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Sea Level Rise in Washington State: State-of-the-knowledge, Impacts, and Potential Policy Issues

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SEA LEVEL RISE IN WASHINGTON STATE: STATE-OF-THE-KNOWLEDGE, IMPACTS, AND POTENTIAL POLICY ISSUES

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Douglas J. Canning

Shorelands & Coastal Zone Management Program
WASHINGTON DEPARTMENT OF ECOLOGY
Olympia, Washington 98504-7600

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Douglas J. Canning
Shorelands and Coastal Zone Management Program
Washington Department of Ecology
Post Office Box 47600
Olympia, WA 98504-7600
Telephone: 206.407.6781
Telefax: 206.407.6535
Internet: dcanning@igc.apc.org

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SUMMARY

Sea level rise is an existing phenomenon, as well as a future likelihood of global climate change. The existing sea level rise is caused by long term global warming as Earth emerges from the last ice age. During the past century, sea level has risen approximately 0.12 meter (0.4 foot).

Accelerated sea level rise is an expected secondary effect of global climate change due to a warming and expansion of the existing ocean water, plus an increase in the amount of ocean water from the melting of snow fields and glaciers. Just as there is a good measure of uncertainty about exactly how greenhouse gases will affect global climate, there is uncertainty as to both the exact timing and magnitude of accelerated sea level rise. The original US Environmental Protection Agency scenarios for sea level rise through 2100 ranged from 1.8 to 11.3 feet (0.6m to 3.5m), with the mid-range low scenario (4.7 feet; 1.5m) considered most likely. Since EPA published their original scenario in 1983, scientific thinking has focused on acceleration scenarios ranging from 0.5m (1.6 ft) to 2.0m (6.6 ft) rise by 2100. This is a 5- to 20-fold increase over the present rate of rise.

Absolute (global) sea level rise is affected by local vertical land movement—uplift or subsidence—resulting in a relative sea level change. Uplift moderates or negates absolute sea level rise; subsidence produces a greater rate of relative sea level rise. Washington state is affected by both uplift along portions of the Pacific Ocean coast and subsidence within Puget Sound.

The obvious effects of sea level rise include an increased frequency and intensity of coastal flooding, inundation of coastal wetlands and lowlands, and increased shoreline erosion. Less obvious effects include increased sea water intrusion into coastal fresh water aquifers, alteration of sewage treatment plant outfall hydraulics, and changes in tidal currents and patterns in marine bays such as Puget Sound, Grays Harbor, and Willapa Bay.

Some governments agencies are considering or have already enacted policy decisions relating to sea level rise effects. A key finding of the National Research Council's *Committee on Engineering Implications of Changes in Relative Sea Level* (1987) is that the appropriate levels of government to address sea level rise response are the state and local levels. The San Francisco Bay Conservation and Development Commission adopted amendments to their Bay Plan in February 1989, requiring engineering design for existing sea level rise and conceptual planning for accelerated sea

level rise. The US Army Corps of Engineers adopted a policy of designing for existing sea level rise. Planning and policy studies have been initiated by a number of states; these efforts are reviewed in the reports prepared for Shorelands' Sea Level Rise Policy Alternatives Study.

The Shorelands and Coastal Zone Management Program, Washington Department of Ecology, initiated the Sea Level Rise Response program in 1988. During 1988-89 an interagency Task Force was established to assist Shorelands with problem definition and identification of potential policy issues. The Task Force was merged with the Department of Ecology's Environment 2010 Global Warming Subcommittee in January 1989.

The effects of sea level rise will cut across agency and program areas of authority and expertise. The Shorelands & CZM Program will be particularly affected because it administers the state's Shoreline Management Act and Flood Plain Management Act, and Washington's federal Coastal Zone Management Program.

Conclusion

We don't yet know, and in the near term can't know with absolute certainly, when sea level rise acceleration will begin, and precisely how much sea level will rise in the future. Research evidence tells us that sea level is rising, and solid scientific theory tells us that the rate of rise may increase substantially in the future. Logic, therefore, tells us that we must prepare for changes in our planning for coastal land uses and facilities while monitoring sea level rise.

How, though, can coastal planners and engineers reasonably prepare for changes in our planning for coastal land uses and facilities without certainty as to the rate and amount of increase?

There is a model for planning and engineering design in the face of high uncertainty, one that has worked well in practice, and with which planners and engineers have become quite comfortable. This model is the hydraulic design storm—the 50 year event, the 100 year event, etc.

Through time, a generally accepted practice has evolved whereby hydraulic structures such as culverts and bridges are designed to withstand or pass storm discharges of varying volumes depending on what is at risk and how much risk we are willing to accept. For low risk (high-risk-tolerance) situations, a 25 or 50 year storm event is the design standard; for progressively higher risk (lower-risk-tolerance) situations the 100 year or 500 year storm event is the design standard. We accept this with little question, even in the face of weather records of less than 100 years.

We will likely come to accept a similar approach to planning and designing for sea level rise acceleration as that in itself becomes more common. For high-risk-tolerance situations, a sea level rise scenario of 0.5 m by 2100 may become the standard. For progressively lower-risk-tolerance situations, progressively greater sea level rise scenarios will be applied. For example, a coastal highway can be relatively easily raised if the sea level rise design projections are found to have been set too low. Conversely, repeated remediation of a coastal hazardous waste site may be judged too risky from a fiscal and public health stand point, thus warranting a higher design standard.

Finally, regardless of greenhouse effects, there are present adverse effects of sea level rise—erosion, bluff landsliding, and wetlands modification—which should be addressed. To a large degree, response to sea level rise acceleration will involve little more than prudent coastal zone management—abstaining from development of and building in the coastal zone in imprudent ways.

