elliott Bay in Seattle using as an initiating event a magnitude 7.3 earthquake on the Seattle Fault, which roughly parallels Interstate 90 through Seattle. The area modeled includes the portions of Seattle highlighted on the map below. The projected at-risk population of this area is 42,466.

The tsunami is projected to hit the shoreline within two-and-a-half minutes of the earthquake and reach heights of up to 20 feet.



Eastern Strait of Juan de Fuca[53]

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for communities at the east end of the Strait of Juan de Fuca. The model uses an initiating event of a magnitude 9.1 earthquake on the Cascadia Subduction Zone off the Pacific Coast. The area modeled includes the highlighted areas on the maps below of the areas in Island, Skagit and Whatcom Counties.

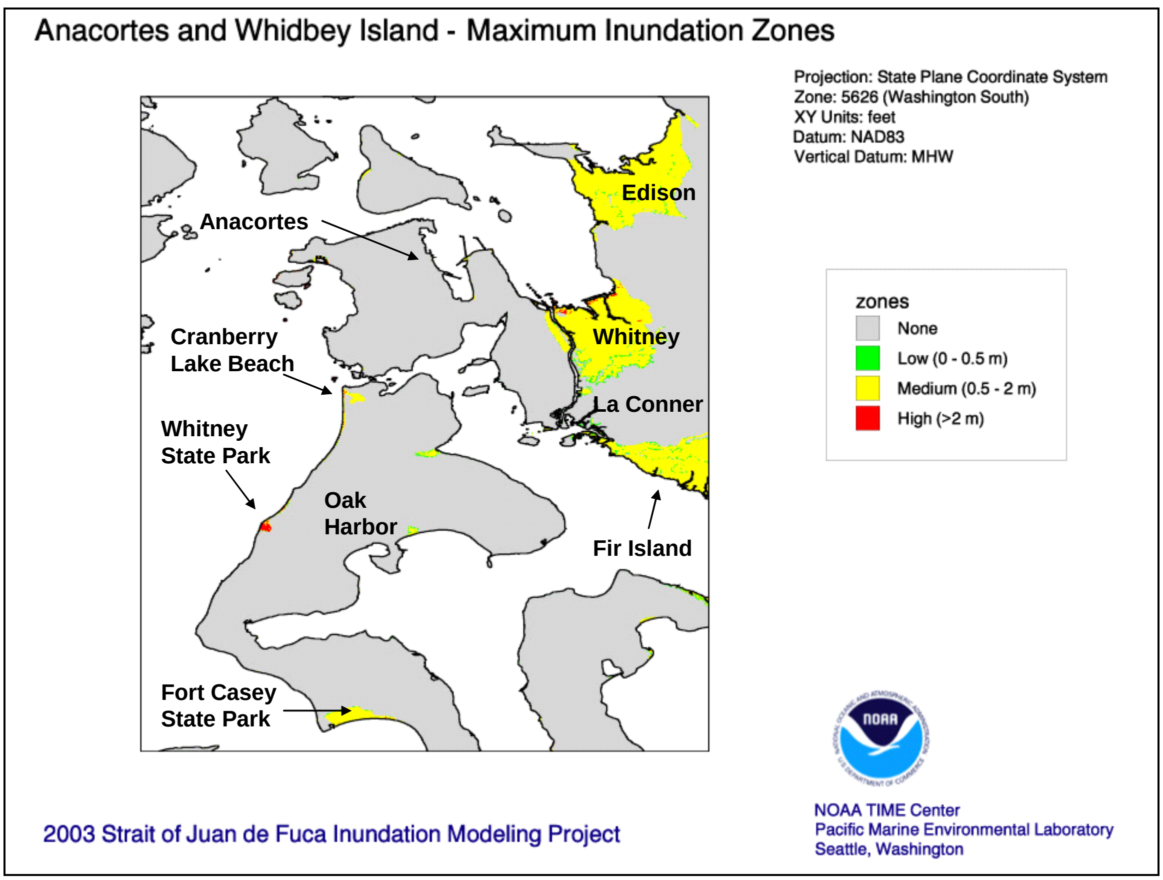
In the model's simulation, the first tsunami wave would hit the area two hours after the Cascadia Subduction Zone earthquake. Maximum tsunami wave heights are projected to reach 11 feet in the Nooksack River delta near Bellingham, 8 feet at Whitney State Park on Whidbey Island, and 6.5 feet in the Anacortes area.

