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INTEGRATED HAZARD ASSESSMENT FOR A COASTAL COMMUNITY: GRAYS HARBOR

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Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing and Reducing Earthquake Hazards in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

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ABSTRACT

The project described in this paper is to develop and apply a methodology for an integrated hazard assessment which treats the earthquake-generated tsunami/flood event not as the sole threat, but as the initiator of a suite of interrelated hazards. Only through such an integrated approach can relatively accurate loss estimates and subsequent mitigation efforts be conducted with accuracy and effectiveness.

Since vulnerability to discrete risk factors varies from community to community, a risk-based urban planning approach is developed which 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 implications of the tsunami hazard generated on the outer Washington coast and impacting Grays Harbor is used as a case study.

OBJECTIVES

Four underlying objectives were addressed by the project:

- I. Identify threat.
  Characteristics and dimensions of the potential tsunami threat to a coastal community such as the Grays Harbor area were defined. This investigation used numerical simulations of locally generated tsunamis arising from offshore earthquakes to define direction of energy and wave heights.
- II. Delineate vulnerability zone.
  Vulnerability patterns based on land utilization were defined. Local land use and population distribution patterns vulnerable to tsunami impacts were identified.
- III. Identify secondary hazards.
  Secondary hazards that could result from the earthquake ground motion and/or impact of a tsunami or flood water were defined. Specific attention was directed to potential for toxic and hazardous release.
- IV. Microzonation
  Primary and secondary hazards were correlated with vulnerability patterning and a system of microzonation was proposed.

The first three objectives were achieved with relative independence. The first involved numerical simulation; the second required field work to assess land use patterns for the Grays Harbor area and identify use characteristics which could become potential hazards. The third involved a combination of field inventory, multi-disciplinary data analysis, and application of an air dispersion model. The fourth required interactive analysis.

The project defines characteristics of coastal risks and projects the geographic area of vulnerability. A case study methodology focuses on Grays Harbor, Washington (see fig. 1). This study area generally corresponds to the location of sand lenses discovered on the outer Washington coast at Willapa Bay and Grays Harbor (Atwater, 1987; Bourgeois and Reinhart, 1988) which has been interpreted as the area which has experienced tsunami impacts from great subduction events in the past.

BACKGROUND/APPROACH

In the past decade considerable interest has been generated in the possibility of major, subduction type earthquakes occurring in the Juan de Fuca Plate region of the Pacific northwest (for example, Heaton and Hartzell, 1986, 1987; Heaton and Kanamori, 1984; Rogers, 1988). Evidence presented in recent investigations (Bourgeois and Reinhart, 1988; Atwater, 1987) and in Indian legends (Heaton and Snavely, 1985) indicates that the outer coasts of the Cascadia subduction zone are vulnerable to tsunami activity. Atwater (1987) reported evidence for at least six subsidence episodes in the last 7,000 years. In all cases, vegetated coastal lowlands were 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 comm.) cites additional evidence for subsidence and possible tsunami-related flooding in the past thousand 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 carries with it the potential for generating a destructive tsunami, which could cause considerable damage to coastal habitation zones. Table 1 shows maximum wave heights (in ft) recorded along the Pacific coast for five tsunamis from 1946 to 1964. The 1946, 1952, and 1957 tsunamis originated in the Aleutian Island region of the north Pacific; the 1960 tsunami originated in Chile; and the 1964 tsunami originated in Alaska. The figures, while spotty, show that significant waves *have* struck the Pacific coast in recent history.

It is known that the coasts of Washington and Oregon suffered damage as a result of the 1964 Prince William Sound (Alaska) earthquake and tsunami (Hogan and others, 1964). Table 2 lists wave elevations and damage descriptions for portions of the Washington coast following the 1964 tsunami. Note that a wave of approximately 3 meters (9.7 feet) was observed at Ocean Shores, Washington, just to the north of the entrance to Grays Harbor.

Analysis of the 1964 earthquake indicates that damage is caused by four relatively discrete aspects of the tsunami hazard. Primary causes of damage are from direct water forces including hydrodynamic forces, buoyancy and hydrostatic pressures, and by loss of ground support through subsidence, compaction, erosion, liquefaction, and/or sand transport. Secondary causes of damage are from the interaction between direct forces and land uses. They include impacts from floating debris (logs, buildings, vehicles, boats), fire, and contamination from oil, fuel, and other stored materials. In Alaska, the dominant causes of damage are the secondary impacts of tsunamis. For example, buildings weakened by the water velocity were subsequently dislodged when foundations have been scoured out by the erosive actions of the drawdown. Thus, even when the water level is not high, dislocations have been severe. Figure 2 illustrates the types of damage patterns observed in Seward, Alaska, from the 1964 tsunami.

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 during the 1964 tsunami. The town of Seaside sustained approximately $275,000 in damage in residential and commercial areas several blocks from the shore. The waves surged up both the Necanicum River and Neawanna Creek damaging bridges and structures well inland.

These historical data do not establish the likelihood of locally generated tsunamis (source within 200 km or 120 mi of the shore), but they do indicate that the offshore topography of the region does not provide any naturally protective barrier to incoming waves. This lack of material protection means that a local tsunami would, indeed, pose a threat to be taken seriously.

A recent study (Hebenstreit and Murty, 1989) used numerical modeling techniques to examine the potential threat to the Pacific coasts of Washington, Oregon, and British Columbia from tsunamis generated within the Juan de Fuca Plate. A companion study (Murty and Hebenstreit, 1990) examined similar threats in the inland waters of the Strait of Juan de Fuca-Strait of Georgia-Puget Sound area. The results of the former study indicated that certain areas of the coastline were more susceptible to concentrated wave energy than others, because of variations in offshore topography (a finding described earlier by Hebenstreit and Bernard, 1985, for the case of 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 uses located in the inundation areas. The level of risk is based on projections of the near field calculations. 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 vulnerabilities to distinct and definable risks. The hazard analysis for this project consists of two parts. One is to project the geographic areas vulnerable to the direct tsunami hazard. The methodology to define this risk is application of numerical simulation. The other aspect of the hazard analysis is identification of secondary hazards caused by the earthquake and/or interaction of earthquake effects and tsunami. These base conditions were obtained through secondary sources such as soils data from the Washington State Department of Natural Resources.

HAZARD ANALYSIS

Numerical simulations of possible locally generated tsunamis were carried out in an earlier study (Hebenstreit and Murty, 1990) of the general threat to the Pacific coast from hypothesized subduction earthquakes in the Juan de Fuca Plate. Earthquake source parameters were postulated from an examination of such parameters 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 events. Several arbitrary vertical thrust values were used to provide a range of possibilities. By specifying reasonable parameters for these earthquakes, simulations identified the portions of the coast most susceptible to tsunamis originating in several specific sections of the plate. One such section, the Cascadia Zone, lies due west of the Washington-Oregon coast. Tsunamis originating in this area would focus a large portion of their energy on the southwest coast of Washington, including Grays Harbor.

Definition of general regions most likely to be threatened by a tsunami generated in the Cascadia subduction zone required a two-step process. The first step used a wave propagation model and a source model which indicates wave direction and general wave elevation. The second step used a site specific numerical model of the case study area, Grays Harbor. This analysis indicated that, as a result of source motions, highest tsunami energies would be directed toward the outer Washington coast and possibly the San Juan straits (Hebenstreit, 1988). Contours of the calculated seafloor uplift were first superimposed on contours of bottom topography for each of three source areas along the Cascadia subduction zone (Gorda Plate, South Cascadia, and North Cascadia zones). In all cases, the model indicates that uplift takes place offshore with some subsidence on land.

In the Cascadia south zone, as with other areas examined, the extreme wave height values are found along the coast within the source region. Dominant wave energy distributions are confined to the immediate source area, that is, the most extreme wave heights are found along the coastal zones within the source uplift zone. It was also found that the elevations do tend to taper off (although not uniformly) to the north and south of the immediate area of the uplift (Hebenstreit, 1988). The projected vulnerability also corresponds to the location of sand lenses discovered on the outer Washington coast at Willapa Bay and Grays Harbor by Atwater and others (1987) and Bourgeois and Reinhart (1988).

The mean value of the simulated wave heights in the South Cascadia zone indicates heights just below 6 m (20 ft) above MLLW. As figure 3 indicates, areas with projected mean wave heights in the range of 8 or 9 m (26-29 ft) are, however, found in the area between Newport, Oregon ,and Grays Harbor, Washington.

The results of this set of simulations were used to guide the application of a site-specific numerical model of the Grays Harbor area. This model, called SURGE II, allows for the simulation of long waves running to and onto a coastline. Thus the model can not only represent wave activity, but also can isolate flooding in low-lying areas along the shore. The model has been used in a number of tsunami simulations, including an extensive study of 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. Wave runup is **not** calculated in this model, only inundation. Radiation boundary conditions are applied to open ocean boundaries to ensure that wave energy leaving the grid is only minimally reflected back into it.

The model uses a numerical computation grid with variable seafloor and land topography. A realistic rendition of actual conditions is vital, since the process of interaction between long surface waves and the shoreline is heavily influenced by changes in water depth, as in coastal flooding. Figure 4 shows a plan view of elevation contours for the full model area, which includes both the area offshore and the Harbor itself. Grays Harbor is in the middle of the right edge of the plot. The contour line labelled "0" marks the approximate location of the shoreline.

One of the dominant features of the Harbor is the extensive mudflats. A large portion of the Harbor is extremely shallow, to the point 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.

The procedure used in the simulations is as follows:

- 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.

- These parameters are used in the Mansinha-Smylie (1971) model to predict the movement of the seafloor that such an earthquake would produce.
- This seafloor motion is translated directly into a disturbance of the sea surface which propagates toward the shoreline as a long wave (tsunami).
- The waves are allowed to interact with the coastal area and water level time series are recorded at specific points, as well as the locations on the grid where flooding is indicated.

The tsunami sources used in this study are located offshore of Grays Harbor. One source was centered approximately 200 km (120 mi) from the coast (the approximate location of the surface expression of a fault located at depth under the continental slope). The second was located only 100 km (60 mi) offshore to include possible inshore subsidence effects in the simulation. Since the model is essentially linear, both source motions produced approximately the same results, varying only slightly in the magnitude of wave heights calculated along the coast.