> Throughout this report "boxes" of special information will appear inset and single spaced, thusly. These boxes provide extra technical information not entirely necessary to the flow of the main text. They can be thought of as in-text glossary entries.

GLOBAL CLIMATE CHANGE AND SEA LEVEL RISE

This section will briefly place global climate change and sea level rise in context. This is not a comprehensive review of global greenhouse effect or sea level rise. There are sufficient publications commonly available which do that admirably—two that are recommended are *Greenhouse effect and sea level rise* (Barth and Titus, 1984) and *Projecting future sea level rise: Methodology, estimates to the year 2100, and research needs* (US Environmental Protection Agency Publication EPA 230-09-007). Much of this section is summarized from an edited and updated version of a Department of Ecology Environment 2010 project report on global warming and ozone depletion (Canning, et al., 1990).

Global Greenhouse Effect

The "greenhouse effect" is a natural atmospheric effect whereby carbon dioxide and other greenhouse gases absorb energy radiated from the Earth's surface, trapping it in much the same way the glass of a greenhouse traps radiant energy, warming the interior of the greenhouse. Current evidence shows that carbon dioxide accounts for about half the greenhouse effect, with other gases such as nitrous oxide, methane, carbon monoxide, water vapor, and chlorofluorocarbons (CFCs) accounting for the other half. Greenhouse gases are any atmospheric molecules made up of three or more atoms.

What is really at issue here is a modification of the greenhouse effect by industrial emissions during the past century. Prior to the beginning of the Industrial Revolution in the 19th Century, the atmospheric carbon dioxide level was about 280 ppm. By 1955 it had increased to about 315 ppm, and in 1989, about 350 ppm, an increase of 70ppm. The principal sources of increased carbon dioxide are from combustion of fossil fuels—petroleum hydrocarbons and coal—and the burning of the tropical forests. Carbon dioxide levels are predicted to at least double during the next century. Corresponding increases in nitrous oxide, methane, and CFCs are also expected to continue. Nitrous oxide increases are combustion by-products; methane increases are derived from increased cattle keeping and rice planting; CFCs are used as coolants, industrial cleaning fluids, etc., and are man made substances with no natural analog.

> When the National Science Foundation released its first report on global warming (Charney, et al., 1979), the analyses were based on a doubling of carbon dioxide which was then expected to occur sometime late in the 21st century. Since then, the importance of

the other greenhouse gases has become better known. Global warming analyses now include consideration of all the greenhouse gases, but generally speak in terms of an "effective doubling" of carbon dioxide, that is, a doubling of greenhouse gas effect due to the combined effect of carbon dioxide plus the other greenhouse gases. The phrase "effective carbon dioxide doubling" is often represented as "$2XCO_2$" in the technical literature, and present conditions as "$1XCO_2$." An effective doubling of carbon dioxide is now predicted as early as 2030, and at least by 2050.

Climate Change

The greenhouse effect results from the trapping of radiant energy in the troposphere (lower atmosphere) by greenhouse gases. Most, but not all ultraviolet (UV) radiation is filtered by the stratospheric (upper atmosphere) ozone layer, and some penetrates the troposphere. Visible radiation penetrates the troposphere and is reflected from the surface of the earth as infrared (IR) radiation. IR radiation does not pass out through the troposphere, and thus is trapped, warming the Earth. Without the greenhouse gases, the Earth's surface would be approximately 30°C cooler than it is, thus prohibiting life—the planet would be frozen. If Earth had a carbon dioxide atmosphere as does Venus (95% CO_2) or Mars (98% CO_2), Earth's average surface temperature would be about 290°C.

There is good agreement (and some dissent) in the scientific community that:

- Carbon dioxide and the other greenhouse gases are accumulating in the atmosphere.
- As these gases accumulate, they are expected to cause a gradual increase in global average temperature; an effective doubling of CO_2 may occur as early as 2030.
- An effective doubling of CO_2 is expected to eventually cause global average temperature increases of at least 1.5°C and as much as 4.5°C; however, some researchers believe the delay may be as much as 60 years.
- With this gradual warming changes in wind, rainfall, and other climatic patterns are expected.
- There will be substantial regional variability. In general, temperature increases will be greater in the polar latitudes and lesser at equatorial latitudes; some areas may be cooler than at present.
- Global precipitation will likely increase; regional precipitation may increase or decrease.
- Sea level rise due to warming and expansion of the oceans plus ice and snow melt could result in increases of 0.5 to 2.0 meters by 2100.

Uncertainty

Global climate change and sea level rise are characterized by a high degree of uncertainty, and a high degree of risk if we (society) are wrong in our assessment. Funtowitz & Travetz (1985; in Gerlach & Rayner, 1988) characterized three kinds of science and decision making: (1) "consensual (applied) science," (2) "clinical consultancy," and (3) "total environmental assessment." Consensual science is characterized by low decision making stakes, high consensus in professional circles, large amounts of data, and therefore high certainty; the architectural and engineering design sciences are consensual science. Clinical consultancy issues are characterized by uncertainty and considerable decision stakes, but are ones in which professional expertise is still a useful guide; most environmental impact analysis is clinical consultancy. When decision stakes and uncertainty are both high, the process is permeated by qualitative judgements and value commitments; global climate change and sea level rise evaluation are just such "total environmental assessment" issues.