Skagit County – Projected at-risk population: 29,991.

Communities with population at risk: Edison, LaConnor, Fir Island, Whitney.

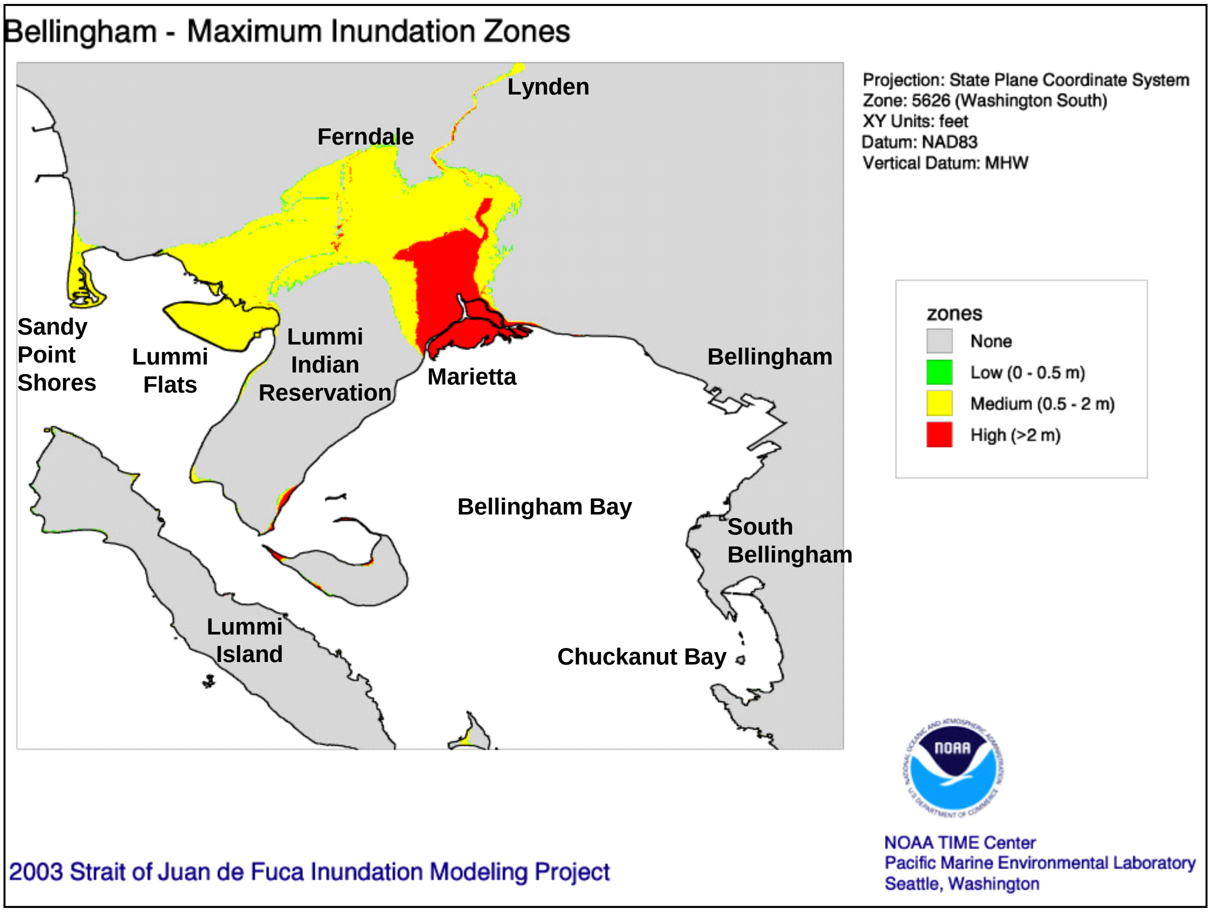
Island County – Projected at-risk population: 6,988.

Communities with population at risk: Oak Harbor, Cranberry Lake Beach, Fort Casey State Park, Whitney State Park.



Whatcom County – Projected at-risk population: 32,845.