Figure 5 shows contours of seafloor (and hence sea surface) uplift from the more distant source. Positive values indicate **upward** motion. The uplift pattern was calculated by using the Mansinha-Smylie (1971) source displacement model with the parameters specified in table 3.

The source zone specified for this earthquake lies in the southern portion of the Cascadia zone, spanning the coast from near Coos Bay, Oregon, to just north of Grays Harbor. This source is one of the ones used in an earlier study (Hebenstreit, 1988) of generalized tsunami threat due to the Juan de Fuca Plate. The uplift pattern depicted in figure 6 is the northern end of the larger pattern.

In order to characterize the effects of the tsunami on the coast, a series of recording points were specified, and wave elevations at those points in the grid stored every simulation time step. The locations of these points are shown in figure 6.

Time series for several sets of these points are shown in figure 7 (stations on the outer coast), figure 8 (stations roughly along the axis of the main channel in the harbor), and figure 9 (stations at the far eastern end of Grays Harbor). Each plot contains data from several stations. In order to keep the plots from overlapping, an arbitrary offset 2 m (6.5 ft) has been added to every plot after the first (lowest) one.

Figure 7 shows the high amplitude waves which strike the outer coast soon after the uplift, with amplitudes of 7 or 8 m (22.75 - 26 ft). The figure indicates the initial wave and the successive waves which follow. In figure 9, we see that the stations closest to the mouth of the Harbor (stations 14, 19, 15) are initially subject to high waves which rapidly damp down to low amplitude, high frequency waves. Farther into the channel, initial amplitudes are greatly reduced. By the time the water reaches the Hoquiam/Aberdeen area (figure 8), it is less a wave and more of a gentle fall and rise in water level of about 0.5 m (1.6 ft).

Figure 10 shows the rough area of high level inundation predicted by the model. The axes are labelled in terms of grid locations in the numerical model. Grays Harbor is located between 70 and 75 on the y-axis. Except for some low-lying areas in the region of the Harbor opening, especially around the Westport area, all of the flooded sections are on the outer coast, which in this part of Washington is largely sandy beaches with dune barriers on their shoreward side. It is interesting to note that the embayment to the south of Grays Harbor, Willapa Bay, is the site of some of the recent sediment dating work which seems to indicate the possibility of subsidence events and tsunami inundation in the recent geological past (for example, Atwater, 1987).

The simulations indicate that for a number of reasons the interior of Grays Harbor appears to be relatively well protected from a serious tsunami threat. Grays Harbor essentially has a diamond shape. It has a 2.2 km (1.4 mi) narrow configuration at the mouth of the harbor and widens to approximately 21 km (13 mi), then narrows again at the mouth of the Chehalis River. One important factor in projection of tsunami impacts is that its configuration is expected to cause the wave to break at the mouth. Energy is dissipated as the wave breaks. Another factor contributing to the relatively moderate level of tsunami threat is that extensive shallow mud flats will quickly dissipate a large portion of the wave energy, resulting in reduced wave height inside the harbor. The amplitude continues to decline as the wave travels inland up the harbor to the Chehalis River. An initial wave amplitude of 2 to 3 m (6.5 to 9.75 ft) above the tidal level at the mouth of the harbor would diminish to 0.5 m (1.6 ft) by the time the incident wave reaches Aberdeen. Because other waves break at the mouth of the harbor, energy will be considerably reduced. It is, therefore, anticipated that the tsunami will be a relatively low-velocity event. A wave period of approximately twenty minutes is anticipated.

Even relatively small tsunamis have the potential to 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 structures can be severely damaged by anomalous surface motions, either due to drawdown or to seiching set up in a harbor. In addition, objects torn loose from their moorings can become dangerous floating projectiles. If the small tsunami occurs during a time of severe storm seas, anomalously high tides, or river flooding, it can prove destructive inland since under these conditions surface waves can propagate much farther inland than normally. Finally, if the resonance of the bay coincides with the period of the tsunami, the wave would be amplified by an unknown factor instead of dissipated.

Although the simulations were not run under flood conditions, historic flood levels are well documented. Flooding in the Aberdeen area is generally the result of high riverflows caused by winter rainfall generated by Pacific weather fronts combined with tidal flows. Tidal influence from Grays Harbor extends up the Chehalis and Wishkah rivers. High river flows may coincide with high tide to increase flooding. These conditions can be aggravated during rainstorms by backup of the City's storm drainage system when intense local runoff is prevented from entering the rivers because of high water.

The highest river and harbor water stages in the Aberdeen area result from a combination of high astronomic tides, low barometric pressure, strong onshore winds, and heavy rains. This combination of conditions has resulted on numerous occasions in extensive water damage to homes, businesses, and public property. High tide conditions occur frequently in Aberdeen. The highest water levels, measured at the Port of Grays Harbor staff gauge in Aberdeen, are shown in table 4. Flooding along the lower sections of the small streams in Aberdeen is primarily caused by high water in the rivers backing up to the creeks and inundating adjacent low areas. The Wilson Creek drainage basin was first clearcut in 1974. Additional logging operations have caused an increase in volume of water that comes down this creek during rainstorms.

A tsunami occurring at high tide and/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 (1.5 ft) could easily overtop and/or weaken the dikes protecting Aberdeen. The drawdown from the first tsunami wave can be expected to cause severe scouring on inland sides of the dikes; the second tsunami wave would probably destroy them.

VULNERABILITY ANALYSIS

The vulnerability analysis consisted of two primary components. One focused on definition of the population at risk within the coastal hazard zone (generally defined as below the 6.1-meter or 20-foot contour) based on the National Geodetic Vertical Datum (NGVD). The other was to define land use patterns and to identify specific characteristics of those uses which could result in secondary hazards; for example, presence of hazardous materials which are stored/or frequently transported frequently to or through a site.

Population at Risk

Population at risk from tsunami will vary seasonally. If the event occurs between late October and late March, it could coincide with periods of heavy rain-elevated river heights which would magnify the potential for extensive damage; population levels would, however, be relatively low. On the other hand, if the event occurs during the summer months, there would be high populations in the beach and resort communities along the open coasts.

The largest year round population center in Grays Harbor County is the Aberdeen/Hoquiam/Cosmopolis area with an estimated population of 30,605 (State of Washington Forecasting Division, 1988). As figure 11 indicates, this urban complex lies at the eastern end of Grays Harbor, a body of water fed by several rivers (including the Chehalis and the Wishkah) and open to the sea through a channel flanked by Westport on the south and Ocean Shores on the north.

Year-round population levels of the coastal communities are low. Winter populations tend to be below 5,000 residents. These levels fluctuate seasonally. During the summer, the wide sandy beaches of the Washington and Oregon coast are popular destinations for both Seattle/Tacoma and Portland urban areas. The 1986 population estimate for the greater Seattle/Tacoma area was 2,285,000, while the estimated population for Portland, Oregon/Vancouver, Washington was 1,350,000. Thus, virtually the entire coast is heavily populated during the summer months by campers and by tourists staying in the many beachfront facilities.

At worst, in the summer, the potential for life loss in the event of a local tsunami can be high in these coastal communities. For example, while the year round population of Ocean Shores is reported to be on the order of 5,000, approximately 35,000 people attended a one-day sand castle building contest in a nearby community. A large number of people working and residing in the urbanized Aberdeen/Hoquiam area could also be severely disrupted.

Land Use and Topography

Projection of land use disruption must rely on estimates of the inundation areas, which to a large extent, is a function of ground elevation. The analysis, therefore, encompasses all the area below the 6.1 m (20 ft) contour, the slope for which is 0 to 2 percent. The low-lying state of the land around the edges of Grays Harbor is illustrated in figure 12, which shows in three dimensions the elevations of Grays Harbor above mean sea level. Note the general lack of a distinct land/harbor boundary.

The three dimensional terrain model shown in figure 11 is used as the base for the land use analysis. Correlation of topography with land use permits rapid assessment of geographically based vulnerability. Land use patterns indicate that the urban/industrial areas in the central business districts (CBD) of Hoquiam and Aberdeen are on coastal lowlands, virtually all of which is unconsolidated fill. The urbanized area of the predominantly second home community of Ocean Shores, Washington is located entirely below 3 m (10 ft) grade elevation. The shores of Grays Harbor are the site of a number of industrial complexes. Approximately 25 percent of the workforce in Grays Harbor County are 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 wood pulp facility (owned by Weyerhaeuser) is located in South Aberdeen. Several port facilities are to be found in Grays Harbor; in 1985, a total of 5.8 million tons of materials were shipped through the Harbor, with approximately 55 percent of the total being logs. In addition, Westport is a center for commercial fishing. In summary, the Grays Harbor area, while not exceptionally large as economic centers are measured, contains a large investment in terms of both the commodities handled and the infrastructure required to serve the industries present. It is the busiest port in the Northwest with respect to distribution of northwest produced lumber. The figures quoted above are taken from the US Department of Interior (1988) Minerals Management Service.

This area of potential inundation encompasses all of the industrial areas, numerous bridges, and the state highway linking Grays Harbor with points to the north and the south. In addition, the CBD for both Aberdeen and Hoquiam, as well as residential areas in both communities are within the inundation areas, as figure 13 indicates. The headquarters of the fire station in Hoquiam and both fire stations in Aberdeen are within the coastal hazard zone.

A complete network of state highways, county roads, and city streets serve the coastal communities. Two principal state 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 system corridor. SR 101, which is basically a two-lane highway, serves the Olympic Peninsula and southwest Washington. Two-lane routes connect Ocean Shores and Westport and points north and south along the Pacific Ocean. Note that the routes of the highways are characterized by soft soils. As such, there is a high probability that transportation will be interrupted, making response and rescue difficult; for example, transporting fire fighters to the port.

Review of data collected in conjunction with analysis of damage in the 1964 Alaskan tsunami specifically mentions damage to four bridges in the southern Washington-northern Oregon region. Disruption from the projected event in the proximity could be even more disruptive to the industrialized area. For example, there are many bridges over rivers feeding into Grays Harbor including three draw bridges over the Chehalis and Wishkah rivers and one draw bridge crossing the Chehalis River between Aberdeen and South Aberdeen/Cosmopolis.

