

INTEGRATED TSUNAMI-HAZARD ASSESSMENT FOR A COASTAL COMMUNITY, GRAYS HARBOR, WASHINGTON

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ABSTRACT

The Grays Harbor region of southwestern Washington lies at the east edge of the Cascadia subduction zone. This study was conducted to examine the potential hazards to Grays Harbor arising from tsunamis generated just offshore by possible thrust earthquakes involving the Juan de Fuca plate. A series of numerical simulations were conducted to delineate the effects of tsunamis, either in the form of flooding or as high waves, in the populated areas around the shores of Grays Harbor and along the outer coast to the north and south of the harbor. Once the basic tsunami threat potential was identified, the soil structure and land-use patterns in and around Grays Harbor were examined to establish what hazards could arise from secondary tsunami and earthquake effects. These effects include damage to storage containers due to wave impacts, collapse of coastline structures due to wave scour and erosion, and flotation of storage containers (both moored and free standing) due to flooding. Attention was given to the possibility of the coincidence of tsunami waves and riverine flooding due to runoff. In the analysis, the Grays Harbor area was represented by microzones, each characterized by the type of hazard peculiar to its soil and land-use patterns. The study shows that such an integrated hazard-analysis methodology can be of great value in helping communities to plan for specific disasters rather than a broad spectrum of possibilities.

INTRODUCTION

This study was conducted to develop and apply a methodology for making an integrated hazard assessment that treats an earthquake-generated tsunami as the initiator of a suite of interrelated hazards rather than as the sole threat to a community. Through such an integrated approach to hazard

assessment, relatively accurate loss estimates and subsequent mitigation efforts can be made effectively.

Because vulnerability to specific risk factors varies from community to community, a risk-based urban planning approach was developed that balances the needs of waterfront activities (industrial and resort) with safety and preparedness requirements in coastal areas vulnerable to tsunamis and earthquake-induced flooding. The study had four objectives:

1. Identify the threat of tsunamis. Characteristics and dimensions of the potential tsunami threat to a coastal community were defined. Numerical simulations of locally generated tsunamis arising from offshore earthquakes were used to define the direction of energy and wave heights.

2. Delineate the vulnerability zone. Patterns of vulnerability to tsunamis were defined based on land use and population distribution. Field work was used to make these determinations.

3. Identify secondary hazards. Secondary hazards that could result from earthquake ground motion and (or) impact of a tsunami or flood were defined. Specific attention was directed to the potential for release of hazardous materials. A combination of field inventory, multidisciplinary data analysis, and an air-dispersion model was used.

4. Microzonation. Primary and secondary hazards were correlated with vulnerability patterns, and a system of microzonation was proposed. Interactive analysis was used.

Grays Harbor, Wash. (fig. 236), was the location used to characterize earthquake-hazard risks along the Washington coast and to calculate the geographic area of vulnerability to earthquake hazards. The study area generally corresponds to an area of sand lenses discovered on the outer Washington coast at Willapa Bay and Grays Harbor (Atwater, 1987; Bourgeois and Reinhart, 1988) that has been interpreted as having been subjected to multiple tsunami impacts from great subduction events in the past.

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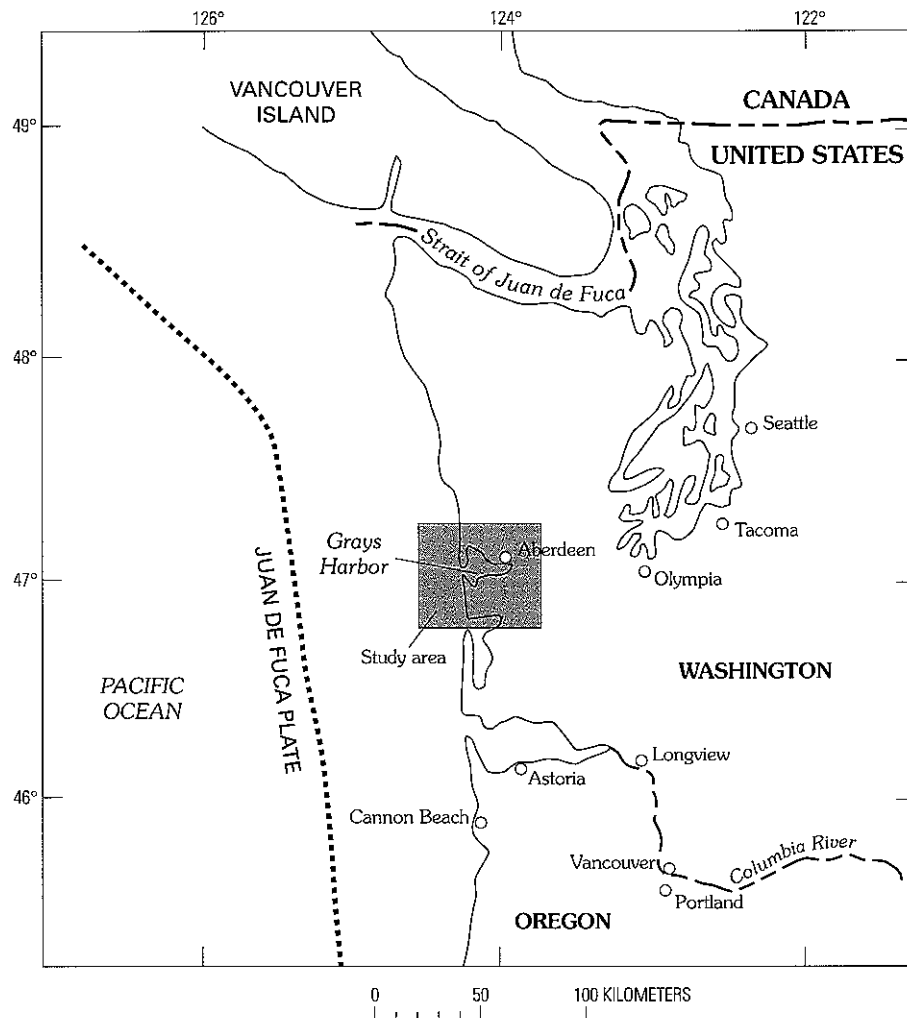


Figure 236. Index map showing the Grays Harbor study area (shaded). Heavy dashed line indicates shoreward boundary of Juan de Fuca plate. The south Cascadia portion of the Cascadia subduction zone extends from just north of Grays Harbor to southern Oregon.

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BACKGROUND OF AND APPROACH TO THE STUDY

In the past decade, considerable interest has developed in the possible occurrence of major subduction-related earthquakes along the Juan de Fuca plate boundary in the Pacific Northwest (for example, see Heaton and Hartzell, 1986, 1987; Heaton and Kanamori, 1984; Rogers, 1988). Evidence from recent investigations (Bourgeois and Reinhart, 1988;

Atwater, 1987) and from Indian legends (Heaton and Snively, 1985) indicates that the coasts of Washington and Oregon are vulnerable to tsunamis. Atwater (1987) reported at least six episodes of coastal subsidence due to earthquakes in the last 7,000 years, with vegetated coastal lowlands being buried by intertidal mud. In three of the episodes, patterns of sand sheets lying atop the buried lowlands could be explained by inundation due to tsunamis and the resulting shoreward transport of sand. Other research (Reinhart and Bourgeois, 1987; Atwater and others, 1987; Johnson, written commun.) cited additional evidence for subsidence and possible tsunami-related flooding in the past 1,000 years.

Although the hazards most commonly expected from major earthquakes are ground movement and failure attributable to the seismic motion, an earthquake occurring offshore in a subduction zone always has the potential to generate a destructive tsunami, which could cause considerable damage

to inhabited areas of coastlines. Tsunamis in 1946, 1952, and 1957 originated in the Aleutian Islands region of the North Pacific; a 1960 tsunami originated in Chile; and a 1964 tsunami resulted from an Alaskan earthquake. The recorded data (table 50), although spotty, show that significant waves struck the Pacific coast during these events. The coasts of Washington and Oregon were significantly damaged by the 1964 Prince William Sound, Alaska, earthquake and tsunami (Hogan and others, 1964) (table 51). A wave of about 3 m was observed at Ocean Shores, Wash., just north of the entrance to Grays Harbor.

Analysis of the 1964 Alaska earthquake damage in Seward, Alaska (fig. 237) indicates that there were four relatively distinct causes of tsunami damage. Primary causes were from direct water forces, including hydrodynamic forces, buoyancy, and hydrostatic pressures, and from loss of ground support through subsidence, compaction, erosion, liquefaction, and (or) sand transport. Secondary causes of damage were from direct water forces acting on land uses, including impacts from floating debris (logs, buildings, vehicles, boats), fire, and contamination of land and water from oil, fuel, and other stored materials. Most of the damage was due to the secondary impact of the tsunami. For example, buildings weakened by water-pressure forces were subsequently dislodged when foundations were scoured by the erosive actions of the drawdown following the incoming waves. Thus, even if water levels were not high, damage was still severe.

It is also important to note that considerable tsunami damage in coastal areas can occur away from the shoreline. Spaeth and Berkman (1972) described such damage in Oregon from the 1964 tsunami. The town of Seaside sustained about \$275,000 in damage to residential and commercial areas several blocks from the shore. The waves surged up both the Necanicum River and Neawanna Creek, damaging bridges and structures set back from the coast.

These historical data do not establish the likelihood of locally generated tsunamis (source within 200 km of the shore), but they do indicate that the offshore topography of the region does not provide any natural protective barrier to incoming waves. This lack of natural protection means that a locally produced tsunami could indeed be a serious threat.

A recent study (Hebenstreit and Murty, 1989) used numerical modeling techniques to examine the potential threat to the coasts of Washington, Oregon, and British Columbia from tsunamis caused by earthquakes within the Juan de Fuca plate. The results of the study indicated that certain areas of the coastline were more susceptible to concentrated wave energy than others because of variations in offshore topography (similar to a finding by Hebenstreit and Bernard, 1985, for the Hawaiian Islands).

Tsunamis, like earthquakes, vary in magnitude and intensity. In addition, the nature of the tsunami risk is profoundly influenced by characteristics of land use in the inundated areas. The level of risk is examined by combining the likelihood of tsunami impact in a given geographic area with an inventory of the types of land-use-related hazards that could be exposed to that impact. The first step in mitigation-based land-use planning is to develop a clear understanding of scientific criteria for delineation of the hazard. Subsequently, land-use decisions can be based on specific vulnerability to distinct and definable risks.

The hazard analysis for this study consists of two parts. One is the identification of the geographic areas vulnerable to direct tsunami damage. Numerical simulation was used to identify this risk. The second part is the identification of potential secondary hazards caused by the earthquake and (or) the interaction of earthquake effects and tsunami. Identification of these potential hazards was based on secondary sources such as soils data from the Washington State Department of Natural Resources.