Communities with population at risk: Ferndale, Lynden, Marietta, Lummi Indian Reservation, Lummi Flats, Sandy Point.



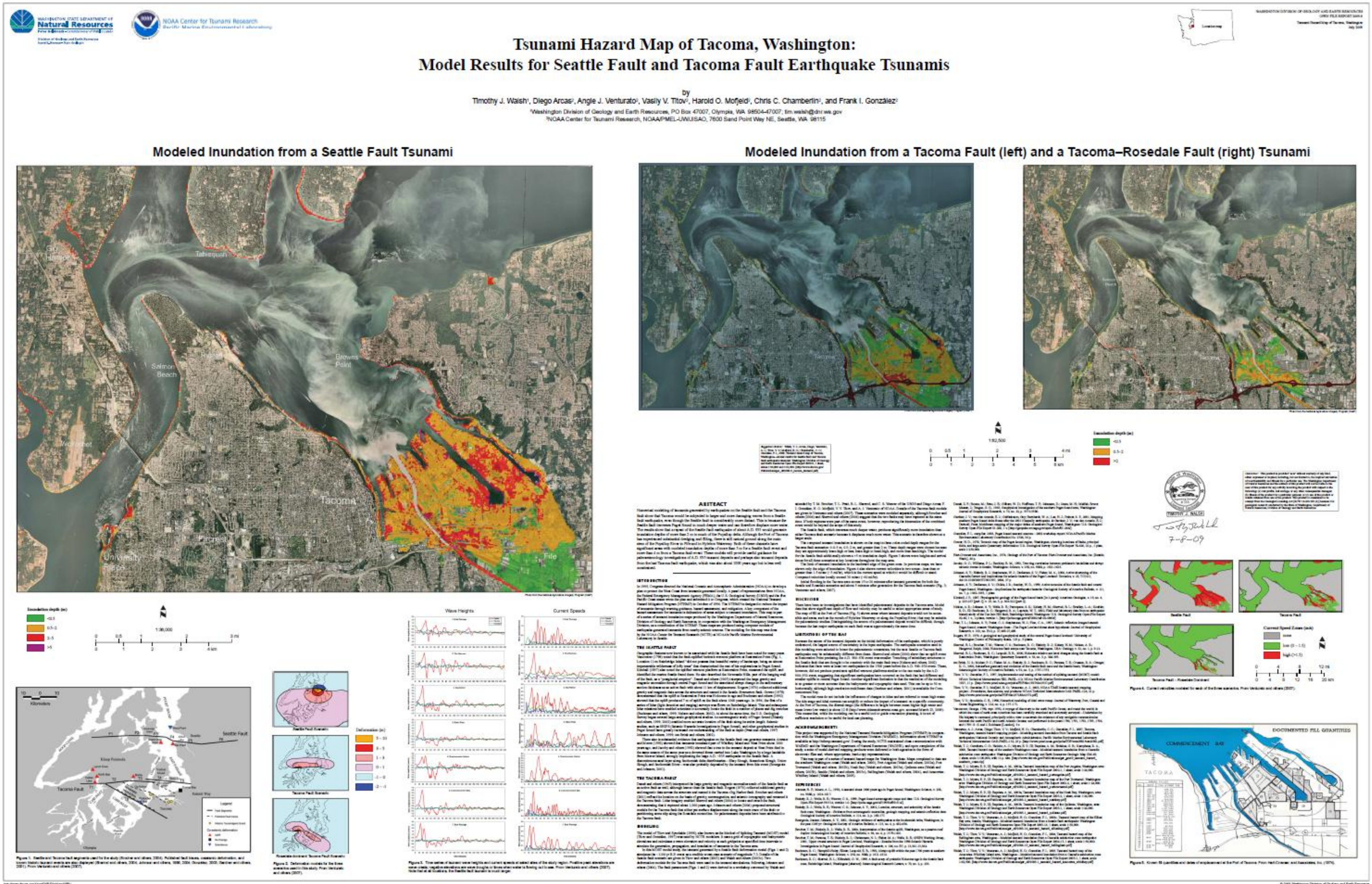
Tacoma[54]

The National Tsunami Hazard Mitigation Program's Center for Tsunami Inundation Mapping Efforts has developed a tsunami inundation model for Tacoma using as an initiating event a magnitude 7.3 earthquake on the Seattle Fault, and two earthquakes on the Tacoma Fault. The area modeled includes the portions of the Tacoma area highlighted on the map below.