SECONDARY HAZARDS

Subsidence

One underlying earthquake-related threat which could enhance the destructiveness of a tsunami is susceptibility to subsidence caused by compaction under strong ground motion and/or tectonic displacement. Coastal subsidence commonly accompanies great subduction earthquakes where coseismic subsidence occurs in a primarily 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 approximately 1.6 to 2 m (5 to 6.5 ft) respectively (Curt Peterson, oral comm. 1990).

The effects of the 1964 Alaska subduction earthquake are well documented. These effects were particularly severe in areas where the 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 surface. Lateral spreading, too, caused lowering of surface levels in places (Plafker, 1969). In coastal areas where local subsidence was superimposed on regional tectonic subsidence, the damaging effects were magnified.

Two examples in Alaska from 1964 illustrate the combined effects of tectonic displacement and subsidence. On Kodiak Island, local subsidence of as much as 3 m (10 ft) was widespread in noncohesive granular deposits through compaction, flow, and sliding that resulted from vibratory loading during the earthquake. Subsidence in excess of 1.8 m (6 ft) occurred throughout the northern part of the zone. This phenomenon which was largely restricted to saturated beach and alluvial deposits or artificial fill, was locally accompanied by extensive cracking of the ground and attendant 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 attendant damage to intertidal organisms, nearshore terrestrial vegetation, and salmon spawning areas (Plafker and Kachadoorian, 1966).

Another example from the 1964 Alaska earthquake occurred in the Cook Inlet area which was downwarped. At the head of Cook Inlet near Portage, estuarine silt buried 18 km^2 (6 mi^2) of pre-earthquake lowland that had subsided 1.6 m (5.2 ft) and settled an additional 0.8 m (2.6 ft) for a total of 2.4 m (7.8 feet) (Atwater, 1987).

As the foregoing discussion of Alaska indicates, 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 soft and highly saturated such as the alluvium in virtually the entire urbanized Hoquiam/Aberdeen areas (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. Some areas are mantled by artificial fill. The dominant soil types of the flood plain area are approximately 1.5 to 1.8 m (5 to 6 ft) deep and range from moderately well drained, 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 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, there are zones of coarse sand and gravel. It appears that these zones are probably interbeaded with finer grained materials (Washington State Department of Natural Resources, 1987).

Figure 14 shows that existing conditions are predominantly non-engineered fill and/or highly saturated alluviums; both soil types are prone to compaction. If it is assumed that a combination of tectonic displacement, subsidence, and consolidation will occur in approximately equivalent amounts to the 1960 Chile, 1969 Alaska, and the Holocene Period Puget Sound events, then between 1.5 to 2 m (5 to 6.5 ft) would be likely to occur again. Under this assumption, all of the industrial areas, the majority of the commercial centers, and a significant component of the residential areas are at risk. Loss of these industrial facilities could have a long-term, devastating effect on the economy of the area.

In the event of subsidence, wave scouring action could further erode foundations and lead to structural failures. Furthermore, note that much of the area is made up of sand and sandy clay, which could liquify under severe shaking, causing foundations to sink differentially, breaking pipes, and storage structures. Finally, ground already saturated by the flooding will lose its bearing capacity. There will be a high incidence of foundation failures and buildings floating off their foundations.

Since subsidence appears to have been experienced in the past and seems likely to occur again, a simulation was run to project inundation under a subsidence scenario. Figures 15a and 15b compare the geographic area in Hoquiam under present conditions and with 1.8 m (6 ft) of subsidence, respectively. This latter assumption extends the flood-prone area inland.

Usual by Pacific coast tidal action causes the Chehalis River at Aberdeen to vary about 3 m (10 ft) in elevation on average -5.02 feet at Mean Lower Low Water (MLLW) to +5.11 at Mean Higher High Water (MHHW). Flooding problems develop first near the southeast city boundary when the Chehalis River reaches elevations between 2 and 2.3 m (6.5 and 7.5 ft) above mean sea level. This flooding remains fairly localized on land which is undeveloped. From elevation 2.3 to 2.6 m (7.5 to 8.5 ft), flooding spreads inland to affect residential and commercial properties in the southeast of South Aberdeen along Highway 101. In addition, properties along the Wishkah River in North Aberdeen are affected. The ten-year flood is estimated to be 2.7 m (8.8 ft); at elevation 2.8 m (9.0 ft), general flooding problems occur. The dikes protecting South Aberdeen, which generally are overtopped in many places with a crest between 2.6 and 2.8 m (8.5 and 9 ft) is reached. In addition, water enters the downtown area from the Wishkah river immediately to the east. Above 2.9 m (9.5 ft), which is equivalent to the 25-year flood, major flooding is experienced throughout the city. Flood-water velocity will become a problem at this stage since overtopped dikes will fail due to saturation and scouring.

If extraordinarily high tides or tide surges are accompanied by heavy rainfall, it is likely that flooding will occur earlier than when the above-mentioned river levels are reached. Since the peak astronomical tide for Grays Harbor coincides with the greatest threat of winter storm surge and rainfall for the area, the combinations of factors which potentially result in flooding occur every year between November and February. Ordinary high tides can be approximately 1.6 m (5.11 ft) at MHHW; an additional 0.5 m (1.6 ft) of tsunami inundation brings the level to 2.1 m (6.7 ft). Flooding problems have been noted to develop at 2 to 2.3 m (6.5 to 7.5 ft). The extra 0.5 m (1.6 ft) during winter flood conditions of 2.3 to 2.6 m (from 7.5 to 8.5 ft) inundate the downtown areas as well as the coastal highway.

Throughout the city, storm water runoff is fed directly into adjacent rivers and sloughs. The system in North Aberdeen is made up of underground culverts; in South Aberdeen, the system is open ditches. Storm drains become filled to overflowing when tide gates at the storm drain out-falls close due to high river levels. This storm water flooding can occur throughout the city and storm water ponding will remain as long as high river levels persist. Another problem which would develop is sewer overflow. The dikes would be overtopped at water level 1.9 m (6.9 ft) which is significantly below the 10- year flood event. If the 0.5 m (1.6 ft) of tsunami flood are added to the estimated 1.5 to 2.15 m (5 to 7 ft) of subsidence, then the flood level is essentially raised by roughly 2.3 m (7.6 ft) which would be damaging even at low tide.

Figure 16 indicates critical flood levels experienced in the past and defines flood elevations under conditions with a tsunami and with subsidence.

Battering

An important aspect of tsunami hazard often overlooked is the nature of secondary effects caused by incoming waves. A sudden rise in water level can lead to extensive damage from flooding and wave action on structures. It can also lead to less direct effects as coastal debris (such as logs, boats, 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 marinas in Westport, contains boats which, if torn from their moorings by currents set up 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 hotels and processing plants. Spaeth and Berkman (1972) and Wilson and Torum (1972) cite instances of this type of damage in the 1964 tsunami.

A wood pulp facility such as the Weyerhaeuser facility in South Aberdeen contains a number of characteristics which could result in a hazard from battering. Most notable are the logs piled up near the water's edge awaiting processing. Smaller piles could be floated under severe conditions and, like the fishing boats, become projectiles. Vessels moored at the plant's dock could suffer the same fate or be battered by other vessels and/or the logs. As an aside, it should be noted that every year during storm conditions people are hit and killed by an errant "killer log". Under tsunami inundation conditions, the increased velocities will turn these log storage areas into high hazard zones. In a similar vein, the ITT-Rayonier plant in Hoquiam, at the mouth of the Hoquiam River, is serviced by a railroad track. The cars standing on the tracks during flooding conditions are potential floating hazards.

Another hazard source in an industrial area is toxic materials stored on plant sites. For example, it is not known if the piles of waste materials found on the grounds of the paper plant could pose a long-term health and contamination hazard if they were set to dispersing under flooding conditions.

Fire and Air Contamination

Hoquiam/Aberdeen populations are at risk from possible fires and contamination erupting in the industrial port area which could spread to the neighboring residential and commercial areas. Although the precise cause and dimensions of fire or contamination have not been predicted, it is clear that toxic chemicals could pose a devastating hazard if, for whatever reason -- ground motion, wave action, or flotation -- their storage containers were to be breached.

Grays Harbor is a principal port for the Northwest forest products industries. Manufacturing of a wide range of products, for example, wood shakes, use an extensive range of chemicals in conjunction with preservative, fire retardant, and related treatment. Fire is always a problem when storage tanks are breached; toxic materials storage facilities are a major threat when facilities are disrupted. Contamination could occur in two ways. One would be contamination of surface and/or groundwater. Surface water contamination would essentially be coterminous with the projected inundation area. The other would be airborne contamination.

The Environmental Protection Agency SERA Title III Program requires mandatory public disclosure of hazardous materials stored in an amount exceeding a threshold level for each chemical as specified. 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, a simulation of selected materials under two scenarios was applied to the study area for a site which had registered the presence of toxic materials.

The Computer-Aided Management of Emergency Operations (CAMEO™ II) program developed by the National Oceanic and Atmospheric Administration (NOAA) Hazardous Materials Response Branch was used to project the geographic extent of vulnerability. This model is designed to help emergency planners and first responders both plan for and safely handle chemical accidents.

CAMEO's air dispersion model has the capability to simulate potential dispersion of toxic gases under a variety of wind and weather conditions. It simulates the extent of a plume downwind from a chemical spill and the "footprint" of the chemical plume drawn by the computer from a defined location pinpointed on a base map. The analysis reported in this paper entered project base maps to facilitate correlation of the air dispersion analysis with land use patterns. Since concentrations differ for each chemical, the results of adverse effects vary widely. Two scenarios were developed by the project to illustrate the patterning of possible air contamination:

- Scenario I: Small Quantity
  - > Threshold limits: 100 lbs. or 500 lbs. (ammonia and chlorine projected)
- Scenario II: Large Quantity
  - > Release from partial rupture of an average railroad tank (5,000 lbs. of chlorine)
- Other variables as shown in table 5 were based on average wind and temperature conditions during summer versus winter:

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

- Immediately Dangerous to Life and Health (IDLH)
  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. During the period immediately following a spill, no one should enter an IDLH atmosphere without a self-contained breathing apparatus.
- Threshold Limit Value-Time Weighted Average (TLV-TWA)
  This condition occurs within the first 30 minutes after the spill. In TLV conditions the gases are more disperse and pose a less general, but still serious, threat.