Global climate predictions, or more accurately, scenarios, are based on General Circulation Models (GCMs), complex computer models. Five GCMs are in common use, four American and one British. The American GCMs are: the GISS model developed by James Hansen's team at NASA's (National Aeronautics and Space Administration) Goddard Institute for Space Studies, New York City; the GFDL model developed by the Princeton University Geophysical Fluid Dynamics Laboratory for the National Oceanic and Atmospheric Administration (NOAA); the OSU model developed by Michael Schlesinger's team at the Department of Atmospheric Sciences, Oregon State University (Schlesinger has since moved to the University of Illinois); and the ORNL model developed at the US Department of Energy's Oak Ridge National Laboratory, Oak Ridge, Tennessee.

General Circulation Models do not have sufficiently fine resolution to produce consistent regional scenarios. The grid or cell compartments used in GCMs are a few hundred miles on a side, usually covering an area larger than the state of Washington. A stack of cells represents the atmosphere. Each cell is assigned a set of single values to represent temperature, precipitation, etc., at a particular time. Each GCM uses a different cell size and makes different assumptions about global climate interactions. Other sources of uncertainty include an imperfect knowledge of exactly how the atmosphere functions and interacts with the oceans. Thus, the GCMs, while in good general agreement as to global average temperature changes, show less agreement, and often disagreement as to regional climate change patterns. A more expansive discussion of uncertainty can be found in the companion report, *Global climate change and ozone depletion: The state-of-the-knowledge for Washington State* (Canning, et al., 1990).

Sea Level Rise

Sea level rise is an existing and long term phenomenon. At the close of the last glaciation 14,000 years ago sea level began to rise rapidly, totaling about 70m (230 feet) of rise by about 6,000 years ago, at an average rate of nearly a meter per century or about 2.9 feet per century. The rate of rise then slowed, and in recent times, sea level risen about 0.10 to 0.15 m (0.3 to 0.5 feet) per century. (Barth & Titus, 1984:8; Fairbridge & Krebs, 1962; Barnett, 1984). Recent research in San Francisco Bay indicates a sea level rise rate of 0.0039 feet per year (0.4 feet/century) (Moffat & Nichol, 1988:42). Presently, 1.2 mm/yr is the generally accepted rate of existing rise for predictive modeling (Park, et al., 1988; Titus, 1988). Recent trends in global average temperature and global sea level are shown in Figure 1. Sea level rises and falls through intervals ranging from seconds to geologic ages. Variability may be periodic or secular (nonperiodic). The variability in sea level shown in Figure 1 is caused by variations in meteorological conditions (barometric pressure, winds, etc.), evaporation, salinity, precipitation, river discharge, and water temperature (Hicks, Debaugh & Hickman, 1983:2). In the North Pacific, short term increases and decreases in sea level have been associated with *El Ninos* and *La Ninas* during the 1980s.

Awareness of long term sea level rise has been hampered by a lack of emphasis even in the scientific community. As recently as 1974, a major scientific monograph titled *Sea level changes* (Lisitzin, 1974), published by one of the leading scientific publishers emphasized short term sea level variations due to winds, atmospheric pressure, seasonal water balance, and seiches ("sloshing" in oceanic basins). Eustatic factors—long term sea level changes—were dismissed in four pages in this 280 page book.

Sea Level Rise Scenarios

Accelerated sea level rise is an acknowledged secondary effect of the greenhouse effect. Only the rate of acceleration is debated. The US Environmental Protection Agency scenarios for sea level rise through 2100 range from 1.8 to 11.3 feet (Hoffman, Keyes & Titus, 1983), with the mid-range low scenario (4.7 feet) considered more likely.

Sea level rise is predicted to occur due both to global warming of the oceans (and thus their expansion) as well as the melting of snow and ice, adding to the amount of water in the oceans. The factors which are thought to influence future sea level rise are summarized in Table 1. These factors are the basis for sea level rise scenarios developed by the US Environmental Protection Agency and summarized in Table 2. The low range scenarios were developed using the low assumptions, and the high range scenarios, the high assumptions. The US EPA researchers then acknowledged that it is unlikely—though possible—that either extreme scenario (high or low) would occur. Therefore, two mid-range scenarios were developed. In recent years, the generally accepted sea level rise scenarios have fallen into a range from at least 0.5 m to 1.5 or 2.0 meter rise by 2100 (see Figure 2).

Other scenarios have been developed which go beyond the US EPA predictions. One scenario postulates a collapse of the West Antarctic shelf ice in addition to any sea level rise due to thermal expansion and ice and snow field melting. A collapse of the West Antarctic shelf ice would result in a sea level rise of about 6 m (20 feet) at rates over 30 mm/yr, taking about 200 years to realize the full 6 m of rise. There is evidence for this kind of collapse having occurred approximately 150,000 years ago. Many glaciologists have great concern that global climate change could initiate such a collapse; on the other hand, many climatologists do not yet find evidence for future global warming sufficient to cause such a collapse. In recent years at least two large icebergs about the size of the state of Rhode Island have broken off the main Antarctic ice mass and drifted out to sea. It's not known how frequently this occurred in past decades or centuries.

The most far-reaching theory envisions a complete melting of the Greenland and Antarctic ice caps, resulting in a sea level rise of about 200 feet. This is last thought to have occurred approximately 2 million years ago. A melt-down such as this would require many thousands of years. There is little scientific support for this scenario.

In the fall of 1988, *The Seattle Weekly* published a cover story on global climate change and sea level rise. The writers and editors chose to feature the ice cap melt-down scenario. This enabled an interesting front page illustration of Seattle's Space Needle mostly under water, and inside story maps showing Puget Sound covering the Green and White river valleys, creating an island of the plateau stretching from Federal Way to West Seattle. Future local effects might become serious, but hardly that dramatic!