A tsunami from a Seattle Fault earthquake is projected to hit shorelines in Tacoma and Gig Harbor within 20 minutes of the earthquake and reach heights of up to 12 feet. A tsunami generated by a Tacoma Fault earthquake is projected to hit shorelines in Tacoma and Gig Harbor within 10 minutes of the earthquake and reach heights of up to 4 feet.

The projected at-risk population of this area is 55,900.

Communities potentially at risk: Gig Harbor, Tacoma, University Place.


Tsunami Hazard Map of Tacoma, Washington:
Model Results for Seattle Fault and Tacoma Fault Earthquake Tsunamis
by
Timothy J. Walsh, Diego Arcas, Angie J. Venturato, Vasily V. Titov, Harold O. Mofjeld, Chris C. Chamberlin, and Frank I. González
Modeled Inundation from a Seattle Fault Tsunami
Modeled Inundation from a Tacoma Fault (left) and a Tacoma–Rosedale Fault (right) Tsunami
Tahlequah
Salmon Beach
Browns Point
Tacoma
Fife
ABSTRACT
Wave Heights
Current Speeds
COMMENCEMENT BAY
DOCUMENTED FILL QUANTITIES

Puget Sound – Everett to Olympia[55]

Future projects planned by the Washington State Emergency Management's Earthquake, Tsunami and Volcano program and the Department of Natural Resources, Geology and Earth Sciences program through the National Tsunami Hazard Mitigation Program's National Center for Tsunami Research (formerly known as the Center for Tsunami Inundation Mapping Efforts) is to develop tsunami inundation models for the following census designated and incorporated places.

Snohomish County – Projected at-risk population within one kilometer of the coastline: 55,661.

Communities potentially at risk: Edmonds, Everett, Marysville, Mukilteo, Picnic Point-North Lynnwood, Shaker Church, Stanwood, Tulalip Bay, Warm Beach, Weallup Lake, Woodway.

Potential projects include the following areas:

King County (outside Seattle) – Projected at-risk population within one kilometer of the coastline: 45,996.

Communities potentially at risk: Burien, Des Moines, Federal Way, Normandy Park, Vashon.

Kitsap County – Projected at-risk population within one kilometer of the coastline: 61,731.

Communities potentially at risk: Bainbridge Island, Bremerton, Erlands Point, Manchester, Navy Yard City, Parkwood, Port Orchard, Poulsbo, Silverdale, Suquamish, and Tracyton.

Mason County – Projected at-risk population within one kilometer of the coastline: 1,994.

Community potentially at risk: Allyn-Grapeview.

Thurston County – Projected at-risk population within one kilometer of the coastline: 15,939.

Communities potentially at risk: Lacey, Olympia, and Tumwater.

Potential Climate Change Impacts[56,57,58,59]

With the advent of climate change coming into worldwide focus; it is necessary to take into account the potential effects this emerging climate crisis may have on the dangers associated with tsunamis. The research done so far indicates the potential for unusual or more frequent heavy rainfall and flooding is greater is some areas while the potential for drought is predicted in other areas. Landslide frequency is correlated with heavy rainfall and flooding events. Sea level rise may impact inundation areas.

According to a 2005 Governor's report prepared by the Climate Impacts Group titled *Uncertain Future: Climate Change and its Effects on Puget Sound*, from "paleoclimatological evidence, we know that over the history of the earth high levels of greenhouse gas concentrations have correlated with, and to a large extent caused, significant warming to occur, with impacts generated on a global scale." While the report also indicates that the "ultimate impact of climate change on any individual species or ecosystem cannot be predicted with precision," there is no doubt that Washington's climate has demonstrated change.

In July 2007, the Climate Impacts Group launched an unprecedented assessment of climate change impacts on Washington State. *The Washington Climate Change Impacts Assessment* (WACCIA) involved developing updated climate change scenarios for Washington State and using these scenarios to assess the impacts of climate change on the following sectors: agriculture, coasts, energy, forests, human health, hydrology and water resources, salmon, and urban stormwater infrastructure. The assessment was funded by the Washington State Legislature through House Bill 1303.