Figures 17a and 17b show the extent of potential airborne contamination from a release of 45 kg (100 lb) of chlorine gas at the ITT-Rayonier plant under both summer and winter average wind conditions. When reviewing the following spill scenarios, it is important to realize that CAMEO tends to *understate* heavy gases such as chlorine by a factor of approximately 2. Thus, the IDLH is, in reality, approximately twice as extensive as shown for chlorine in figures 17a and 17b.

The conditions depicted in figure 17a are for the summer period under IDLH and TLV conditions. Note that the threatened areas are primarily residential and that the Fire Department is potentially within the contamination zone. This type of threat is twofold, since not only are the lives of the fire station personnel at risk, but also the ability of the community to respond to the emergency. Figure 17b is for the same parcels as are shown in figure 17a under conditions of winter prevailing winds.

INTEGRATED HAZARDS MANAGEMENT

Once the base data was developed with respect to delineation of the threat and the characteristics of vulnerability it becomes possible to correlate the two. The physical threat including inundation, strong currents, and a potential for ground subsidence, is correlated with land use characteristics. An integrated (physical/social/economic) basis is thereby created for projecting 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 serves to highlight the reality that hazards are cumulative. That is, the water hazard, while itself dangerous, can precipitate still other hazards with even farther reaching consequences.

The geographic location, land use, and underlying soils constitute a system of base perimeters resulting in variable vulnerability. Defining tsunami hazard boundaries can be used for two purposes. One is to define possible vulnerability areas which can be used to plan for damage mitigation. The other is to define evacuation parameters. Once risk locations are defined it becomes possible to develop a risk reduction program responding to the specific characteristics organized according to sub-areas. Analysis of risks indicate that they are primarily a function of use. Thus, for example, the apparent lack of a high-impact tsunami threat within the inner harbor indicates that the dominant threats for which Grays Harbor must be prepared relate to the "secondary hazards". These secondary hazards include battery, loss of soil strength, and fire and/or air contamination. During high tide and/or river-line flood conditions, major flooding may exacerbate high water conditions created by the tsunami.

Microzonation

The specific nature of the tsunami threat is very much determined by underlying soil conditions and land use patterns. Once the conditions are clearly defined, an integrated hazard management system organized into a series of microzones which reflect these conditions can be applied. A word of caution must be interjected at this point. This hazard analysis constitutes the basis for geographically delineating the risk area. The next step in the planning process requires more specific data upon which actual design can be based. The microzones defined by the project and illustrated in figure 18 are as follows:

■ Tsunami High Impact Zone

> Area Delineation

Based on the flooding delineation as shown in figure 10, it is apparent that the only outer coastal areas encompassing the communities of Ocean Shores and Westport are vulnerable to direct tsunami impact. Since the ground elevation of both communities is approximately 3 m (10 ft) above grade, most of the town areas are within the high hazard zone. The remainder of the study area does not appear vulnerable to direct high level high velocity tsunami impact.

> Preparedness and Mitigation Issues

In Ocean Shores, critical planning issues pertain to warning and evacuation. Population levels in this second home community fluctuate seasonally; a tsunami event which occurs in the summer could result in comparatively high life loss, while the risks during winter are considerably less.

In Westport, primary concerns relate to the presence of the fishing fleet. A major cause of destruction in the 1964 Alaska tsunami and earthquake was caused by 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. The tendency for boat owners who have any warning of an approaching tsunami is to remove their vessels from their anchorage and head to the open sea. Many of the preventable deaths in Alaska during the 1964 tsunami 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 made knowledgeable of proper procedures to be followed in the event of a tsunami warning. It may be necessary to bar owners from entering the marina area if warning time is not sufficient for evacuation before the first several waves have passed.

- Flooding and High Probability of Subsidence Zone
  - > Area Delineation

    The majority of the urbanized Hoquiam/Aberdeen Central Business District/Port is below 5.5 to 6.1 m (16.5 to 20 ft) in elevation and is reported to be on fill and/or soft alluvial soils. This type of soil has a tendency to amplify ground motion. It is also prone to subsidence. If the experiences of great subduction earthquakes are assumed (Chile, Alaska, Holocene age), approximately 0.5 m (1.6 ft) of subsidence from compaction could accompany approximately 1.5 m (4.9 ft) of tectonic subsidence resulting in a total flood elevation of 2 m (6.5 ft) above existing MHHW of 1.7 m (5.5 ft). Under these assumptions, the area vulnerable to flooding effects encompasses all of the land inland to the present 6.1 m (20 ft) grade elevation. Dominant uses of the urbanized areas are commercial in the CBD area and industry which is associated with the port or with forest products industries.
  - > Preparedness and Mitigation Issues

    Two categories of issues based on use have been identified in the urbanized zone. For the commercial zone preparedness and mitigation must address conditions related to risk from damage and/or collapse of structures. For industrial uses critical issues pertain to vulnerability of hazardous materials either transported and/or stored on site, the effects of which could be transported either by flood waters or by air. Preparedness plans consider two zones of risk:
    - > the immediate inundation area including airborne contamination hazard zone under IDLH conditions;
    - > the large area vulnerable to TLV (airborne) spread conditions as well as the area disrupted by interruption of major transportation routes.
- Emergency Preparedness Priority Area

  The outer coastal areas of the states of Washington and Oregon are linked to the interstate highway system by state routes. Significant portions of these routes (which include an extensive network of bridges and roadways) lie within the zone projected for flooding. It is thus inevitable that 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, roadway access will be disrupted and 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 two day period before adequate resources through mutual aid can arrive.

CONCLUSIONS

Integrated hazard assessments based on tsunami threat have not, to our knowledge, been undertaken previously; in general, studies have focused almost exclusively on flooding as a threat. It is clear from this effort that an examination of the interconnectedness of many potential hazards can lead to more fruitful analysis of a multi-faceted threat. Additional specific questions remain. These include:

- More data should be collected concerning foundation design/condition of structures in the flood hazard zone.
- Merchant vessels moored in the harbor will be subjected to tsunami-induced current motions. These motions should be calculated and preventive docking practices instituted.
- It should be determined whether toxic material storage facilities are located in areas prone to tsunami-induced flooding. The design of these facilities must be reviewed because of the potential for breaching the containers, thereby releasing toxic chemicals into the air and water
- The impact of the primary (tsunami) and secondary threats on the community response capabilities in the immediate time frame and in the post-disaster time frame should be defined, both in geographic terms and response resources (manpower and equipment)

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TABLE 1: MAXIMUM RECORDED WAVE HEIGHTS (FT) ALONG THE PACIFIC COAST FOR FIVE TSUNAMIS

LOCATION	1946	1952	1957	1960	1964
Tofino, BC	1.9	2.0	...	4.6	8.1
Port Alberni, BC	...	...	...	...	>17(a)
Victoria, BC	0.7	1.2	...	...	4.8
Neah Bay, WA	1.2	1.5	1.0	2.4	4.7
Friday Harbor, WA	...	...	...	0.6	2.3
Seattle, WA	...	...	...	...	0.8
Astoria, OR	...	...	0.5	1.0	2.4
Crescent City, CA	5.9	6.8	4.3	10.9	>13(b)

Notes: (a) Gauge record incomplete; wave height estimated
(b) Maximum excursion before gauge destroyed

Sources: U.S. Department of Commerce (1953), Salsman (1959), Symons and Zetler (undated report), Berkman and Symons (undated report), Wilson and Torum (1968), Spaeth and Berkman (1972)

TABLE 2: WATER LEVELS AND DAMAGE ALONG PACIFIC COAST OF WASHINGTON, MARCH 28, 1964

LOCATION	HEIGHT (FT) ABOVE TIDE	DAMAGE ($)	DAMAGE DESCRIPTION
La Push	5.3	---	Several boats and floating dock broke loose from moorings.
Mouth of Hoh River	1.7	---	None
Tahola	2.4	1,000	Loss of several skiffs and fish nets in inlet at mouth of Quinault River.
Wreck Creek Bridge	14.9	500	Erosion of fill at bridge approach; debris on bridge deck and nearby highway.
Town of 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. reinforced concrete spans (Joe Creek).
Copalis River Highway	---	5,000	Shoulder erosion and deposition of debris on highway.

Town of Moclips	11.1	6,000	Damage to ocean side of buildings by floating logs; one building moved off of foundation; timber pile bulkheads and fills extensively damaged; water over some floors from 6 inches to several feet; heavy debris scattered over yards.
Ocean Shores	9.7	---	Deposition of debris on streets near Central Motel office; debris in streets and yards in vicinity of break in sand dune dike about 3/4 mile south of Central Motel office.
Town of Pacific Beach	---	12,000	Medium size house lifted off foundations and partly torn apart (total loss); several sheds moved off foundations; second building partly damaged; yards eroded and covered with debris.
Town of Seaview	12.5	---	None
Town of Ilwaco	4.5	---	Minor damage
Cape Disappointment	5.7	---	None

Source: Hogan and others (1964) reported by Wilson and Torum (1968).

TABLE 3: SOURCE PARAMETERS USED IN MODEL SIMULATIONS

Source depth	30 km
Fault length	400 km
Fault width	100 km
Dip angle	10 degrees
Maximum vertical displacement	10 m

TABLE 4: HIGHEST KNOWN FLOODS IN ABERDEEN (IN ORDER OF MAGNITUDE) [1]

ORDER NO.	DATE OF FLOOD	WATER LEVEL IN FEET ABOVE MEAN SEA LEVEL [2]
1	December 17, 1933	10.3
2	December 1934	10.0
3	November 1913	9.7
4	December 1923	9.7
5	November 14, 1981	9.7
6	December 3, 1982	9.6
7	1912	9.5
8	December 1920	9.4
9	December 11, 1977	9.4
10	December 21, 1972	9.3
11	December 11, 1973	9.3
12	January 27, 1983	9.3
13	November 24, 1983	9.3
14	December 13, 1941	9.2
15	December 18, 1960	9.2
16	January 27, 1964	9.2
17	December 13, 1977	9.2
18	November 30, 1951	9.1

[1] Information on floods prior to 1971 is based on the June 1971 Flood Plain Information report by the Corps of Engineers which reports 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 acknowledges 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. Updated by Bill Langford, 1990. No major river flooding has occurred since November 1983.