Conclusion

Sea level is expected to rise in the future at a more rapid rate than in the recent past. It may be 20 or 30 years before we can expect more accurate predictions. The National Research Council's *Committee on Engineering Implications of changes in Relative Mean Sea Level* concluded in 1987 that:

> The risk of accelerated mean sea level rise is sufficiently established to warrant consideration in the planning and design of coastal facilities.

The committee went on to recommend that:

> Options should be kept open to enable the most appropriate response to future changes in the rate of sea level rise. Long-term planning and policy development should explicitly consider the high probability of future increased rates of sea level rise.

The National Governors' Association's *Task Force on Global Climate Change* issued their report, *A World of Difference* in 1990, recommending that the following responses to accelerated sea level rise be taken: Strengthen Coastal Zone Management Programs; Develop Appropriate Land Use Plans; and Develop Appropriate Protective Infrastructure.

Modeling the future effects of sea level rise requires the selection of scenarios. Currently, the most commonly used scenarios for accelerated sea level rise are 0.5, 1.0, 1.5, and 2.0 m by 2100, plus existing sea level rise as a base line. Occasionally a 3.0 m rise by 2100 scenario will be used as a scenario.

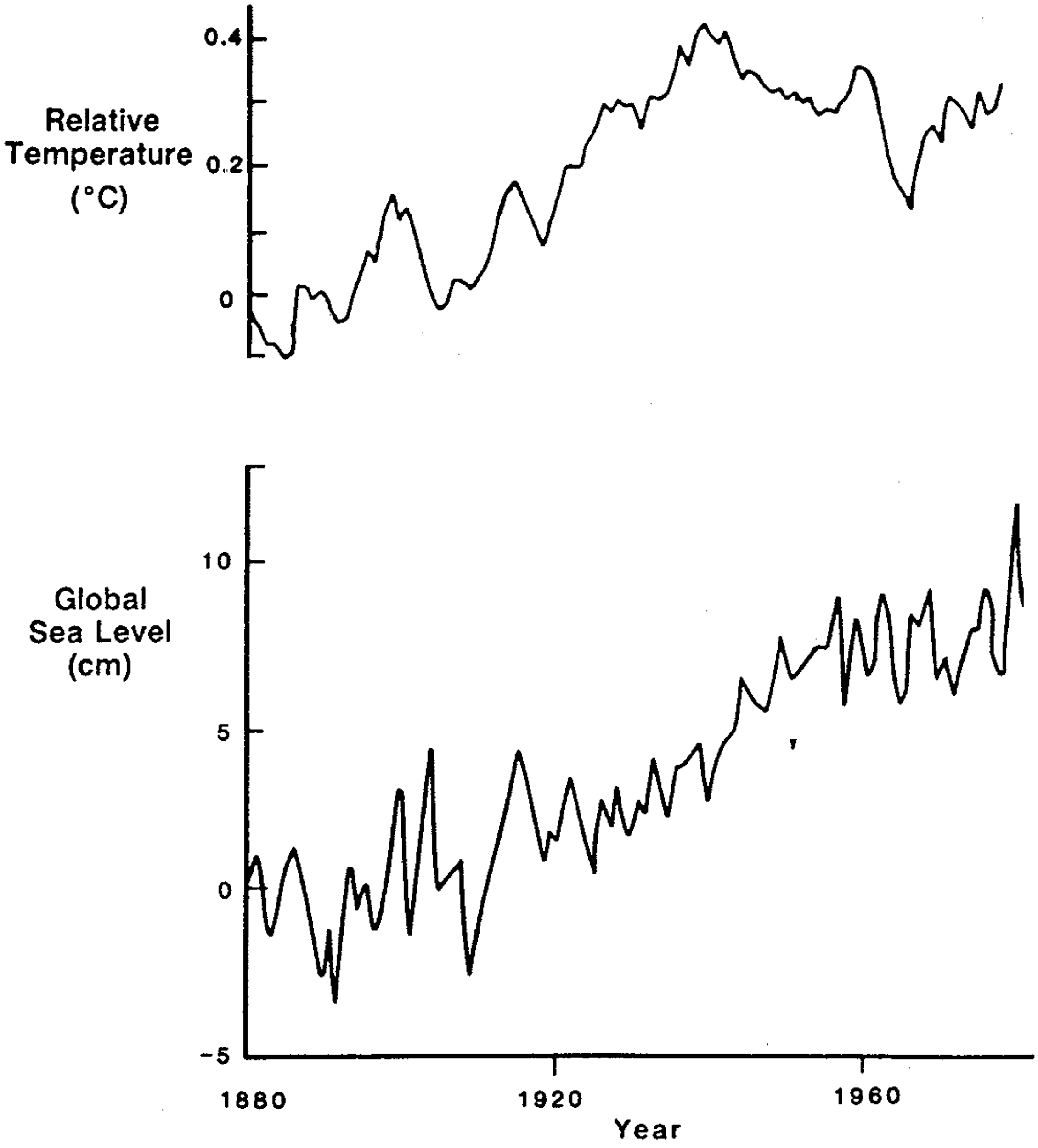


Figure 1. Global temperatures and sea level trends during the last century. Reproduced from Titus, 1987:4. (Temperature curve from Hansen, et al., 1981; sea level curve adapted from Gornitz, Lebedeff & Hansen, 1982.)

Table 1. Summary of high and low assumptions used to estimate sea level rise by the US Environmental Protection Agency.