In 2009, the Washington State Legislature approved the *State Agency Climate Leadership Act* Senate Bill 5560. The Act committed state agencies to lead by example in reducing their greenhouse gas (GHG) emissions to: 15 percent below 2005 levels by 2020; 36 percent below 2005 by 2035; and 57.5 percent below 2005 levels (or 70 percent below the expected state government emissions that year, whichever amount is greater.). The Act, codified in RCW 70.235.050-070, directed agencies to annually measure their greenhouse gas emissions, estimate future emissions, track actions taken to reduce emissions, and develop a strategy to meet the reduction targets. Starting in 2012 and every two years thereafter, each state agency is required to report to Washington State Department of Ecology the actions taken to meet the emission reduction targets under the strategy for the preceding biennium.

Recognizing Washington's vulnerability to climate impacts, the Legislature and Governor Chris Gregoire directed state agencies in 2009 to develop an integrated climate change response strategy to help state, tribal and local governments, public and private organizations, businesses and individuals prepare. The state Departments of Agriculture, Commerce, Ecology, Fish and Wildlife, Health, Natural Resources and Transportation worked with a broad range of interested parties to develop recommendations that form the basis for a report by the Department of Ecology: *Preparing for a Changing Climate: Washington State's Integrated Climate Change Response Strategy*.

Over the next 50 - 100 years, the potential exists for significant climate change impacts on Washington's coastal communities, forests, fisheries, agriculture, human health, and natural disasters. These impacts could potentially include increased annual temperatures, rising sea level, increased sea surface temperatures, more intense storms, and changes in precipitation patterns. Therefore, climate change has the potential to impact the occurrence and intensity of natural disasters, potentially leading to additional loss of life and significant economic losses.

Recognizing the global, regional, and local implications of climate change, Washington State has shown great leadership in addressing mitigation through the reduction of greenhouse gases.

At-Risk State Facilities

State Agency facilities identified as being at-risk to tsunami (see table, page 30) were determined using geo-spatial software to match their location to the tsunami inundation zones represented on maps on the previous pages.

State Agency Structures At Risk **VULNERABILITY ASSESSMENT**

Tsunami:

	# of Facilities	Total Original Cost	Avg. Original Cost	Total Square Feet	Average Sq. Ft.
Owned:	87	$3,945,317	$45,348	209,797	2,411
	# of Essential Facilities	Total Original Cost	Avg. Original Cost	Total Square Feet	Average Sq. Ft.
	4	$102,579	$410,319	12,886	3,221
	# of Facilities	Total Monthly Rent	Avg. Monthly Rent	Total Square Feet	Average Sq. Ft.
Leased:	40	$355,919	$8,897	290,868	7,217
	# of Essential Facilities	Total Monthly Rent	Avg. Monthly Rent	Total Square Feet	Average Sq. Ft.
	4	$75,456	$12,576	44,150	7,358

State owned structure within hazard zone:

Function of at-risk buildings: Included in the state facilities potentially at-risk to tsunami are the following:

- Eight public access points, Lake Whatcom Hatchery and Lake Aberdeen Hatchery operated by the Department of Fish and Wildlife.
- Ferry landings in Bremerton and Seattle.
- A variety of picnic, comfort, shelter and other facilities at 24 locations operated by the State Parks and recreation Commission.
- Seattle Armory and other facilities at Pier 91 in Seattle of the Military Department.
- State Patrol detachments in Hoquiam and Raymond.

One state highway considered an emphasis corridor because of its importance to movement of people and freight is potentially at-risk to tsunami as it traverses near vulnerable shorelines:

1. U.S. Highway 101

State critical facilities at risk within hazard zone:

Function of at-risk critical facilities: Included in the state facilities potentially at-risk to the direct and indirect impacts of tsunami are the following:

- Pump houses, chemical storage, and other facilities of Departments of Fish and Wildlife, Transportation, Ecology, and State Parks and Recreation Commission.
- Seattle Armory and other facilities at Pier 91 in Seattle of the Military Department.
- State Patrol detachments in Hoquiam and Raymond.

One state highway considered an emphasis corridor because of its importance to movement of people and freight is potentially at-risk to tsunami as it traverses near vulnerable shorelines:

1. U.S. Highway 101

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