[2] Grays Harbor Staff Gauge Records were converted to mean sea level, National Geodetic Vertical Datum (NGVD) using the Flood Plain Information Report, C.O.E. 1971 and the Summary of Tidal Elevations and Datum Planes, Aberdeen 1981.

TABLE 5: AIR DISPERSION ASSUMPTIONS FOR HOQUIAM/GRAYS HARBOR

FROM - TO	DIRECTION	AVERAGE SPEED	AVERAGE TEMP
January - March	From Southeast	10.7 mph	35.0° F
July - September	From West	11.6 mph	65.0° F

* Ground Roughness is URBAN. No inversion present.

FIGURE CAPTIONS

Figure 1.	Grays Harbor study area located in South Cascadia Zone.
Figure 2.	Damage from 1964 tsunami: Seward
Figure 3.	Projected wave heights off shore: South Cascadia Zone
Figure 4.	Offshore topography used in numerical simulations. Depths are in meters, with seafloor values < 0.
Figure 5.	Contours of seafloor uplift pattern from a possible earthquake in the Grays Harbor region. Positive values indicate upward motion of the bottom.
Figure 6.	Locations of model grid locations at which time series of waves were recorded.
Figure 7.	Time series taken at several offshore locations during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)
Figure 8.	Time series taken at several channel locations during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)
Figure 9.	Time series taken at several locations in Hoquiam/Aberdeen during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)
Figure 10.	Locations of coastal grid points which were under water at some time during the simulation.
Figure 11.	Grays Harbor land use patterns
Figure 12.	Three-dimensional view of land elevations around Grays Harbor. Note the lack of a truly distinct land-harbor boundary in most places.
Figure 13.	Detailed land use: Aberdeen/Hoquiam CBD.
Figure 14.	Soil and sediment structure around Grays Harbor.
Figure 15a.	Topography correlated with land use patterns in Hoquiam: Existing conditions.
Figure 15b.	Topography correlated with land use patterns in Hoquiam: 1.8 m (6 ft) of subsidence.
Figure 16.	Critical flood levels.
Figure 17a.	Potential spread of chlorine gas from vicinity of ITT-Rayonier plant under summer temperature and wind patterns.
Figure 17b.	Potential spread of chlorine gas from vicinity of ITT-Rayonier plant under winter temperature and wind patterns.
Figure 18.	Zonation of Grays Harbor for earthquake hazards

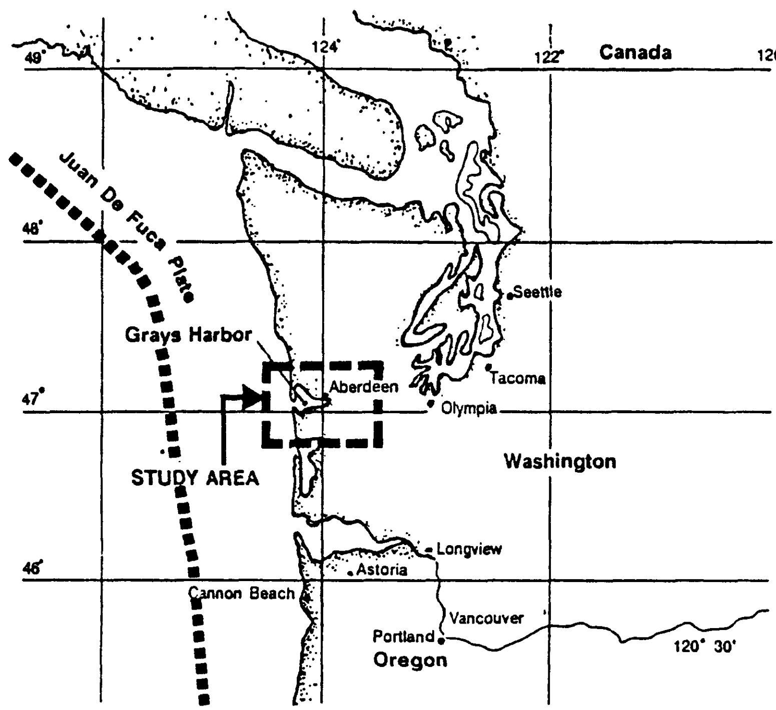


FIGURE 1.–Grays Harbor study area located in South Cascadia Zone.

	BUILDINGS			MARINE STRUCTURES		LIFELINES					OTHER	
Primary Causes of Damage	WOOD FRAME	MASONRY /CONCRETE	STEEL FRAME	WHARVES DOCKS PIERS	JETTIES BREAK WATERS	ROADS AIR STRIPS	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												

○ Least Severe ◐ Moderate ● Most Severe

Source: Planning for Risk: Comprehensive Planning for Tsunami Hazard Areas; Prepared by Urban Regional Research for National Science Foundation; 1988.

Figure 2.–Damage from 1964 Tsunami: Seward

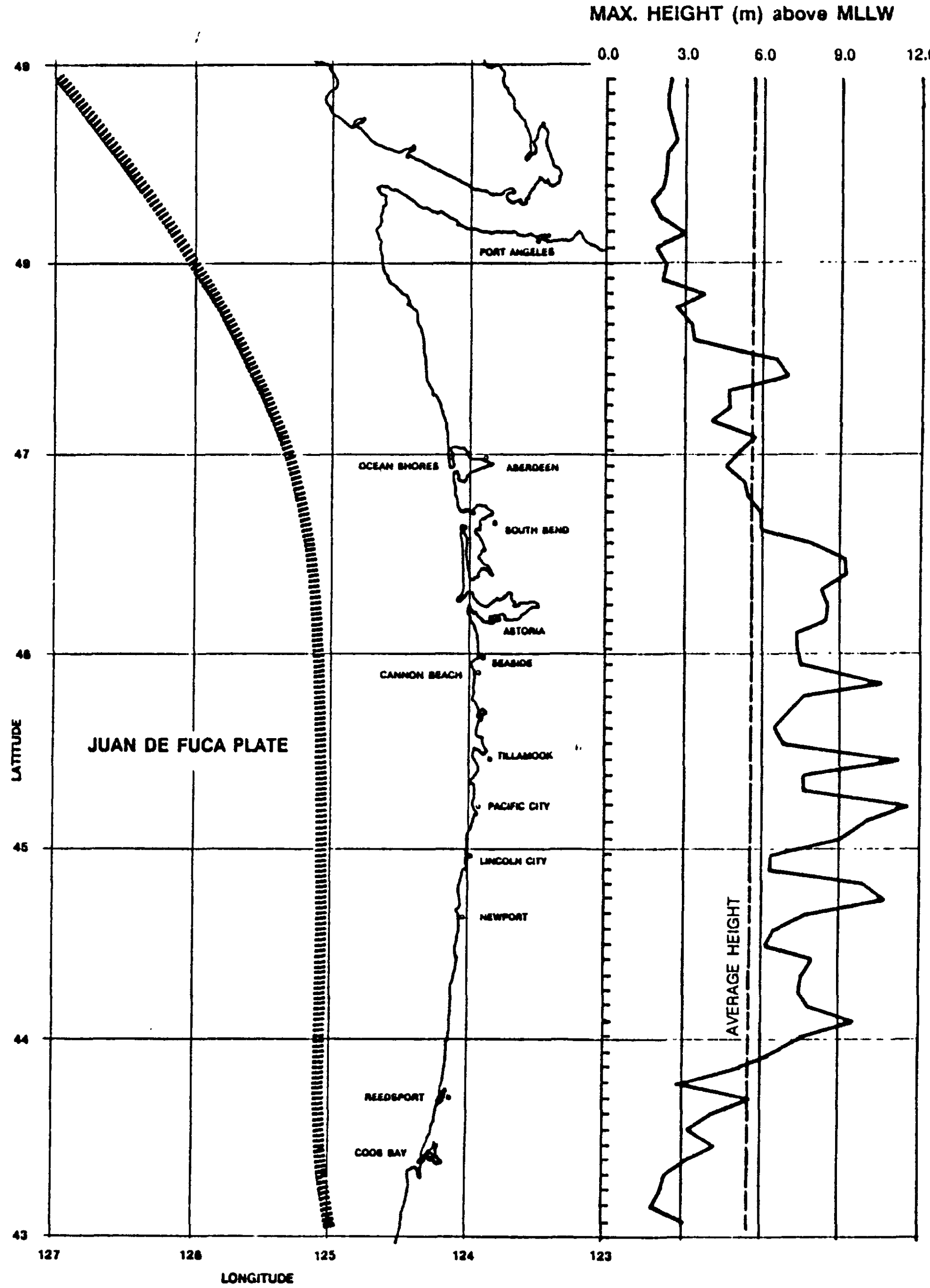


FIGURE 3.--Projected Wave Heights Off Shore: South Cascadia Zone

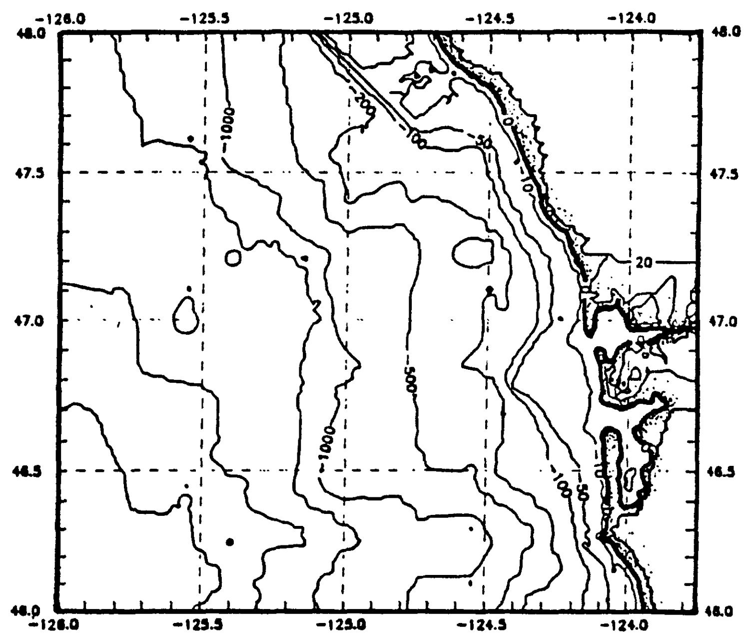


FIGURE 4.--Offshore topography used in numerical simulations. Depths are in meters, with seafloor values < 0.