Factor	Assumption	
	Low	High
Population Growth	All scenarios assumed the world will reach zero population growth by 2075.	
Productivity	2.2% per year; decreases to 1.7% by 2100.	3.5% per year; decreases to 2.2% by 2100.
Energy Technologies	Best estimate; nuclear costs halved arbitrarily.	Best estimates.
Unexpected Additions to Fossil Fuel Base	None.	None.
Energy Conservation	All countries move toward high efficiency (60% improvement in energy efficiency).	
CO_2 Fraction Airborne	53%.	ORNL Model; 60% increases to 80%.
Nitrous Oxide	0.2% per year growth.	0.7% per year growth.
Chlorofluorocarbons	Emissions increase 0.7% of 1980 level per year.	Emissions increase 3.8% of 1980 level per year.
Methane	1% per year growth.	2% per year growth.
Temperature Sensitivity	1.5°C for CO_2 doubling.	4.5°C for CO_2 doubling.
Heat Diffusion of Ocean	1.18 cm^2/sec.	1.9 cm^2/sec.
Glacial Discharge	Equal to thermal expansion.	Twice thermal expansion.

Source: Hoffman, Keyes & Titus, 1983:14.

Table 2. Scenarios for future sea level rise developed by US Environmental Protection Agency. (Values given in Centimeters and *Feet.*)

Scenario	Year				
	2000	2025	2050	2075	2100
High	17.1	54.9	116.7	211.5	345.0
	0.6	*1.8*	*3.8*	*6.9*	*11.3*
Mid-range High	13.3	39.3	78.9	136.8	216.6
	0.4	*1.3*	*2.6*	*4.5*	*7.1*
Mid-range Low	8.8	26.2	52.6	91.2	144.4
	0.3	*0.9*	*1.7*	*3.0*	*4.7*
Low	4.8	13.0	23.8	38.0	56.2
	0.2	*0.4*	*0.8*	*1.2*	*1.8*
Current Trend	2.5	5.7	8.8	11.9	15.0
	0.1	*0.2*	*0.3*	*0.4*	*0.5*

Source: Hoffman, Keyes & Titus, 1983.

Note 1. The values projected by US EPA in this table are absolute sea level rise predictions. The base year is 1980. To apply these values to a particular local area requires consideration of local subsidence or uplift. Subsidence will produce a greater relative sea level rise; uplift will produce a lesser relative sea level rise.

Note 2. Subsequent to developing these scenarios, Hoffman et al. refined their model, and now feel that the "Mid-range Low" scenario is the most probable (Barth & Titus, 1984:16). The Low and High scenarios, however, remain as the outer limits of what is reasonably possible during the next century.

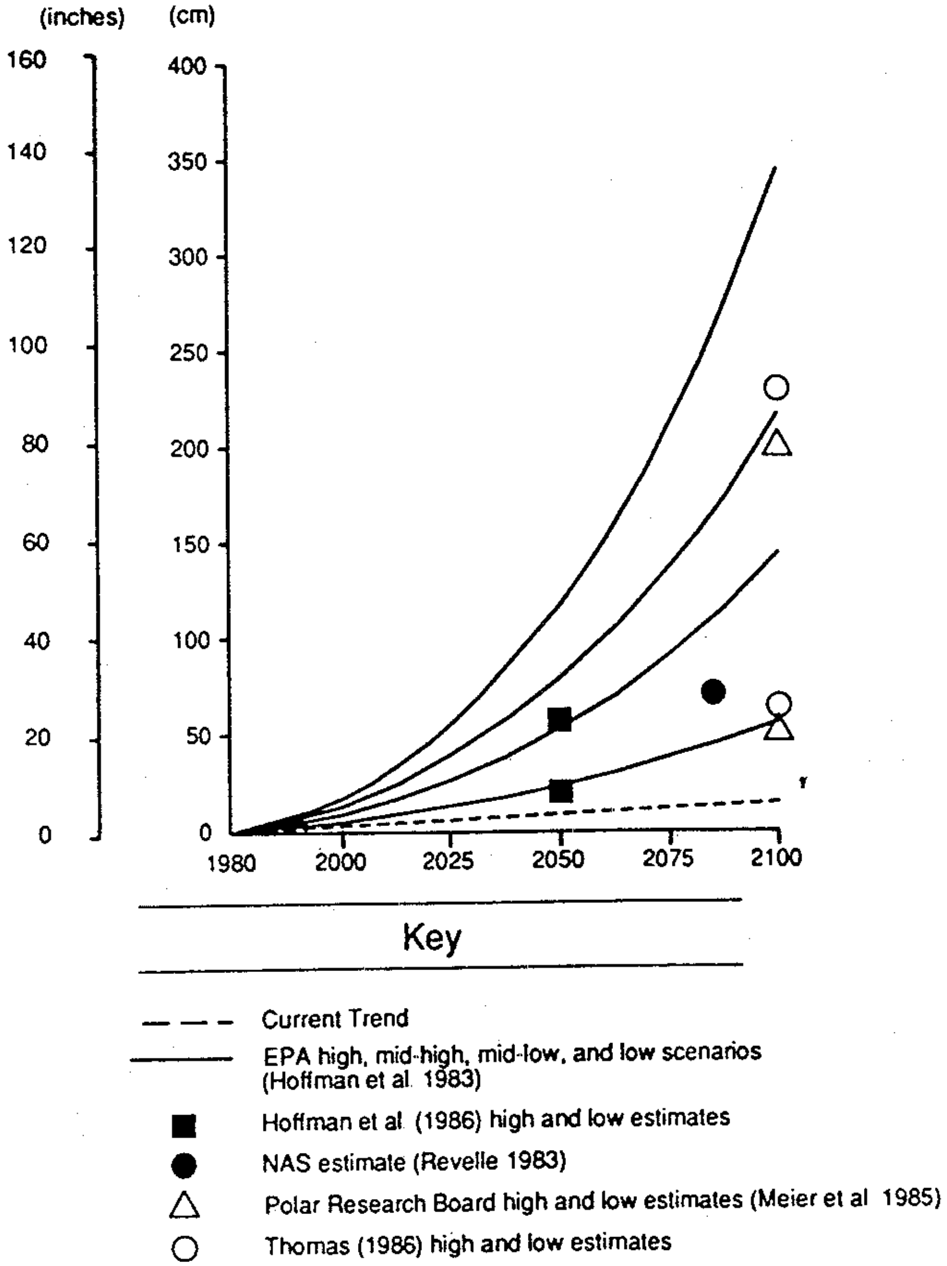


Figure 2. Global sea level rise scenarios. (Reproduced from Titus, 1987:9.)