Table 50. Maximum recorded wave heights for five recent tsunamis along the Pacific Northwest coast.

[Data from U.S. Department of Commerce (1953), Salsman (1959), Symons and Zetler (undated), Berkman and Symons (undated), Wilson and Törum (1968), and Spaeth and Berkman (1972). (>), greater than; (—), no data recorded]

Location	Wave height, in feet (meters)				
	1946	1952	1957	1960	1964
Tofino, British Columbia	1.9 (0.6)	2.0 (0.6)	—	4.6 (1.4)	8.1 (2.5)
Port Alberni, British Columbia . . .	—	—	—	—	¹ >17 (>5.2)
Victoria, British Columbia	0.7 (0.2)	1.2 (0.4)	—	—	4.8 (1.5)
Neah Bay, Wash.	1.2 (0.4)	1.5 (0.5)	1.0 (0.3)	2.4 (0.7)	4.7 (1.4)
Friday Harbor, Wash.	—	—	—	0.6 (0.2)	2.3 (0.7)
Seattle, Wash.	—	—	—	—	0.8 (0.2)
Astoria, Oreg.	—	—	0.5 (0.2)	1.0 (0.3)	2.4 (0.7)
Crescent City, Calif.	5.9 (1.8)	6.8 (2.1)	4.3 (1.3)	10.9 (3.3)	² >13 (>4.0)

¹Gauge record incomplete; wave height estimated.
²Maximum wave height before gauge was destroyed.

Table 51. Wave heights and damage caused by the March 28, 1964, tsunami along the Pacific coast of Washington.

[Data from Hogan and others (1964), reported by Wilson and Tørum (1968). (—), no data reported]

Location	Wave height, in feet, above local tide level (meters)	Amount of damage (in 1964 dollars)	Damage description
La Push	5.3 (1.6)	---	Several boats and floating dock broke loose from moorings
Mouth of Hoh River	1.7 (0.5)	---	None
Tahola	2.4 (0.7)	1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinault River
Wreck Creek Bridge	14.9 (4.5)	500	Erosion of fill at bridge approach; debris on bridge deck and nearby highway
Copalis	---	5,000	Damage to buildings
Copalis River Bridge	---	75,000	Loss of one timber, Joe Creek Bridge bent, and two timber spans near the bridge center and one piling in a four-pile timber bent (Copalis River); 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 (Joe Creek)
Copalis River Highway ...	---	5,000	Shoulder erosion and debris on highway
Moclips	11.1 (3.4)	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 inches to several feet; heavy debris scattered in yards
Ocean Shores	9.7 (3.0)	---	Deposition of debris on streets near Central Motel office; debris in streets and yards near break in sand-dune dike about 3/4 of a mile south of Central Motel office
Pacific Beach	---	12,000	Medium-size house lifted off foundation and partly torn apart (total loss); several sheds moved off foundations; another building partly damaged; yards eroded and covered with debris
Seaview	12.5 (3.8)	---	None
Ilwaco	4.5 (1.4)	---	Minor damage
Cape Disappointment	5.7 (1.7)	---	None

ANALYSIS OF THE TSUNAMI HAZARD

The first step in analyzing the potential tsunami hazard in the study area was to carry out relatively coarse numerical simulations of the likely tsunami propagation patterns due to possible thrust-type earthquakes occurring offshore. These simulations were made in an earlier study (Hebenstreit and Murty, 1989) of the general threat to the Pacific coast from hypothesized subduction-related earthquakes in the Juan de Fuca plate. The plate was subdivided into a number of seismic source regions, including the southern Cascadia subduction zone off the coast of Washington and Oregon. Earthquake-source parameters in each region were postulated from an examination of such factors as the probable length of the fault plane in each section of the plate, the width of the plate, and the depth and dip angle of historical earthquakes in the area. This information was used to produce reasonable depictions of seafloor uplift due to large thrust earthquakes. Several arbitrary vertical-thrust values were used to provide a realistic range of possible tsunami intensities. The various uplift patterns were then translated into

resulting sea-surface displacement fields that could be used as the starting point for simulations of wave propagation toward the local coastlines. The wave-propagation simulations were imposed on actual seafloor bathymetric data to include the effects of variations in the ocean bottom on propagation patterns.

These simulations, based on reasonable assumptions concerning the nature of possible earthquakes, formulated a model that helped identify the parts of the Pacific coast most susceptible to tsunamis originating in the different specific sections of the plate. In all the simulations, the model indicated that seafloor uplift would occur offshore and some subsidence would occur on land. Dominant wave-energy distribution would be confined to the immediate source area; that is, the most extreme wave heights would be found along the coastal areas within the source uplift zone. Also, the elevations would tend to decline (although not uniformly) north and south of the immediate area of the uplift. Tsunamis originating in the southern Cascadia subduction zone would likely focus a large part of their energy on the southwestern coast of Washington, including Grays Harbor.

PRIMARY CAUSES OF DAMAGE	BUILDINGS			MARINE STRUCTURES			LIFELINES				OTHER	
	WOOD FRAME	MASONRY/ CONCRETE	STEEL FRAME	WHARVES DOCKS PIERS	JETTIES BREAK WATERS	ROADS AIRSTRIPS	RAIL LINES	BRIDGES	UTILITY PLANTS	UTILITY LINES	BOATS	OIL TANKS
DIRECT WATER FORCES												
Hydrodynamic forces	●			●			●				●	
Buoyancy	●										●	
Hydrostatic pressure	●										●	
LOSS OF GROUND SUPPORT												
Subsidence	○			○			○			○		
Compaction												
Erosion												
Liquefaction							○	○				
Sand transport						○	○					
SECONDARY CAUSES OF DAMAGE												
FLOATING DEBRIS												
Cars	○											
Boats	○					○						
Logs/Stored materials	○					○		○				
Buildings	●			○		○						
FIRE AND CONTAMINATION												
Oil and fuel storage	●						●		●		○	●
Vehicular/Railroad	●											○
Electrical												
Stored materials												

EXPLANATION

- Least severe
- Most severe

Figure 237. Categories and levels of tsunami damage to structures and other features in Seward, Alaska, due to the 1964 earthquake. From Urban Regional Research (1988).

To characterize the effects of tsunamis on the coast, a series of recording stations were specified in the model grid, and wave elevations at those points in the grid were stored for every simulation time step (fig. 238). The calculated mean value of simulated wave heights in the southern Cascadia subduction zone is just under 6 m above MLLW (mean lower low water—the sea-level datum used by NOAA (National Oceanographic and Atmospheric Administration) bathymetric charts). However, the coast between Newport, Oreg., and Grays Harbor is projected to experience mean wave heights of 8–9 m.

Once the wide-geographic-area simulations had been used to identify likely severe tsunami-impact areas, a more detailed site-specific wave-propagation model was used to investigate wave behavior in regions of high energy concentration. This model, called SURGE II, simulates the behavior of long waves (tsunamis) running toward and onto a coastline and can also delineate flooding in low-lying areas along the shore. The model has been used for many tsunami simulations, including an extensive study for Valparaiso, Chile (Hebenstreit and Gonzalez, 1985). The simulations are obtained by means of an explicit

finite-difference algorithm for numerically solving linearized long-wave equations on a Cartesian (x,y as opposed to latitude, longitude) grid. Bottom friction is included in the model by means of a quadratic term. Inundation of coastal areas is computed by means of a weir-overtopping scheme, but wave runup is not calculated. Radiation boundary conditions are applied to open-ocean boundaries to ensure that wave energy leaving the simulation grid is only minimally reflected.

The procedure used in the detailed tsunami simulations is similar to that used in the wide-area simulations:

1. A seismologically realistic earthquake source is developed using historical evidence to specify parameters such as length, depth, width, and dip angle of the fault plane.
2. These parameters are used in the model of Mansinha and Smylie (1971) that predicts the movement of the seafloor that such an earthquake would produce.
3. This seafloor motion is translated directly into a disturbance of the sea surface that propagates toward the shoreline as a long wave (tsunami).

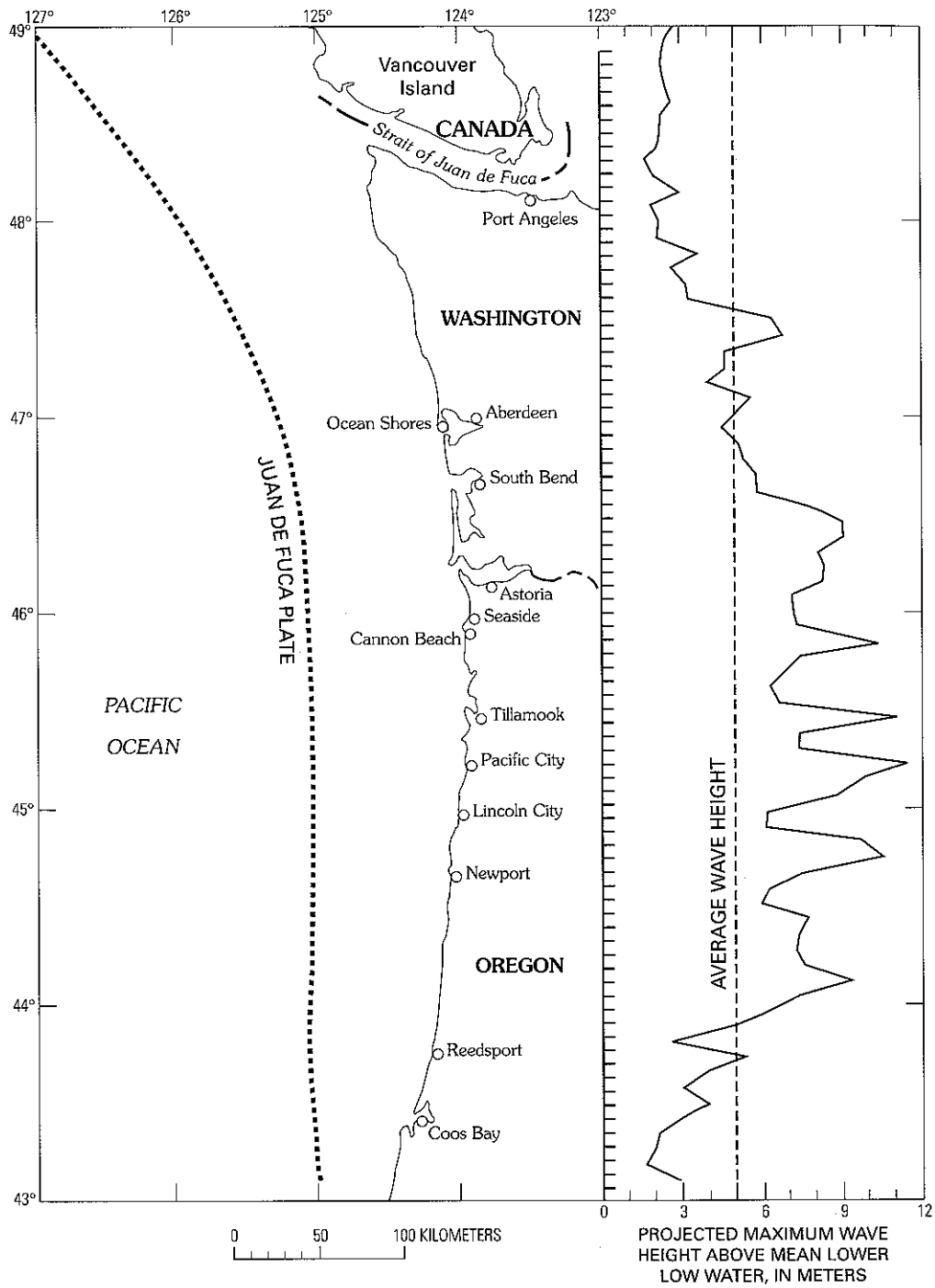


Figure 238. Projected near-shore (about 20 m depth) wave heights calculated for a major thrust earthquake in the southern Cascadia subduction zone of the Juan de Fuca plate (dotted line shows shoreward boundary of plate). Earthquake fault plane extends from north of Aberdeen, Wash., to Coos Bay, Oreg. Line with tick marks indicates model grid recording stations where wave elevations were stored.