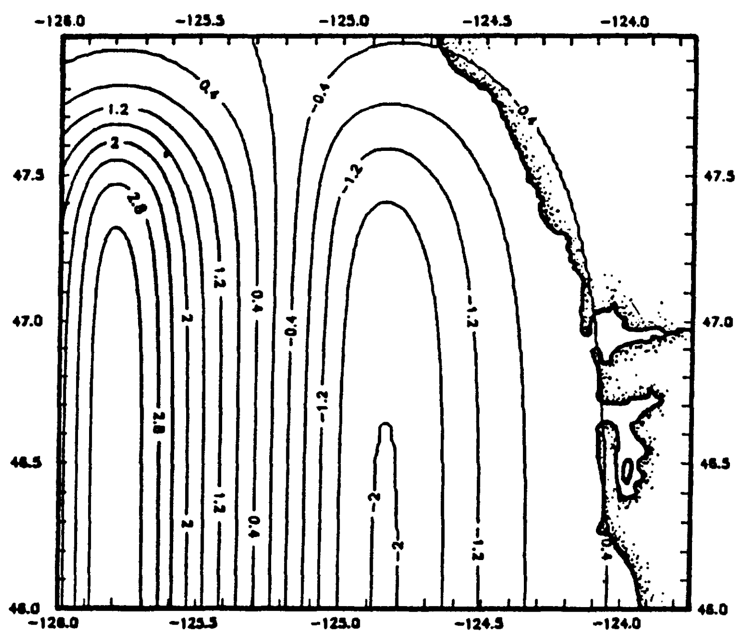


FIGURE 5.--Contours of seafloor uplift pattern from a possible earthquake in the Grays Harbor region. Positive values indicate upward motion of the bottom.

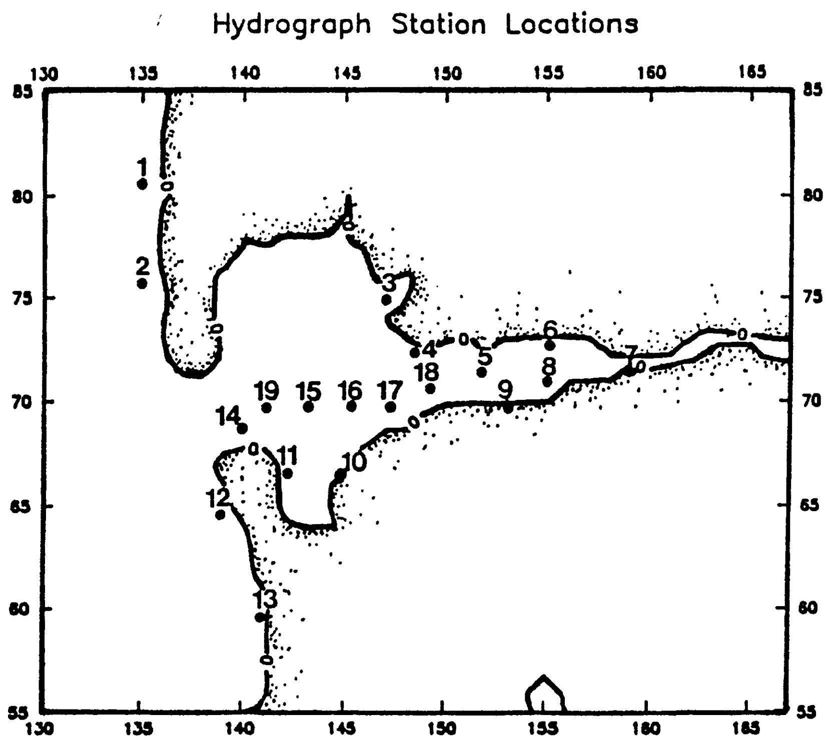


FIGURE 6.–Locations of model grid locations at which time series of waves were recorded.

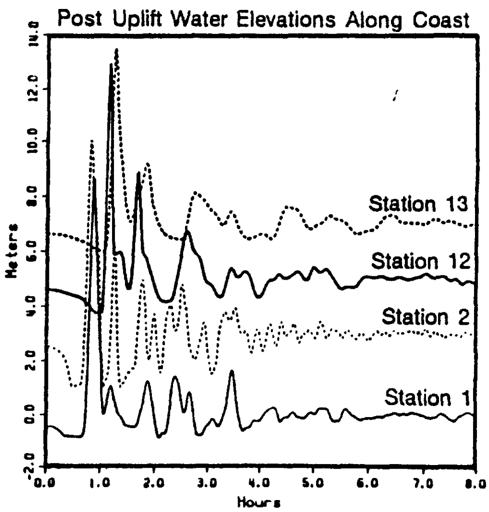


FIGURE 7.--Time series taken at several offshore locations during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)

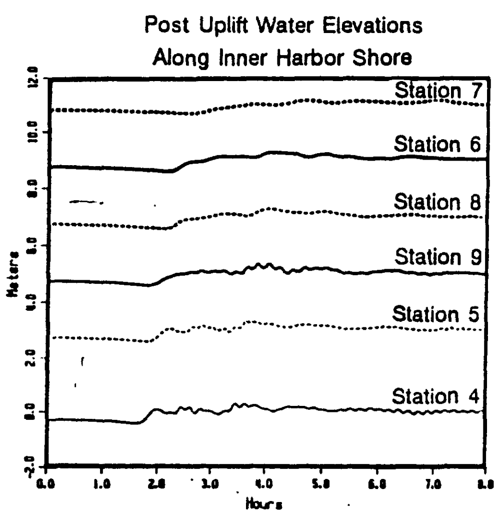


FIGURE 8.--Time series taken at several channel locations during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)

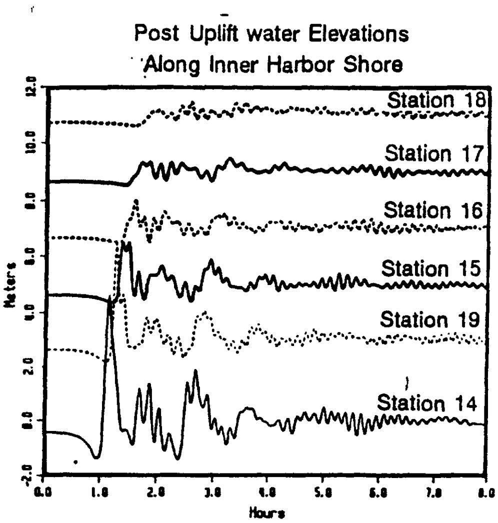


FIGURE 9.--Time series taken at several locations in Hoquiam/Aberdeen during simulation based on Figure 6. (To minimize overplotting, each series is offset by 2 meters from the previous one.)

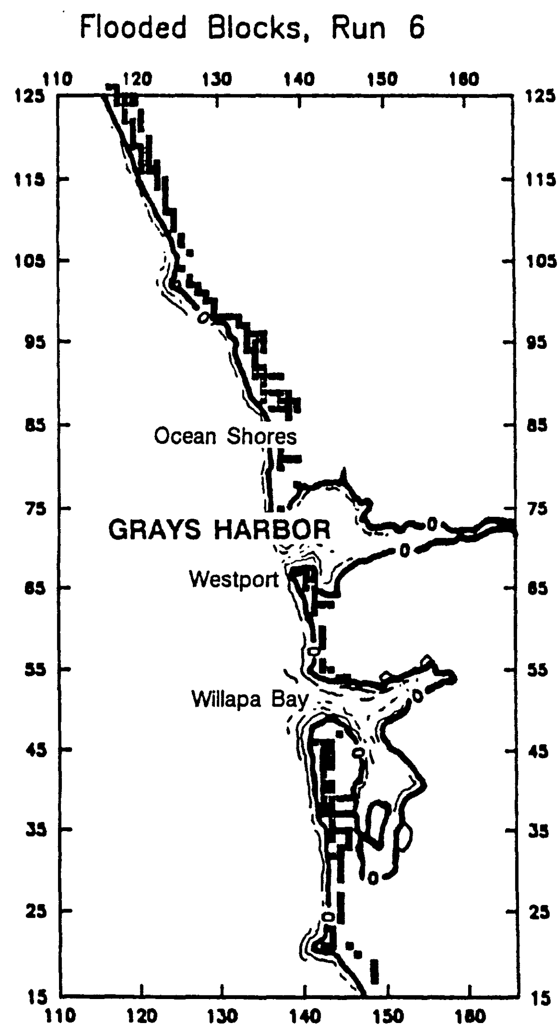


FIGURE 10.--Locations of coastal grid points which were under water at some time during the simulation.