PACIFIC NORTHWEST

Existing sea level change in Washington state is reflected in phenomena such as the imperceptible but chronic erosion of many Puget Sound shorelines; the periodic landslides of coastal bluffs; and the transformation of the forests and fields of the Skokomish River delta into swamps and marshes. (Factors other than sea level rise may cause or contribute to these phenomena.)

Vertical Land Movement

The rate of sea level change is not uniform throughout the state. In fact, in southwest Washington, the sea level has been dropping relative to the land. Global sea level rise must be adjusted for local vertical land movement to arrive at a local relative sea level change.

> Global sea level rise (G) must be adjusted for local vertical land movement (V) to determine local relative sea level rise (R) such that $R = G - V$. Although substantial sea level rise induced by global climate change may alter the mass of the planet, thus producing latitudinal differences in sea level rise rates, presently only uniform global sea level rise is modeled (Titus, 1988).

Vertical land movements may result from a variety of geologic processes. Regional deformation may result from movements of the large tectonic plates which comprise the Earth's skin; from movements of molten material deep within the planet; or from changing distributions of the weight of the Earth's surface. For example, during the last ice age the Puget Sound region was depressed hundreds of feet by the weight of the glacier. After the glacier melted and that weight was removed, the "glacial rebound" in the Puget Sound continued for thousands of years. Most geologists agree that this glacial rebound ended about 5,000 years ago.

Vertical land movement in Washington may be characterized as uplift along portions of the ocean coast and subsidence throughout the Puget Sound basin. Coastal uplift is caused by the subduction of the offshore Juan de Fuca Plate under the continental North American Plate. As the older, lighter, Juan de Fuca Plate slides under the overriding North American Plate, it pushes the continental plate up. (There is evidence that the process also probably results in the occasional sudden lowering of the North American Plate by about a meter every 300 to 500 years [Atwater, 1987].) This coastal uplift results in a downwarping or subsidence of the Puget Sound Basin.

The effects of vertical land movements in Washington are clearly seen in the tide gage records (see Tables 3 and 4, and the discussion in the following section). Vertical land movement patterns in Washington state and nearby Oregon and British Columbia are mapped in Figure 3. The amounts of vertical movement (a maximum of 2.5 mm/year uplift at Neah Bay, and a maximum subsidence at Tacoma of 2.4 mm/yr) are not great in comparison with other locations world wide. These data are based on a study of vertical land movements by Shorelands staff; a detailed report, *Vertical land movements in coastal Washington: Implications for relative sea level rise* (Shipman, 1989), is available from Shorelands' Sea Level Rise Project.

Existing Sea Level Change

The National Oceanic and Atmospheric Administration has compiled sea level data for selected tide gage stations in the United States (Lyles, Hickman & Debaugh, 1988). The oldest continuous tide gage was established in San Francisco in 1855. The oldest tide gage in the Pacific Northwest was established in Seattle in 1899. The other permanent tide gages in the region—Astoria, Neah Bay, and Friday Harbor—were established in the 1920s and 1930s. These sea level data describe relative sea level change at and near the tide gage.

Pacific Ocean Coast

Because the Astoria area is undergoing uplift at a rate greater than sea level rise, the Astoria tide gage reflects a relative sea level change of -0.9 mm/year (-0.3 ft/century) between 1950 and 1986 (Table 4)—that is, a relative sea level decrease. Over the full tide gage record, the longer term rate was -0.3 mm/year (-0.1 ft/century) between 1926 and 1986 (Table 3). This substantial difference reflects the "noisiness" of the Astoria data due to the influence of the Columbia River and the flood control effects of the Columbia River dams.

The Neah Bay tide gage data shows a similar condition. The relative sea level change of -1.6 mm/year (-0.5 ft/century) between 1950 and 1986 (Table 4) is slightly greater than the longer term rate of -1.1 mm/year (-0.4 ft/century) between 1935 and 1986 (Table 3).

No similar tide gage information is available for the stations at Toke Point (Willapa Bay) or Aberdeen (Grays Harbor). However, Holdahl, et al's (1989) work indicates that no substantial uplift is occurring in Grays Harbor area, and that Aberdeen is most likely subsiding slightly (see also Shipman, 1989).