4. The long waves are allowed to interact with the coastal area, and water-level time series are recorded at specific points. Locations on the grid where flooding is indicated are noted.

The tsunami sources used in the simulations were offshore of Grays Harbor. One source was located about 200 km from the coast (the approximate location of the surface expression of a fault at depth under the continental slope).

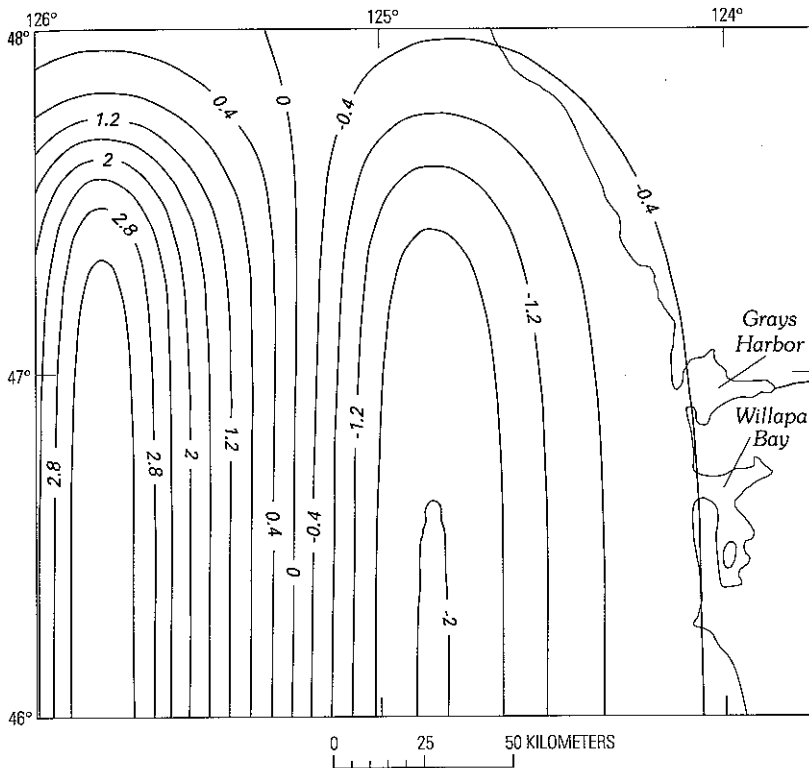


Figure 239. Contours showing relative vertical seafloor response to a possible earthquake in Grays Harbor region. Positive values indicate upward motion of seafloor; negative values indicate downward motion. Irregularities in contours are due to plotting software. Contour interval 0.4 m.

The second was only 100 km offshore, to include possible onshore subsidence effects in the simulation. Because the model is essentially linear, both sources produced about the same results, varying only slightly in the magnitude of wave heights calculated along the coast.

Seafloor (and hence sea surface) uplift from the more distant source (fig. 239) was calculated using the Mansinha and Smylie (1971) source-displacement model with the parameters listed in table 52.

The source zone specified for this earthquake lies in the southern part of the Cascadia subduction zone, along the coast from near Coos Bay, Oreg., to just north of Grays Harbor. This source zone was used in an earlier study (Hebenstreit, 1988) of the generalized tsunami threat from movement of the Juan de Fuca plate. The uplift pattern shown in figure 239 is the north end of a larger pattern from the earlier study.

Table 52. Source parameters used in the source-displacement model to simulate a subduction-zone earthquake off Grays Harbor, Wash.

Source parameter	Parameter value
Source depth	30 km
Fault length	400 km
Fault width	100 km
Dip angle	10°
Maximum vertical displacement	10 m

The site-specific SURGE II model uses a numerical-computation grid with variable seafloor and land topography. A realistic rendition of actual conditions is vital because the process of interaction between long surface waves (tsunamis) and the shoreline is heavily influenced by changes in water depth, as in coastal flooding. Simulated topography in the Grays Harbor model area is shown in figure 240. The contour line labeled "0" marks the approximate location of the shoreline.

One of the dominant landforms in the Grays Harbor area is the extensive mud flats. A large part of the harbor is so shallow that some of the bottom is exposed at low tide. A central channel has been dredged to allow seagoing vessels to reach Hoquiam and Aberdeen.

A series of recording points was identified in the model to facilitate examination of the waves during the course of the simulations (fig. 241A). Time series for several sets of these points are shown in figure 241B (stations on the outer coast), figure 241C (stations roughly along the axis of the main channel in the harbor), and figure 241D (stations at the far east end of Grays Harbor).

In the simulation, high-amplitude waves of 7–8 m height strike the outer coast soon after the uplift (fig. 241B). The recording stations closest to the mouth of the harbor (stations 14, 15, 19, fig. 241C) are initially subjected to high-amplitude waves that rapidly damp down to low-amplitude, high-frequency waves. Farther into the channel, initial amplitudes are greatly reduced. By the time the waves reach the Hoquiam-Aberdeen area (stations 4–9, fig.

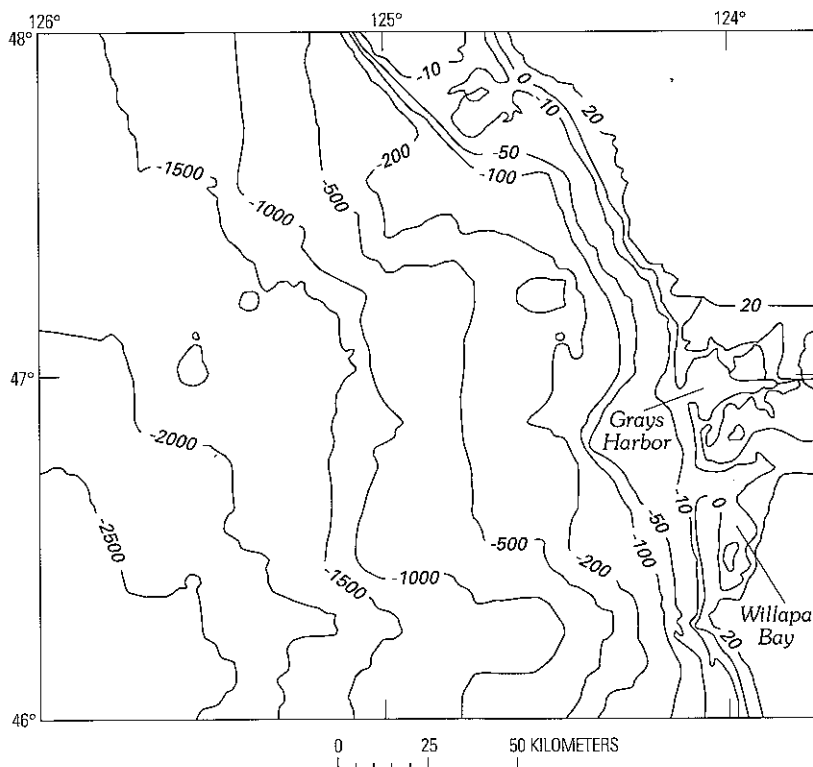


Figure 240. Topography used in numerical simulations of Grays Harbor area. Contour values in meters relative to MLLW (mean lower low water). Small outlines indicate location of small undersea features significantly shallower than surrounding water.

241D), there is only a minor variation in water level (about 0.5 m).

Except for some low-lying areas near the mouth of the harbor, especially around Westport, all the areas predicted to be flooded by tsunamis (fig. 242) are on the outer coast, which in this part of Washington is largely sandy beaches with dune barriers on the shoreward side. This simulation seems to be substantiated at Willapa Bay, south of Grays Harbor, where recent sediment-dating studies seem to indicate the possibility of subsidence events and tsunami inundation in the recent geologic past (for example, see Atwater, 1987).

The simulations indicate that the interior of Grays Harbor is relatively well protected from a serious tsunami threat, for several reasons. For example, Grays Harbor is primarily diamond shaped (fig. 241); it is 2.2 km wide at the mouth, widens to about 21 km, and then narrows at the mouth of the Chehalis River at the east end. This configuration is expected to cause the wave to break at the mouth, dissipating its energy. Another factor contributing to the relatively moderate level of tsunami threat is that the extensive shallow mud flats will quickly dissipate a large part of the wave energy, reducing wave height inside the harbor. The wave amplitude would continue to decline as the wave travels inland across the harbor to the Chehalis River. An initial wave amplitude of 2–3 m above the existing tide level at the mouth of the harbor would diminish to 0.5 m by the time the wave reaches Aberdeen. Because other tsunami waves would break at the mouth of the harbor, energy would be considerably reduced.

Therefore, the simulation indicates that the wave would have relatively low velocity within Grays Harbor. A wave period of about 20 minutes is anticipated.

However, even relatively small tsunamis can cause considerable damage to coastal areas. The drawdown of the sea surface can expose normally submerged bottom areas to erosion and slumping. Boats and ships moored at coastal installations can be severely damaged by anomalous surface motions such as drawdown or seiche (oscillation at the resonant frequency of the basin). In addition, objects torn from their moorings can become dangerous floating projectiles. If a small tsunami occurs during a time of severe storm seas, anomalously high tides, or river flooding, it can cause greater destruction, because under these conditions, surface waves can propagate much farther inland. Finally, if the surface resonance within the bay coincides with the period of the tsunami, the wave would be amplified by an unknown factor instead of being dissipated.