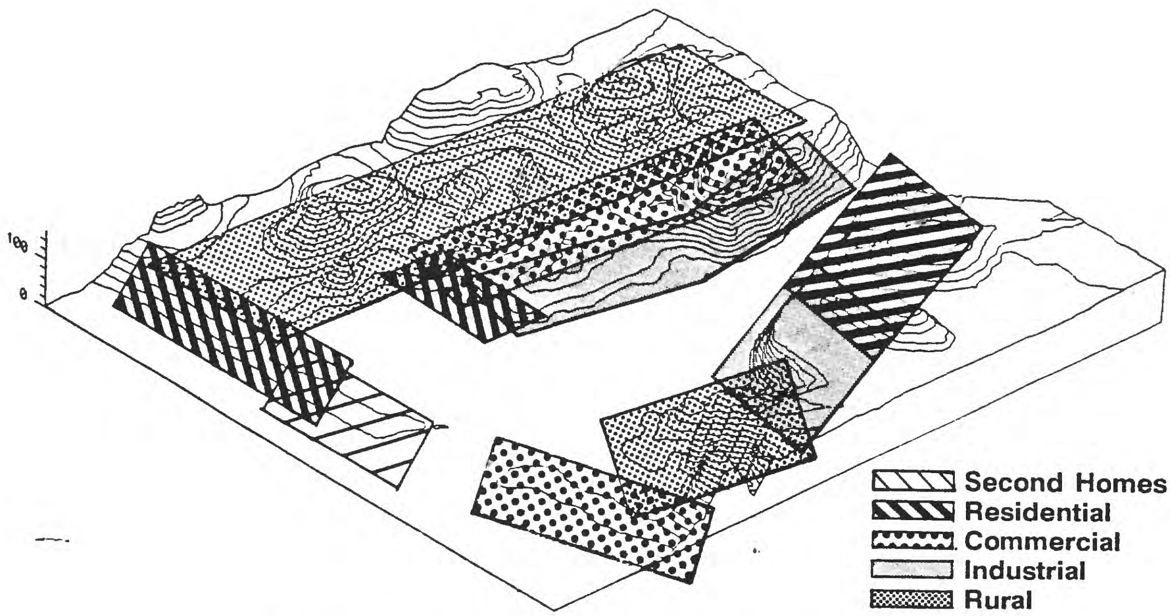


FIGURE 11.--Grays Harbor Land Use Patterns

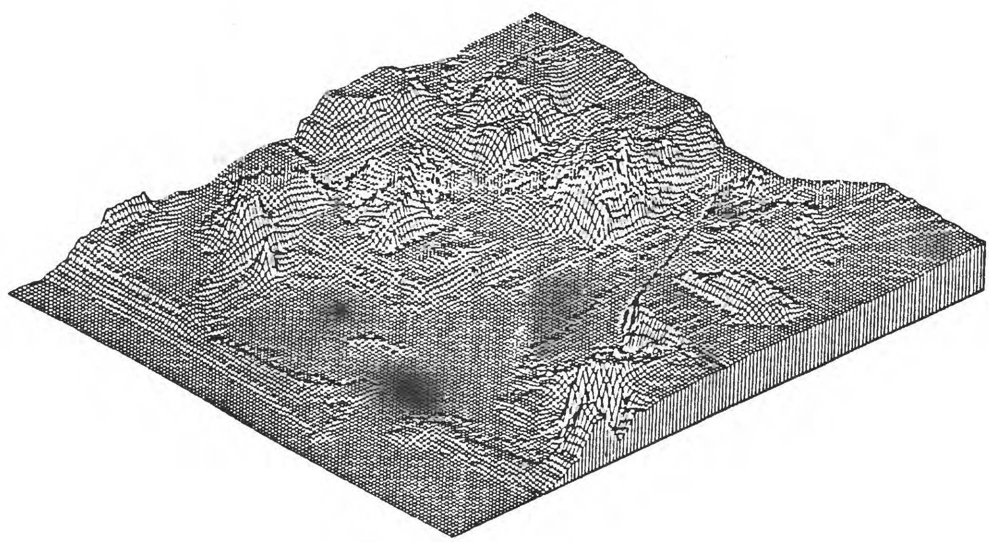


FIGURE 12.--Three-dimensional view of land elevations around Grays Harbor. Note the lack of a truly distinct land-harbor boundary in most places.

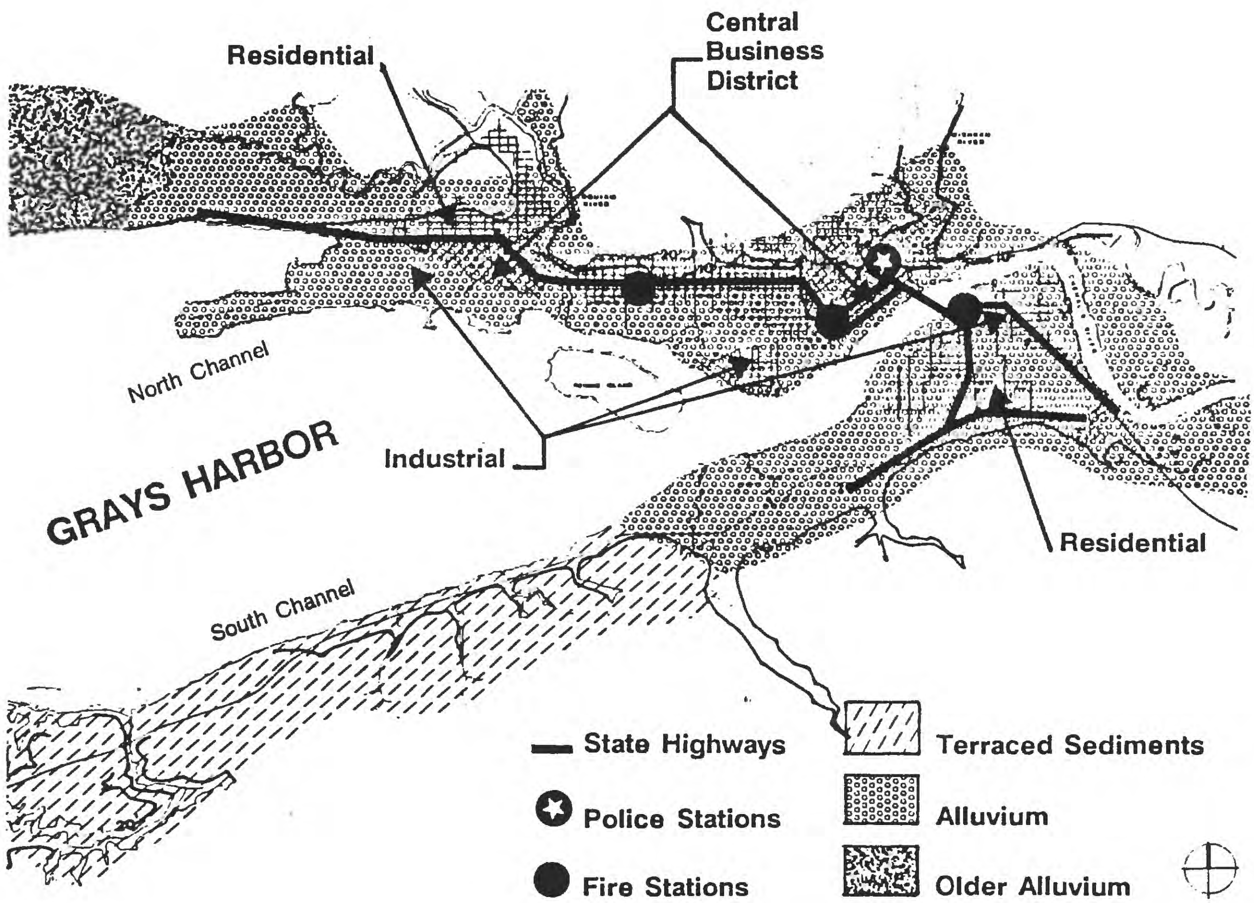


FIGURE 13.–Detailed Land Use: Aberdeen/Hoquiam CBD

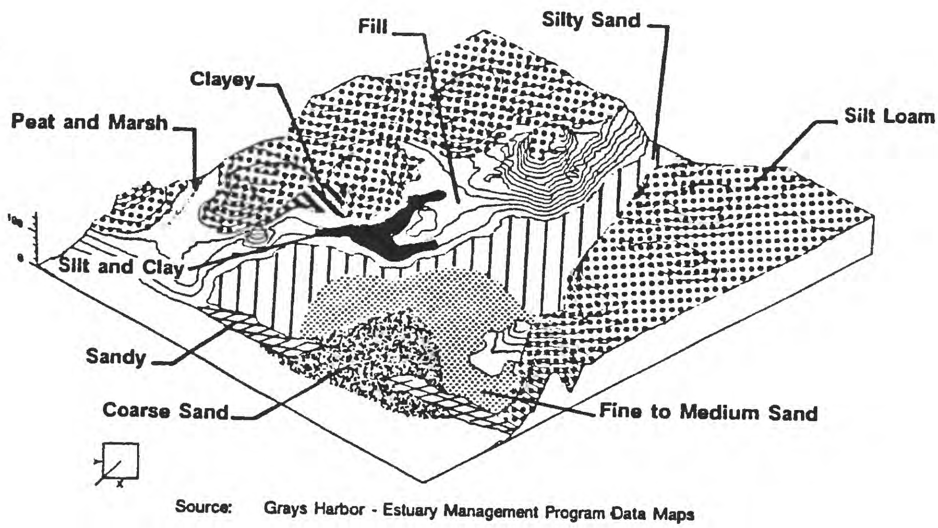


FIGURE 14.–Soil and Sediment Structure Around Grays Harbor

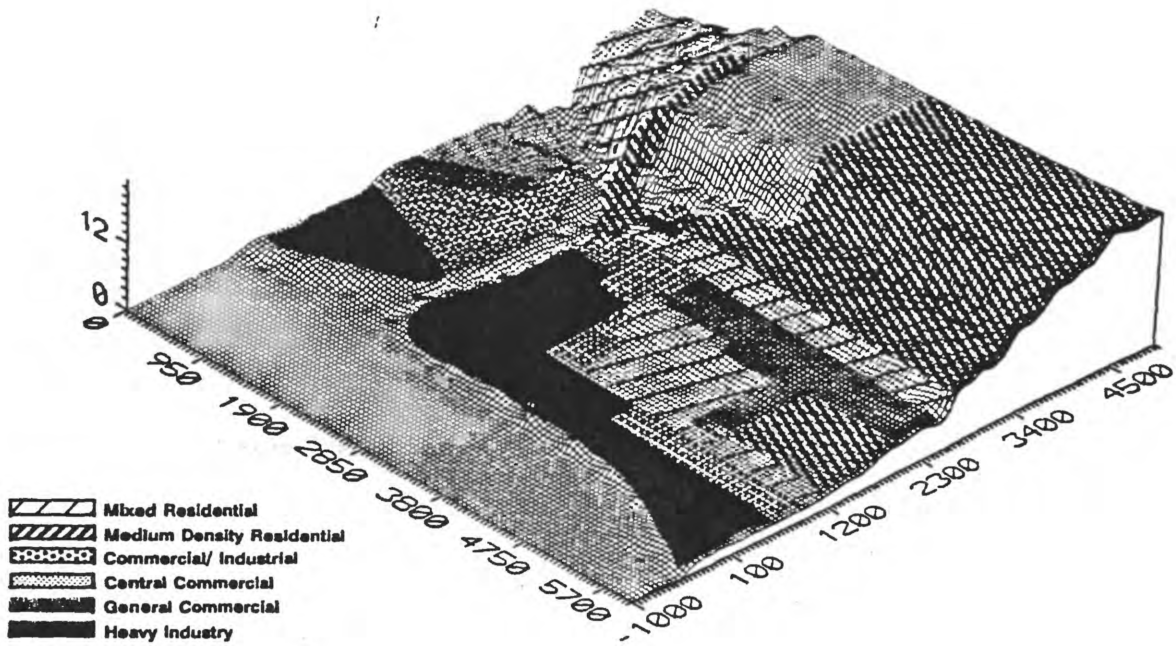


FIGURE 15a.--Topography Correlated with Land Use Patterns in Hoquiam: Existing Conditions