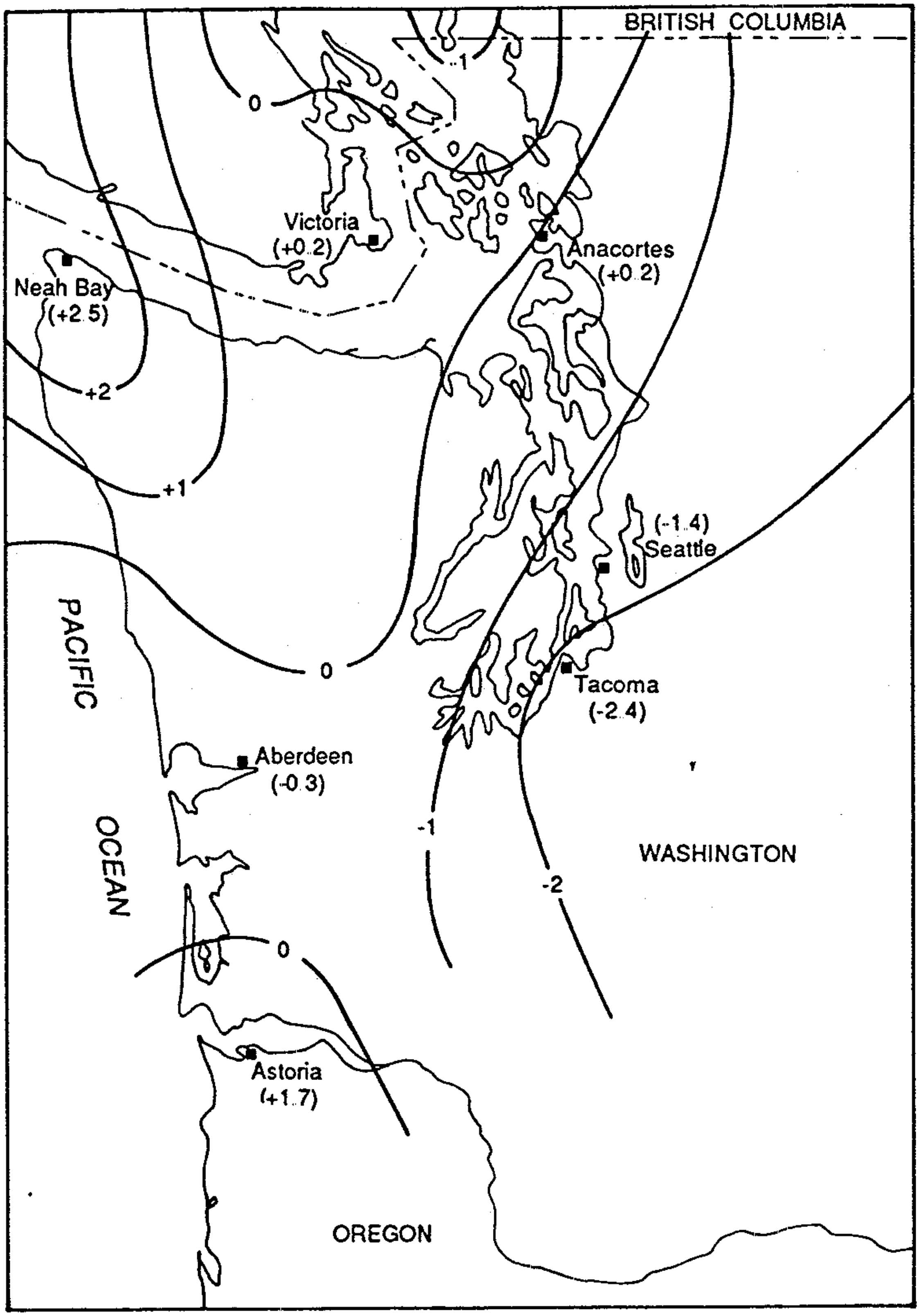


Figure 3. Vertical land movements in western Washington. Uplift (+) and subsidence (-) in millimeters per year. Modified from Shipman (1989) and Holdahl, et al (1989).

Puget Sound Basin

Within Puget Sound, the general pattern is one of subsidence, with the rate increasing from zero in the north—Bellingham Bay, San Juan Islands, and Dungeness Bay—to a known maximum at Tacoma. This is reflected in sea level changes at the tide gages.

The Friday Harbor tide gage reflects a relative sea level change of 1.0 mm/year (0.3 ft/century) between 1950 and 1986 (Table 4) and 1.4 mm/year (0.4 ft/century) over the entire record, 1934 to 1986 (Table 3). These values bracket the generally accepted global sea level rise rate of 1.2 mm/year, indicating that the area about the San Juan Islands is geologically relatively stable.

The Seattle tide gage reflects a relative sea level change of 1.9 mm/year (0.6 ft/century) between 1950 and 1986 (Table 4) and essentially the same over the full tide gage record: 2.0 mm/year (0.6 ft/century) between 1895 and 1986 (Table 3).

By way of comparison, relative sea level rise on the Atlantic coast ranges from 0.9 mm/year (0.3 ft/century; Boston) to 3.6 mm/year (1.2 ft/century; Hampton Roads). In Louisiana, where the Mississippi Delta is rapidly subsiding, relative sea level rise is on the order of 9.5 to 9.8 mm/year (3.1 to 3.2 ft/century; Stevenson, et al., 1986).

Table 3. Sea level trends and variability, entire tide gage record.

Station Number	Location	Trend mm/yr	Trend ft/yr	Standard Error of Trend ±mm/yr	Standard Error of Trend ±ft/yr	Variability ±mm	Variability ±ft
943 9040	Astoria, OR	-0.3	-0.001	0.4	0.0012	47.1	0.154
944 3090	Neah Bay, WA	-1.1	-0.004	0.3	0.0011	35.5	0.117
944 7130	Seattle, WA	2.0	0.006	0.1	0.0004	30.4	0.100
944 9880	Friday Harbor	1.4	0.004	0.3	0.0010	33.7	0.111

Source: Lyles, Hickman & Debaugh, 1988:11.

Table 4. Sea level trends and variability, 1950 through 1986.

Station Number	Location	Trend mm/yr	Trend ft/yr	Standard Error of Trend ±mm/yr	Standard Error of Trend ±ft/yr	Variability ±mm	Variability ±ft
943 9040	Astoria, OR	-0.9	-0.003	0.7	0.0024	43.2	0.142
944 3090	Neah Bay, WA	-1.6	-0.005	0.6	0.0021	37.7	0.124
944 7130	Seattle, WA	1.9	0.006	0.4	0.0014	27.8	0.091
944 9880	Friday Harbor	1.0	0.003	0.6	0.0019	35.8	0.118

Source: Lyles, Hickman & Debaugh, 1988:11.