COASTAL FLOODING CONDITIONS AS AN ADDITIONAL HAZARD

Although the simulations did not factor in river- and rain-induced flood conditions, historical coastal flooding is well documented. Flooding in the Aberdeen area is generally the result of high river flow caused by winter rainfall generated by Pacific weather fronts combining with tidal flows. The tidal influence in Grays Harbor extends

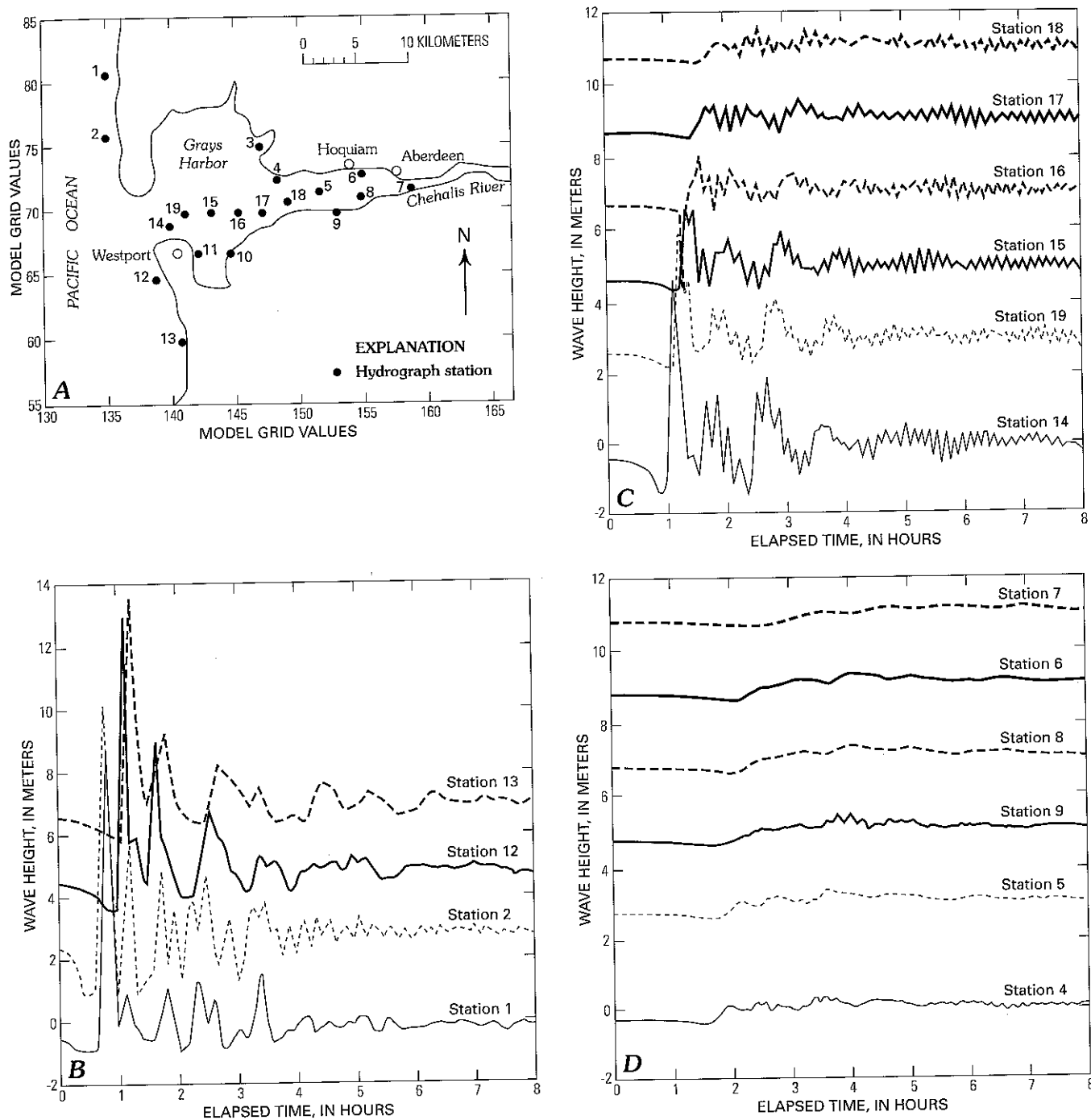


Figure 241. Simulated time-series data for a hypothetical tsunami impacting Grays Harbor area. A, Locations of modeled hydrograph recording stations at which time series of waves were recorded. Values on edge of map are part of the model grid. B, Time series of computed waves at stations just outside Grays Harbor. C, Time series for stations at west end of Grays Harbor. D, Time series for stations at east end of Grays Harbor. For clarity, each time-series curve above lowest is vertically offset by +2 m on each graph.

up the Chehalis and Wishkah Rivers and may coincide with high river flows to increase flooding. These conditions can be aggravated during rainstorms by backups in the city's storm-drainage system, when heavy local runoff is prevented from entering the rivers because of high water levels.

The highest river and harbor-water stages in the Aberdeen area result from a combination of anomalous high astronomic tides (which occur frequently), low barometric pressure, strong onshore winds, and heavy rains. This combination of conditions has produced extensive water damage to homes, businesses, and public property many times in the

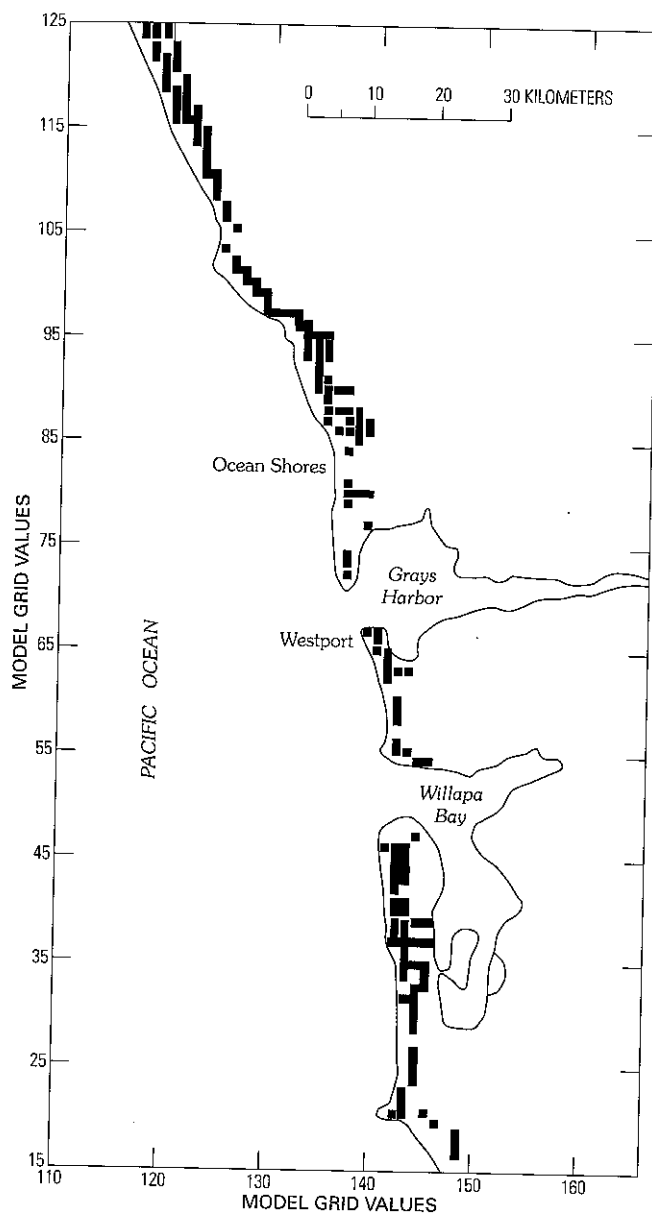


Figure 242. Approximate areas of coastal inundation (rectangles) computed by the tsunami-impact model for Grays Harbor region. Values on edge of map are part of the model grid.

past (table 53). Flooding along the lower sections of the small streams in Aberdeen is primarily caused by high water in the rivers backing up into the creeks and inundating adjacent low areas. Also, the Wilson Creek drainage basin was first clearcut in 1974. Additional logging operations have caused an increase in the volume of water that comes down this creek during rainstorms.

On average, Pacific coast tidal action causes the Chehalis River at Aberdeen to vary about 3 m in elevation, from -1.53 m at MLLW (mean lower low water) to 1.56 m at MHHW (mean higher high water). Flooding problems develop first near the southeastern city boundary when the Chehalis River reaches elevations between 2 and 2.3 m

Table 53. Highest known floods in Aberdeen, Wash.

[Floods are listed in decreasing order of magnitude. Information on floods prior to 1971 is based on the June 1971 Flood-Plain Information report by the Corps of Engineers, which reported the highest water levels as recorded at the Port of Grays Harbor staff gauge. Although the port attempted to record the highest tides of any year, the report acknowledged that records are incomplete. Information since 1971 is based on an internal City of Aberdeen Engineering Department memorandum pertaining to recent flooding from Ron Merila to Rudy Balgaroo on December 8, 1983. That information was updated by Bill Langford in 1990. No major river flooding has occurred since November 1983]

Date of flood	Water level, in feet, above mean sea level (meters) ¹
December 17, 1933	10.3 (3.14)
December 1934	10.0 (3.05)
November 1913	9.7 (2.96)
December 1923	9.7 (2.96)
November 14, 1981	9.7 (2.96)
December 3, 1982	9.6 (2.93)
1912	9.5 (2.90)
December 1920	9.4 (2.87)
December 11, 1977	9.4 (2.87)
December 21, 1972	9.3 (2.83)
December 11, 1973	9.3 (2.83)
January 27, 1983	9.3 (2.83)
November 24, 1983	9.3 (2.83)
December 13, 1941	9.2 (2.80)
December 18, 1960	9.2 (2.80)
January 27, 1964	9.2 (2.80)
December 13, 1977	9.2 (2.80)
November 30, 1951	9.1 (2.77)

¹Measured at the Port of Grays Harbor staff gauge. Staff gauge records were converted to mean sea level, National Geodetic Vertical Datum of 1929, using the Flood Plain Information Report, C.O.E. 1971, and the Summary of Tidal Elevations and Datum Planes, Aberdeen, 1981.

above mean sea level. This flooding is primarily on land that is undeveloped. When the water level reaches 2.3 to 2.6 m height, flooding spreads inland to residential and commercial properties in southeastern South Aberdeen along State Highway 101. Also, properties along the Wishkah River in North Aberdeen are affected. A 10-year flood level for this area is estimated to be 2.7 m; at a height of 2.8 m, general flooding occurs because the dikes protecting South Aberdeen are overtopped in many places when the water rises to between 2.6 and 2.8 m. At that level, water enters the downtown area of Aberdeen from the Wishkah River immediately to the east. Above 2.9 m, which is equivalent to a 25-year flood, major flooding occurs throughout the city. Flood-water velocity becomes a problem at this stage because overtopped dikes can fail due to saturation and scouring.