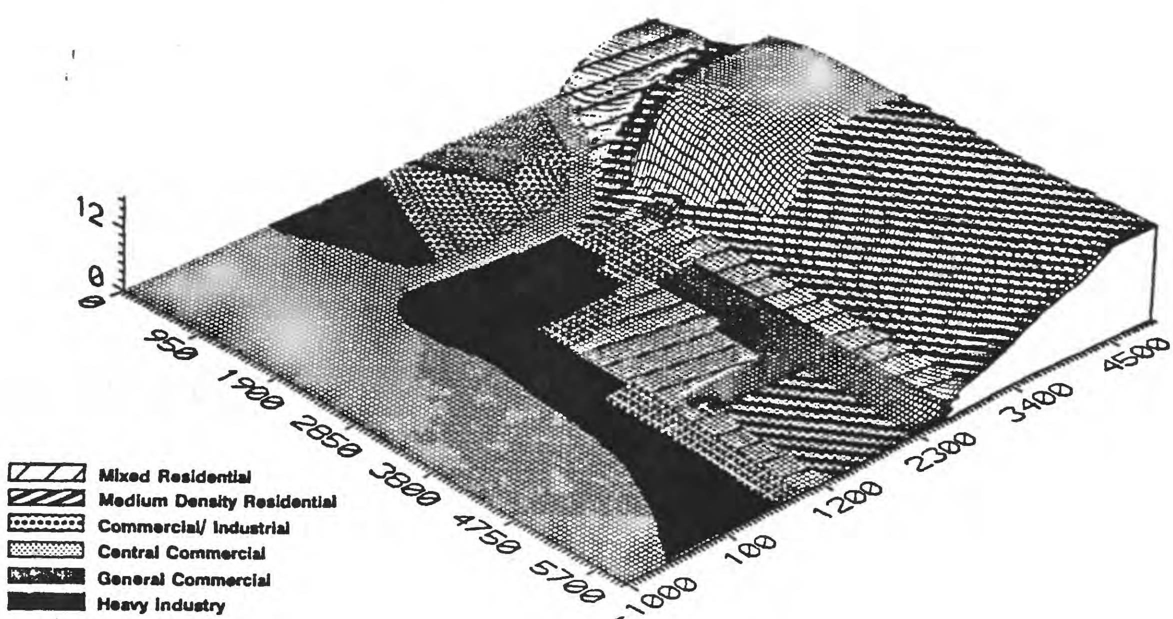


Figure 15b.--Topography Correlated with Land Use Patterns in Hoquiam: 1.8 m (6 ft) of Subsidence

Source: Hazard Mitigation and Preparedness Plan: City of Aberdeen; Prepared By Urban Regional Research for State of Washington Department of Emergency Management, Federal Emergeny Managemnet Agency; 1986.

	METERS	FEET
Mean High Tide	1.6	5.1
Tsunami (approx.)	.57	1.6
Subsidence (approx.)	1.5-2.15	5.0-7.0
Total Susceptible Elevations	2.07-2.72	6.6-8.5
Critical Flood Levels	2.0-2.3	6.5-7.5

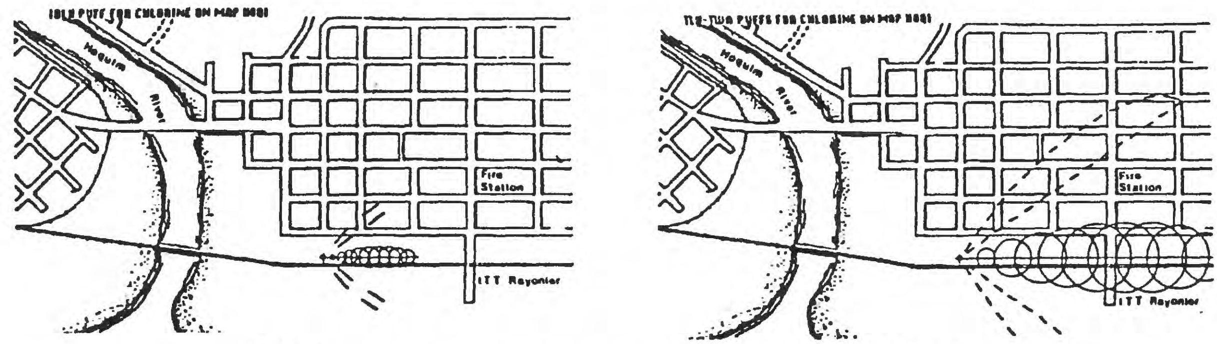
- - - - - - Elevations Above Mean Sea Level NGVD

.... Dikes

▭ 100 Year Flood Boundary (FEMA/NFIP)

Low lying areas will be subject to flooding during low tide; during high tide the entire urbanized area will be subject to extensive flooding which, because of the deeper water level, could be relatively high velocity.

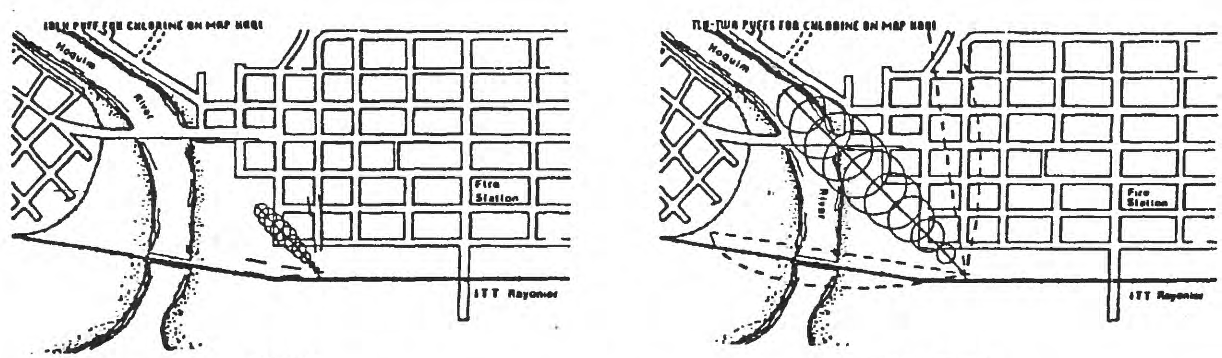
FIGURE 16.--Critical Flood Levels



IDLH
Immediately Dangerous to Life and Health

TLV-TWA
Threshold Limit Value - Time Weighted Average

FIGURE 17a.--Potential spread of chlorine gas from vicinity of ITT-Rayonier plant under summer temperature and wind patterns.



IDLH
Immediately Dangerous to Life and Health

TLV-TWA
Threshold Limit Value - Time Weighted Average

FIGURE 17b.--Potential spread of chlorine gas from vicinity of ITT-Rayonier plant under winter temperature and wind patterns.

- SOURCE STRENGTH: 100 pounds
- TLV-TWA= 1.00 PPM
- IDLH= 30.00 PPM
- CHLORINE
  Extreme irritant to mucous membranes; can react to cause fires or explosions upon contact with some substances; emits highly toxic fumes when heated; reacts with water to produce toxic and caustic fumes.

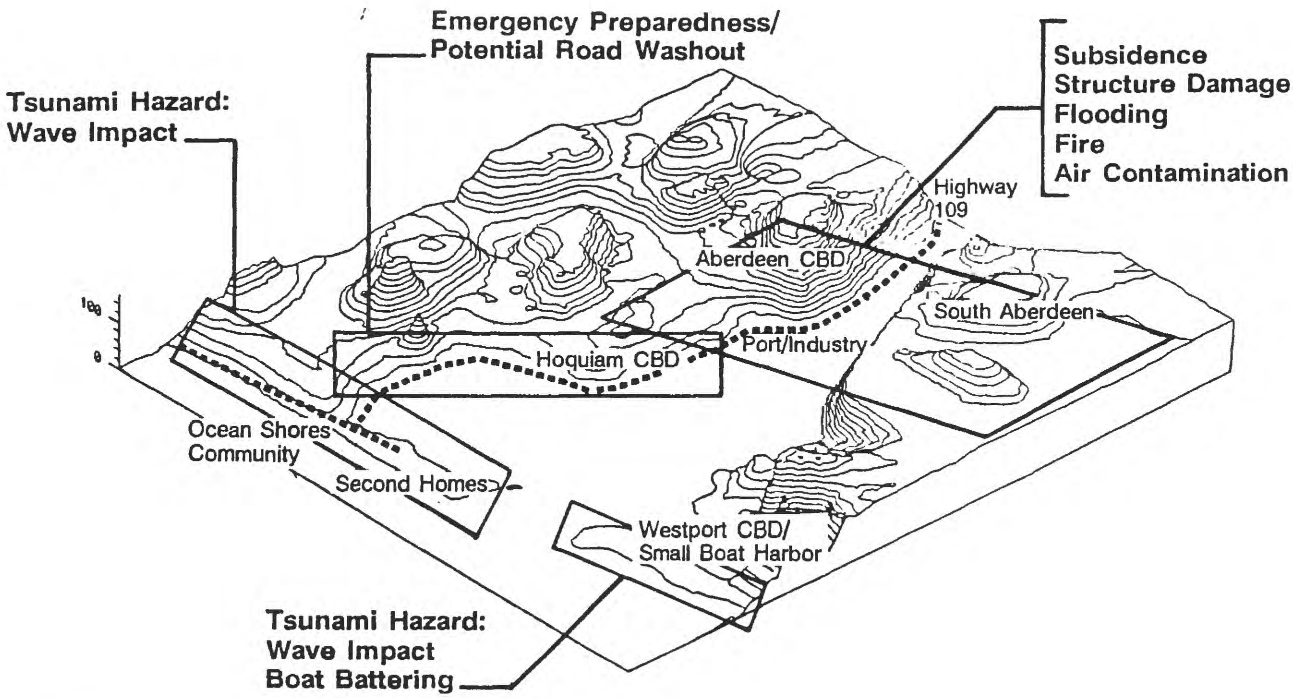


FIGURE 18.–Zonation of Grays Harbor for Earthquake Hazards