If extraordinarily high tides or tide surges are accompanied by heavy rainfall, flooding likely will occur even earlier than in the previous scenario. Because the peak astronomic tide for Grays Harbor coincides with the greatest threat of winter storm surge and rainfall for the area, the combinations of factors that can potentially result in flooding occur every

year between November and February. Ordinary high tides are about 1.6 m at MHHW; an additional 0.5 m of tsunami inundation would raise the level to 2.1 m. Flooding has occurred at 2–2.3 m. The extra 0.5 m of water from a tsunami during winter flood conditions of 2.3–2.6 m would inundate the downtown areas as well as the coastal highway.

Throughout the city, storm-water runoff is directed into adjacent rivers and sloughs. The storm-water-drainage system in North Aberdeen consists of underground drains; in South Aberdeen, the system is open ditches. Storm drains overflow when tide gates at the storm-drain outlets close due to high river levels. This storm-water flooding can occur throughout the area, and storm-water ponding remains as long as high river levels persist. Another problem that can develop is sewer overflow. The dikes protecting the area can be overtopped at a water level of 1.9 m MHHW, which is significantly below the 10-year flood level. If the 0.5 m tsunami flood level is added to the estimated 1.5–2.15 m of potential subsidence (fig. 243) during an earthquake, then the flood level would be raised by roughly 2.3 m, a damaging level even at low tide. These conditions could result in a serious contamination problem.

A tsunami occurring at high tide or during near-flood levels would arrive when the harbor is significantly deeper than normal. Under these conditions it would carry more wave energy into the Hoquiam-Aberdeen area. Thus, if the tsunami occurs during high winter tide conditions, the additional 0.5 m of projected wave height could easily overtop and (or) weaken the dikes protecting Aberdeen. The draw-down from the first tsunami wave can be expected to cause severe scouring of the inland sides of the dikes; the second tsunami wave could destroy them.

VULNERABILITY OF PEOPLE AND PROPERTY

The vulnerability analysis conducted in this study consisted of two primary components. One was the definition of the population at risk within the coastal hazard zone (generally defined as being below 6.1 m above mean sea level, based on the National Geodetic Vertical Datum of 1929). The other was the definition of land-use patterns and specific characteristics of those uses that could result in secondary hazards. For example, the presence of hazardous materials stored at or frequently transported to or through a site could be a secondary hazard.

POPULATION AT RISK

The population at risk from tsunami hazards in the Grays Harbor area varies seasonally. If a tsunami occurs between late October and late March, it could coincide with periods of elevated river heights due to heavy rain, which would magnify the potential for extensive property damage;

population levels would, however, be relatively low during that period. If a tsunami occurs during the summer months, the beach and resort communities along the open coasts would have high populations.

The largest year-round population center in Grays Harbor County is the Aberdeen-Hoquiam-Cosmopolis area, with a population of 14,241 (1990 Census of Population and Housing—Washington). This urban complex lies at the east end of Grays Harbor, fed by several rivers (including the Chehalis and the Wishkah) and open to the sea through the channel flanked by Westport on the south and Ocean Shores on the north.

Average year-round population levels of the coastal communities are low, but there are large seasonal fluctuations. Winter populations tend to be below 5,000 residents. During the summer, however, the wide sandy beaches of the Washington and Oregon coast are popular destinations for both Seattle-Tacoma and Portland urban populations. The 1990 population for the greater Seattle-Tacoma consolidated metropolitan area was 2,259,164, and Portland, Oreg.–Vancouver, Wash. had a metropolitan population of 1,286,222. Thus virtually the entire coast can be heavily populated during the summer months by campers and tourists staying in the many beach-front communities, which would make the potential for loss of life from a local tsunami very high. For example, whereas the year-round population of Ocean Shores is about 5,000, about 35,000 people attended a 1-day sand-castle-building contest in a nearby community during the summer. A large number of people in the urbanized Aberdeen-Hoquiam area could also be at risk, even though their residences are within Grays Harbor.

LAND-USE RISKS AND TOPOGRAPHY

Projections of land-use disruption must rely on an estimate of potential flood areas, which to a large extent is a function of ground elevation. This analysis, therefore, encompasses all the area below 6.1 m elevation (above mean sea level), the slope of which is 0–2 percent. A three-dimensional terrain model was used as the basis for the land-use analysis (fig. 244). Correlation of topography with land use permits rapid assessment of geographically based vulnerability to flooding. The urbanized area of Ocean Shores, a community of predominantly second homes, is entirely below 3 m elevation. Land-use patterns indicate that the urban and industrial areas in the central business districts of Hoquiam and Aberdeen are on coastal lowlands, virtually all of which are unconsolidated fills. Grays Harbor has several industrial complexes located along the shore. About 25 percent of the work force in Grays Harbor County is employed in manufacturing activities. ITT-Rayonier and Grays Harbor Paper have a combined pulp and fine-paper production facility on the waterfront in Hoquiam. A large Weyerhaeuser wood-pulp facility is in South Aberdeen. The harbor has several port

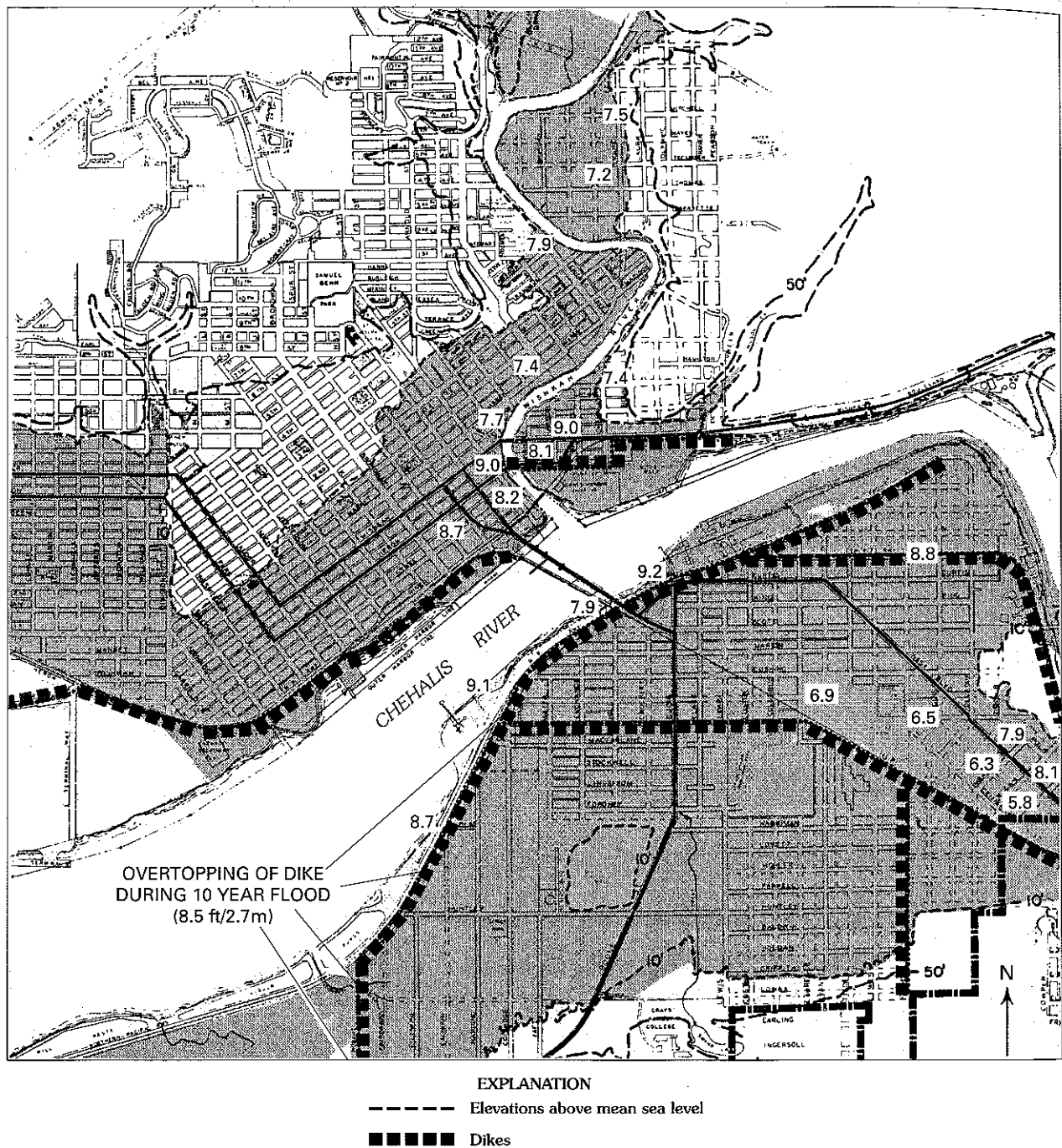


Figure 243. Critical flood levels for Aberdeen (north side of Chehalis River) and South Aberdeen (south side of river). Low-lying areas will be subject to flooding during low tide; during high tide, the entire urbanized area will be subject to extensive flooding that, because of deeper water level, could have relatively high velocity. One hundred year flood boundary defined by FEMA in conjunction with NFIP (National Flood Insurance Program) is the 10-foot contour. From Urban Regional Research (1986).

facilities; in 1985, 5.8 million tons of materials were shipped through the harbor, about 55 percent of which was logs (U.S. Department of the Interior, 1988). In addition, Westport is a commercial fishing center.

In summary, the Grays Harbor area, although not an exceptionally large economic center, contains a significant

investment in both commodities handled and infrastructure required to serve the industries present. It is the busiest port in the Pacific Northwest with respect to distribution of regionally produced lumber.

The area of potential flooding encompasses all the industrial areas, many bridges, and the State highway

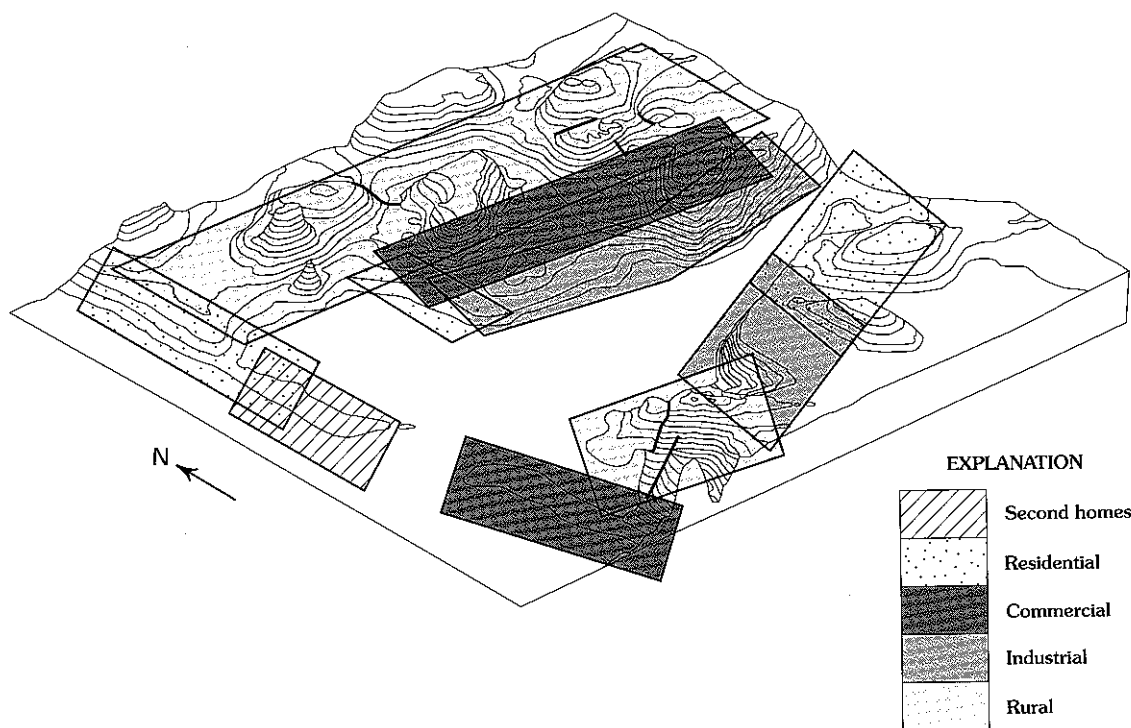


Figure 244. Grays Harbor land-use patterns. Patterns extend past land boundaries for clarity.

linking Grays Harbor with points to the north and south. In addition, the central business districts of both Aberdeen and Hoquiam (fig. 245), as well as residential areas in both communities, are within potential inundation areas. The headquarters of the fire department in Hoquiam and both fire stations in Aberdeen are within the coastal hazard zone.

Two principal highways, State Routes (SR) 12 and 101, serve the area from the east, north, and south. SR 12, a four-lane highway, connects Aberdeen and Hoquiam with the north-south Interstate 5 corridor. SR 101, which is basically a two-lane highway, serves the Olympic Peninsula and southwestern Washington. Two-lane routes connect Ocean Shores and Westport and points north and south along the Pacific coast. Highway routes are characterized by soft soils, so there is a high probability that transportation, such as response and rescue efforts and fire fighting, would be interrupted.

Data collected in conjunction with the analysis of damage from the 1964 Alaska earthquake tsunami specifically mention damage to four bridges in the southern Washington-northern Oregon region. Damage to bridges from a projected tsunami in the Grays Harbor area could be even greater in the industrialized area. Many bridges cross rivers emptying into Grays Harbor, including three drawbridges over the Chehalis and Wishkah Rivers and one drawbridge crossing the Chehalis River between Aberdeen and South Aberdeen-Cosmopolis.

SECONDARY HAZARDS

SUBSIDENCE

An earthquake-related threat that could increase the destructiveness of a tsunami is subsidence caused by compaction of soils under strong ground motion and (or) tectonic displacement. Coastal subsidence commonly accompanies great subduction earthquakes, primarily along an onshore belt flanked by a mostly offshore zone of coseismic uplift (Atwater, 1987). Estuarine deposits of late Holocene age near Washington's outer coast indicate that submergence and shoaling have occurred in cycles that resemble, at least superficially, the known and inferred cycles of coseismic submergence and postseismic shoaling in great-earthquake regions of Alaska and Chile. The amount of subsidence is estimated to be about 1.6–2 m respectively (Curt Peterson, Portland State University, oral commun., 1990).

The seismic effects of the 1964 Alaska subduction earthquake along the Washington coast are well documented. These effects were particularly severe in areas where subsidence was increased by shaking-induced settlement when seismic vibration caused consolidation of loose granular materials. Rearrangement of constituent particles aided by ejection of interstitial water through water spouts or mud spouts caused compaction and local differential subsidence of the ground surface. Lateral spreading, too, caused lowering of the ground surface in places (Plafker,

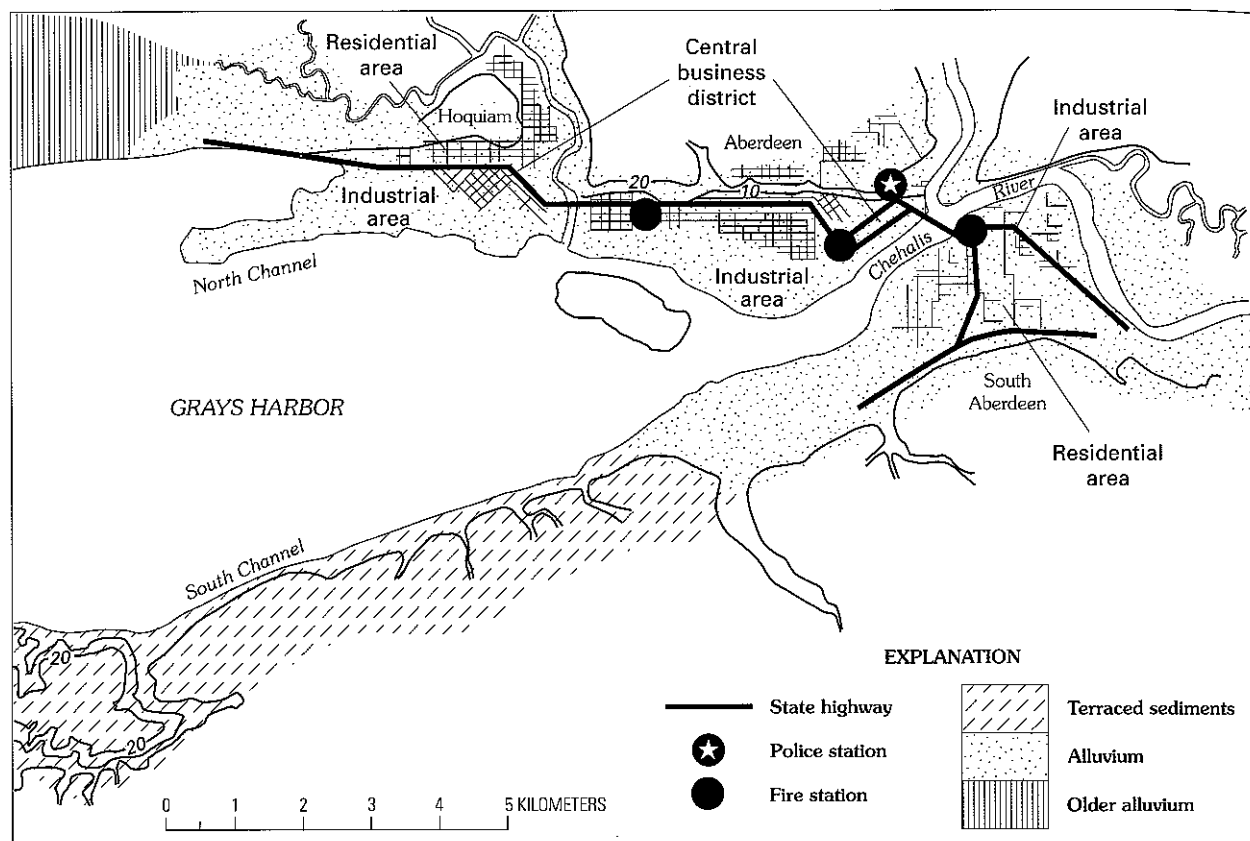


Figure 245. Detailed land use and geology for the Aberdeen (including South Aberdeen) and Hoquiam area of Grays Harbor.

1969). In coastal areas where local subsidence was superimposed on regional tectonic subsidence, the damaging effects were magnified.

Two examples from the 1964 Alaska earthquake illustrate the combined effects of tectonic displacement and subsidence. On Kodiak Island, local subsidence of as much as 3 m was widespread in noncohesive granular deposits through compaction, flow, and sliding that resulted from vibratory loading during the earthquake. Subsidence of more than 1.8 m occurred throughout the northern part of the region. This subsidence, which was largely restricted to saturated beach and alluvial deposits or artificial fill, was locally accompanied by extensive cracking of the ground and ejection of water and water-sediment mixtures. Within the affected area, tectonic subsidence, which was locally augmented by surficial subsidence of unconsolidated deposits, caused widespread inundation of shorelines and damage to intertidal organisms, near-shore terrestrial vegetation, and salmon-spawning areas (Plafker and Kachadoorian, 1966). Subsidence also occurred in the Cook Inlet area, which was down-warped. At the head of Cook Inlet near Portage, estuarine silt buried 18 km² of lowland that had subsided 1.6 m and settled an additional 0.8 m, totaling 2.4 m (Atwater, 1987).

As these examples of Alaskan subsidence indicate, a critical variable in projecting inundation and risk is a

determination of the areas prone to subsidence. These areas can reasonably be expected to be composed of soft and highly saturated material, such as the alluvium in virtually the entire urbanized Hoquiam and Aberdeen areas (fig. 245) (Washington State Department of Natural Resources, 1987).

Soils in the Grays Harbor flood plain are primarily alluvial silt and fine sand, locally with organic material (fig. 246). Some areas are mantled by artificial fill. These soils are about 1.5–1.8 m deep and range from moderately well drained to somewhat excessively well drained, to excessively well drained on the diked tidelands. This soil type formed in sandy and loamy river dredgings. The other type of soil, found primarily in the flood plain of South Aberdeen, is a silty clay loam. It is a deep, artificially drained soil found on flood plains and deltas that are protected from tidal overflow. This soil type formed in clayey alluvium deposited in quiet waters of coastal bays.

Close to the fairly abrupt boundary between the flood plain and the adjacent uplands are zones of coarse sand and gravel. These zones are probably interbedded with finer grained materials (Washington State Department of Natural Resources, 1987).

Existing soils are predominantly nonengineered fill and (or) highly saturated alluvium; both soil types are prone to compaction. If it is assumed that a combination of tectonic

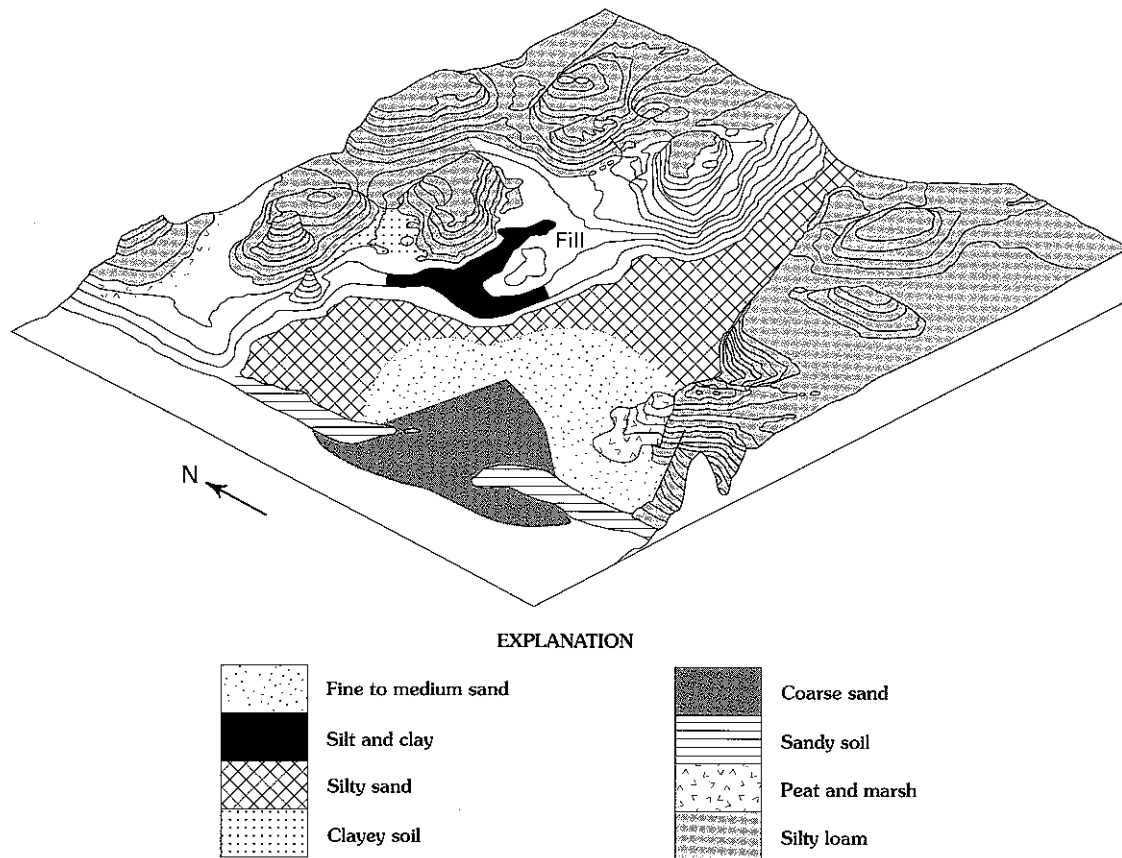


Figure 246. Soil and sediment structure in Grays Harbor area. Source of map data is Grays Harbor Estuary Management Program.

displacement, subsidence, and consolidation will occur to an extent about equivalent to that in the 1960 Chile and 1969 Alaska earthquakes and postulated for Holocene Puget Sound earthquakes, then subsidence of 1.5–2 m would be likely to occur. Under this assumption, all the industrial areas, the majority of the commercial centers, and a significant part of the residential areas are at risk. Loss of the industrial facilities could have a long-term devastating effect on the economy of the area.

In the event of subsidence, wave scouring could further erode foundations and lead to structural failures. Furthermore, much of Grays Harbor and environs consists of sand and sandy clay, which could liquefy under severe shaking, causing foundations to sink differentially and breaking buried pipes and storage structures. Finally, ground saturated by flooding will lose its bearing capacity, and there would be a high incidence of foundation failures and buildings floating off their foundations.

Because subsidence appears to have occurred in the past and seems likely to occur again, a simulation was made to project inundation as a result of subsidence. This simulation found that the flood-prone area would extend somewhat further inland than would occur without subsidence.

BATTERING

A sudden rise in water level can produce extensive damage from flooding and wave action on structures. It can also produce less direct effects such as battering by objects (logs, boats, railway freight cars, vehicles, and storage tanks) which become floating projectiles.

In a fishing enclave, the greatest water-related hazard is the fishing boats themselves. Any dockside complex such as the marina in Westport contains boats that, if torn from their moorings by currents created by rapid rising and falling of sea level, could easily become floating projectiles capable of damaging not only each other but also coastal structures such as industrial and commercial buildings, hotels, and processing plants. Spaeth and Berkman (1972) and Wilson and Törum (1968) cited instances of this type of damage from the 1964 Alaska tsunami.

A wood-pulp facility such as the Weyerhaeuser plant in South Aberdeen has many types of materials that could become battering hazards. Most notable are the logs piled near the water's edge awaiting processing. Smaller piles could float under high-water conditions and, like the fishing boats, could become projectiles. Vessels moored at the

Table 54. Assumptions of air-dispersion patterns for Hoquiam and Grays Harbor, Wash.

[Ground roughness assumed to be urban; no temperature inversions present]

Period	Wind direction	Average wind speed, in miles/hour (km/hr)	Average temperature
January-March	From the southeast	10.7 (17.2)	35.0°F (1.7°C)
July-September	From the west	11.6 (18.7)	65.0°F (18.3°C)

plant's dock could also become projectiles or could be battered by other vessels and (or) the logs. As it is, every year during storm conditions people are killed by errant logs. Under tsunami conditions, the increased water velocities will turn these log storage areas into highly hazardous areas. In addition, the ITT-Rayonier plant in Hoquiam, at the mouth of the Hoquiam River, is serviced by a railroad. The rail cars on the tracks are also potential floating hazards during flooding.

Another potential industrial hazard is toxic materials stored at plant sites. For example, piles of waste materials on the grounds of a paper plant could be a long-term health and contamination hazard if they were dislodged by water-borne objects and then dispersed by flooding.

AIR CONTAMINATION AND FIRE

The Hoquiam-Aberdeen population is at risk from possible fires and airborne contamination that could originate in the industrial port area and spread to the neighboring residential and commercial areas. Although the precise causes and dimensions of fire or air contamination have not been predicted, it is clear that toxic chemicals could be a devastating hazard if their storage containers were to be breached by ground motion, wave action, or floating.

Grays Harbor is a principal port for Pacific Northwest forest-products industries. Manufacturing of a wide range of wood products (for example, wood shakes) involves the use of an extensive range of chemicals as preservatives, fire retardants, and other related agents. Fire is always a problem when chemical storage tanks are breached; toxic-material storage facilities constitute a major threat to public safety when they are damaged and facilities are disrupted. Surface-water, ground-water, and airborne contamination could occur in the flooded areas.

The U.S. Environmental Protection Agency SERA Title III Program requires mandatory public disclosure of stored hazardous materials exceeding a specific amount for each chemical. Among the toxic substances stored in industrial facilities in the Grays Harbor area are ammonia, chlorine, nitric acid, sulfur dioxide, hydrogen peroxide, propane, and formaldehyde gas. In order to demonstrate vulnerability, the release and spread of selected toxic materials from an industrial site were simulated in the study area. The Computer-Aided Management of Emergency Operations (CAMEO™ II) program, developed by the U.S. National Oceanic and

Atmospheric Administration (NOAA) Hazardous Materials Response Branch, was used to project the geographic extent of vulnerability to the spread of toxic materials. This model is designed to help emergency planners and first-response personnel plan for and safely handle chemical accidents.

CAMEO's air-dispersion model can simulate potential dispersion of toxic gases under a variety of wind and weather conditions. It simulates the extent and footprint of a chemical downwind from a chemical spill, using a diagram drawn by the computer from a defined location on a base map. For this analysis, project base maps were used to facilitate correlation of the air-dispersion analysis with land-use patterns. Because concentrations differ for each chemical, the predicted adverse effects vary widely. Two hypotheses were developed by the project to illustrate the pattern of possible air contamination:

Hypothesis 1. Small chemical spill. Release of threshold limits (45 kg or 227 kg) of ammonia and chlorine projected.

Hypothesis 2. Large chemical spill. Release by partial rupture of an average railroad tank-car load (2,270 kg) of chlorine.

Other variables were based on average wind and temperature conditions during summer versus winter (table 54).

Downwind chemical concentrations from a chemical accident were simulated under two base-time conditions:

1. IDLH: Immediately dangerous to life and health. This condition exists in the immediate vicinity of the spill within minutes after it occurs. Under IDLH conditions, the gases remain concentrated and pose a serious threat. Just after a spill, no one should enter an IDLH atmosphere without a self-contained breathing apparatus.

2. TLV-TWA: Threshold limit value—time weight average. This condition occurs within the first 30 minutes after the spill. In TLV-TWA conditions, the gases are more dispersed and pose a less general but still serious threat.

The extent of potential airborne contamination from a release of 45 kg of chlorine gas at the ITT-Rayonier plant under both summer and winter average wind conditions is shown in figure 247. When reviewing the simulation results, it is important to know that the CAMEO program tends to underestimate the dispersal of heavy gases such as chlorine by a factor of about 2. Thus the IDLH is really more extensive than shown in the figure.

Under summer conditions (fig. 247A), the threatened areas are primarily residential, and the fire station is within

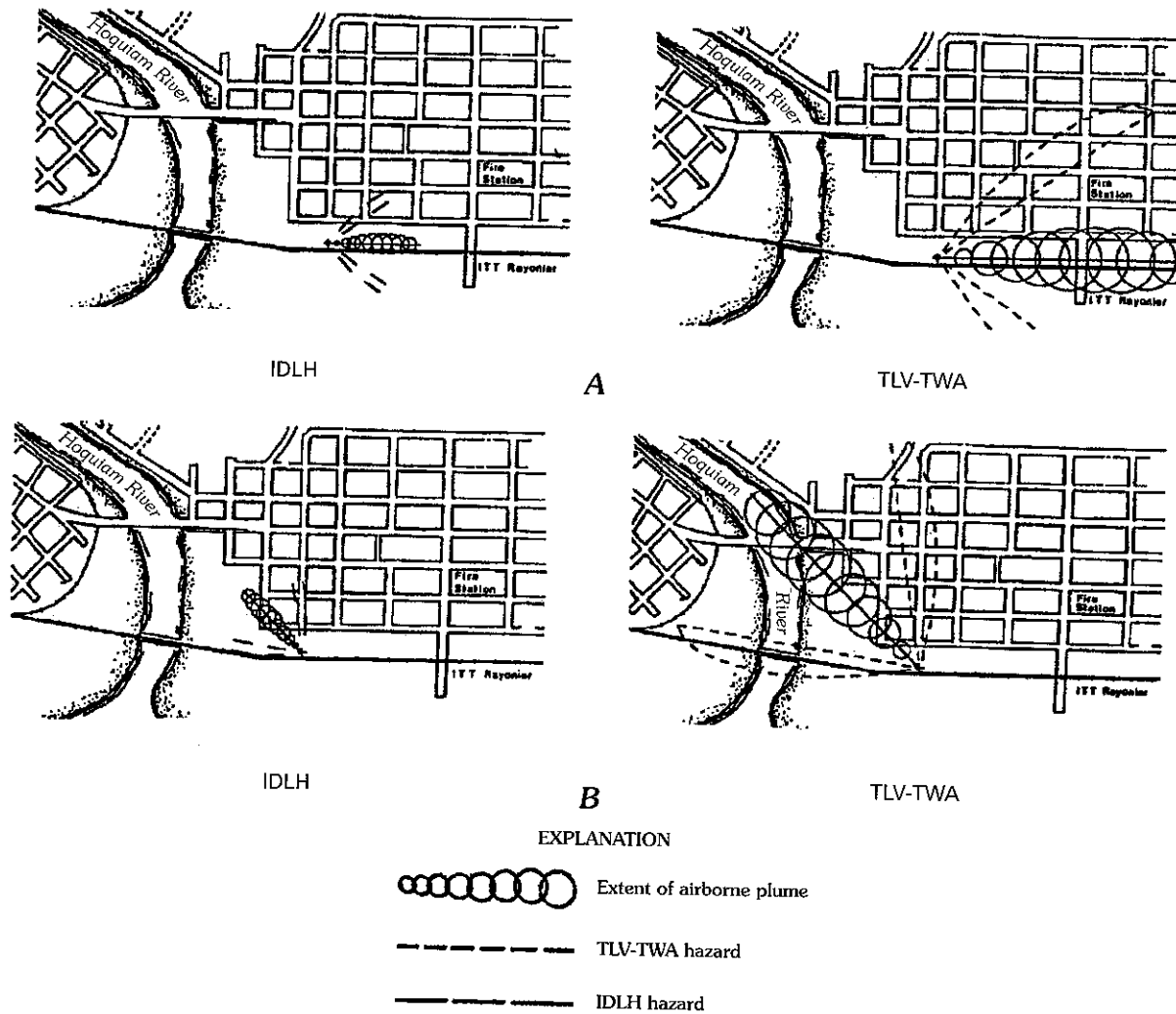


Figure 247. Potential dispersion patterns for chlorine gas spreading from a simulated spill (45 kg) at ITT-Rayonier pulp and paper plant in Hoquiam. Overlapping circles, extent of airborne plume; dashed lines, wider envelopes of potential hazard under IDLH (immediately dangerous to life and health) and TLV-TWA (threshold limit value–time weighted average) scenarios. IDLH concentrations assumed as 30 ppm (parts per million); TLV-TWA concentrations assumed as 1 ppm. A, Dispersion under summer temperature and wind conditions. B, Dispersion under typical winter temperature and wind conditions.

the potential contamination zone. The threat is exacerbated because when the lives of fire personnel are at risk, the ability of the community to respond to the emergency is reduced.

INTEGRATED HAZARDS MANAGEMENT

Once the base data for delineation of the tsunami threat and the characteristics of vulnerability were developed, it was possible to correlate these two factors. The physical threat, including flooding, strong currents, and potential for ground subsidence, could be correlated with land-use characteristics. An integrated physical-social-economic data

base was thereby created for estimating potential damage caused by floating debris, fire, and contamination from hazardous substances. In essence, this integrated methodology treats the tsunami threat as a system rather than a single physical process. The analysis also highlights the reality that hazards are cumulative, that is, whereas the immediate water hazard is dangerous, it can precipitate still other hazards with even greater consequences.

The geographic location, land use, and underlying soils constitute a system of base perimeters of variable vulnerability. Defining tsunami-hazard boundaries can serve two purposes. One is to define possibly vulnerable areas in order to plan for damage mitigation; the other is to define evacuation procedures. Once at-risk locations are

defined, a risk-reduction program can be developed that organizes the specific characteristics of vulnerability according to subdivided areas of risk. Analyses of risks in the Grays Harbor area indicate that they are primarily a function of land use. For example, the apparent lack of a high-impact tsunami threat within the harbor indicates that the predominant threat for which Grays Harbor must be prepared is secondary hazards. These secondary hazards include battering, erosion and scouring, loss of soil strength, fire, and air contamination. During high tide and (or) riverine flood conditions, major flooding may exacerbate high-water conditions created by the tsunami.

MICROZONATION OF THE RISK AREA

The specific nature of the tsunami threat is determined mostly by underlying soil conditions and by land-use patterns. Once the soil conditions are clearly defined, an integrated hazard-management system organized into a series of microzones can be applied that reflect these conditions. This hazard analysis constitutes the basis for geographically delineating the risk area. The next step in the hazard-mitigation planning process requires more specific data upon which actual design can be based. The microzones defined by this study (fig. 248) are discussed following.

TSUNAMI HIGH-IMPACT ZONE

Area Delineation.—Based on the flooding simulations, only the outer coastal areas encompassing Ocean Shores

and Westport are vulnerable to direct tsunami impact. Because the elevation of both communities is about 3 m above mean sea level, most of the residential areas are within the high-impact hazard zone. The rest of the study area does not appear to be vulnerable to direct high-level, high-velocity tsunami impact.

Preparedness and Mitigation.—In Ocean Shores, the critical planning issues are warning and evacuation. Population levels in this second-home community fluctuate seasonally; a tsunami that occurs in the summer could result in comparatively high life loss, whereas the risks during winter would be considerably less.

In Westport, primary concerns relate to the presence of the fishing fleet. A major cause of destruction from the 1964 Alaska tsunami and earthquake was boats being swamped, battered, and (or) thrown inland against nearby structures. Although boats are normally moored to withstand prevailing currents, tsunami-induced flows may overpower mooring lines. Boat owners who have any warning of an approaching tsunami tend to move their vessels from their anchorage and travel toward the open sea. Of the preventable deaths in Alaska during the 1964 tsunami, many resulted when fishermen tried to save their boats. In Westport, similar damage patterns could be expected to occur. Boat owners and radio-dispatch operators in the Westport area should be informed of proper procedures to be followed in the event of a tsunami warning. It may be necessary to prevent boat owners from entering the marina area if the warning time is not sufficient for evacuation before the first several waves arrive.

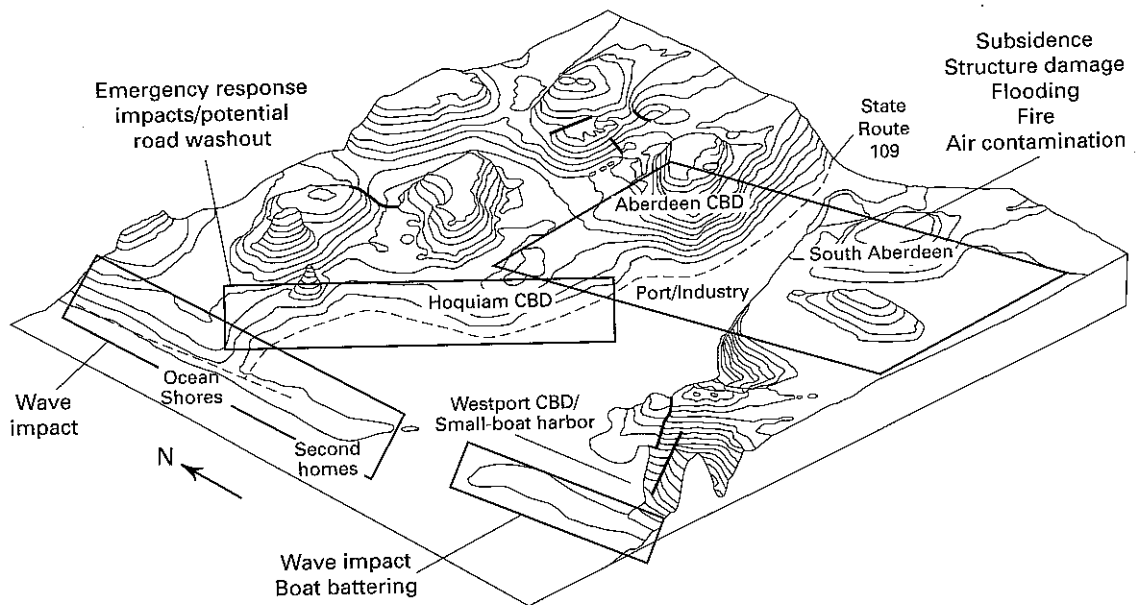


Figure 248. Grays Harbor microzones (polygons) defining hazards arising from tsunamis and earthquakes. Dashed line, major State route. A smaller roadway along south shore of harbor provides local access between Aberdeen and Westport. CBD, central business district. Base prepared by Urban Regional Research.

ZONE OF FLOODING AND HIGH PROBABILITY OF SUBSIDENCE

Area Delineation.—The majority of the urbanized Hoquiam-Aberdeen central business district and port is less than 5.5–6.1 m above mean sea level and is reported to be built on fill and (or) soft alluvial soils. This type of soil may amplify ground motion and is also prone to subsidence. Based on the effects of historical great subduction earthquakes in the Pacific Northwest and elsewhere, about 0.5 m of subsidence from compaction could accompany about 1.5 m of tectonic subsidence, resulting in a total flood elevation of 2 m above the existing MHHW of 1.7 m. Under these assumptions, the land vulnerable to flooding encompasses all the commercial and industrial areas inland to the 6.1 m elevation.

Preparedness and Mitigation.—Two categories of issues based on use have been identified in the urbanized areas. In the commercial zone, preparedness and mitigation must address conditions related to risk from damage and collapse of structures. In the industrial zone, a critical issue is vulnerability of hazardous materials, either transported into or stored on site, which could be dispersed either by flood waters or by wind. Preparedness plans consider two zones of risk: (1) the immediate flooded area, which contains airborne contamination-hazard zones under IDLH conditions; (2) the larger area vulnerable to TLV-TWA (airborne) spread as well as the area disrupted by interruption of major transportation routes.

EMERGENCY PREPAREDNESS PRIORITY AREA

Area Delineation.—The outer coastal areas of Washington and Oregon are linked to the Interstate highway system by State highways. Significant parts of these routes, which include an extensive network of bridges and roads, lie within the zone projected for flooding. Inevitably, coastal routes of the State highway system will be disrupted.

Preparedness and Mitigation Issues.—The preparedness process must assume that in the event of a major earthquake, road access will be disrupted and outside assistance will not be able to reach the area for several days. A self-reliance contingency plan for search and rescue, emergency medical, and repair should assume a delay of 2 days before adequate outside resources through mutual aid can arrive.

CONCLUSIONS

Integrated hazard assessments based on the tsunami threat have not, to our knowledge, been undertaken previously; instead, studies have focused almost exclusively on flooding as a threat. It is clear from this study that an

examination of the interconnection of many potential hazards can lead to more fruitful analysis of a multifaceted threat. Additional specific studies should be made, including the following:

1. Collection of more data concerning the foundation design and condition of structures in the flood-hazard zone.
2. Calculations to describe motions of merchant vessels moored in the harbor and subject to tsunami-induced current motions. Such studies should include examination of preventive docking practices.
3. Determination of the location of toxic-material storage facilities in areas prone to tsunami-induced flooding. The design of these facilities must be reviewed because of the potential for breaching of the containers, thereby releasing toxic chemicals into the air and water.
4. Assessment of the impact of the primary (tsunami) and secondary threats on community-response capabilities (immediately after the event and in the postdisaster time frame, both in geographic terms and in terms of response resources (manpower and equipment).

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