Accelerated Sea Level Rise

When sea level rise acceleration scenarios are combined with vertical land movement scenarios for Washington state, the results appear as depicted in Figure 4. Three acceleration scenarios—0.5, 1.0, and 2.0 m by 2100—were modified in accordance with the vertical land movements at Tacoma, Neah Bay, Seattle, and Friday Harbor. An extension of the existing rate of sea level rise is shown for comparison as a moving base line.

Another way of looking at this kind of information is to plot the 1.0 m rise scenario for each location on the same graph as in Figure 5. The effect of vertical land movement is readily apparent. Under this scenario, a 0.5 m sea level rise would occur in Tacoma by 2050, in Seattle by 2055, and in Friday Harbor by 2067. The uplift at Neah Bay would delay occurrence of a 0.5 m rise until about 2080. Consistent with the scenario, a 1.0 m rise would occur at Friday Harbor in 2100 because there is essentially no vertical land movement at Friday Harbor over the long term. At Seattle and Tacoma, the 1.0 m rise occurs sooner because of the subsidence.

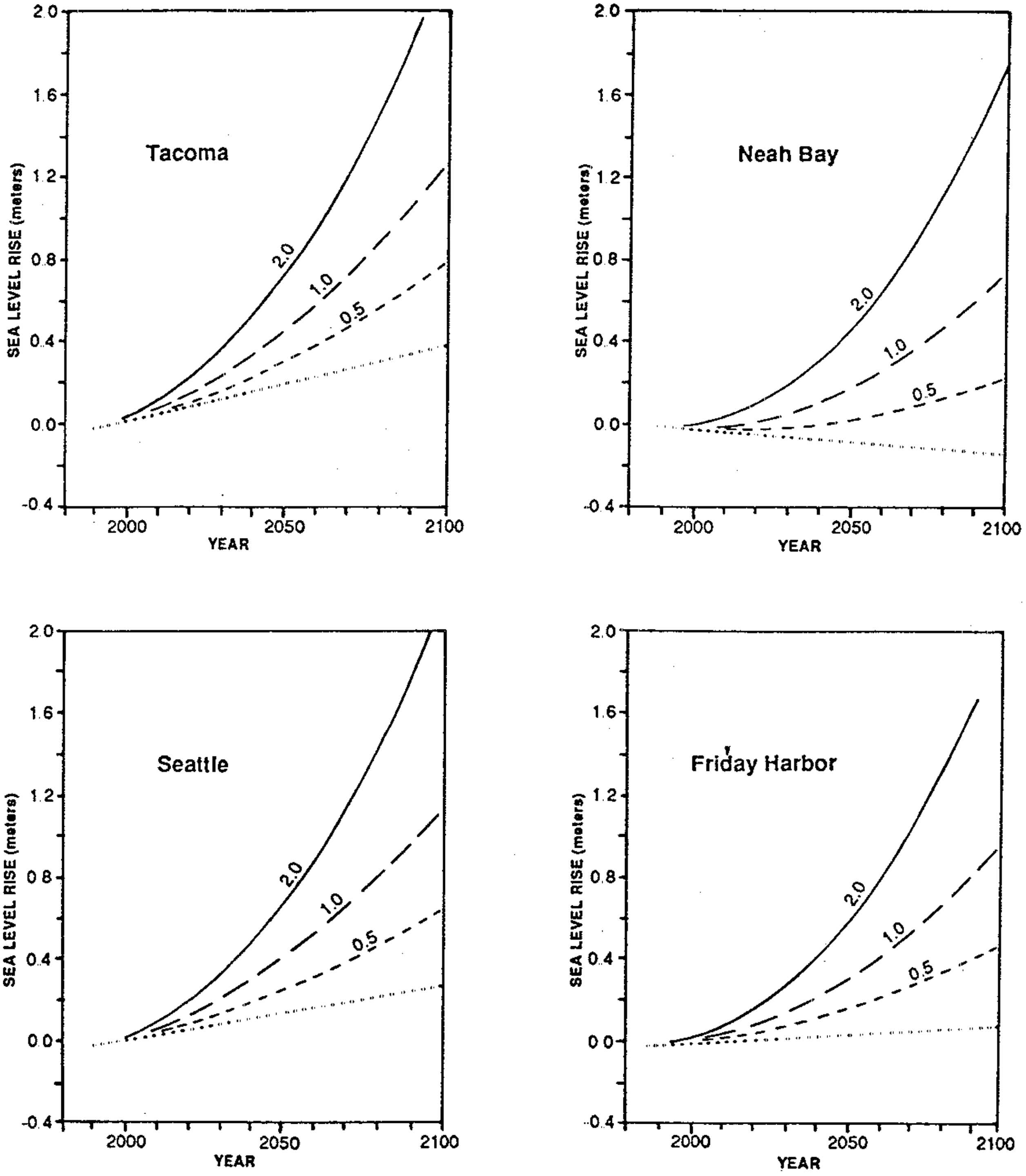


Figure 4. Accelerated sea level rise at Tacoma, Neah Bay, Seattle, and Friday Harbor. For each location, four scenarios are shown. The lowermost curve is the projection based on current trends. The upper curves are based on global sea level rising by 0.5, 1.0, or 2.0 meters (1.6, 3.3, or 6.6 feet) by 2100. All scenarios include a consideration of vertical land movement.

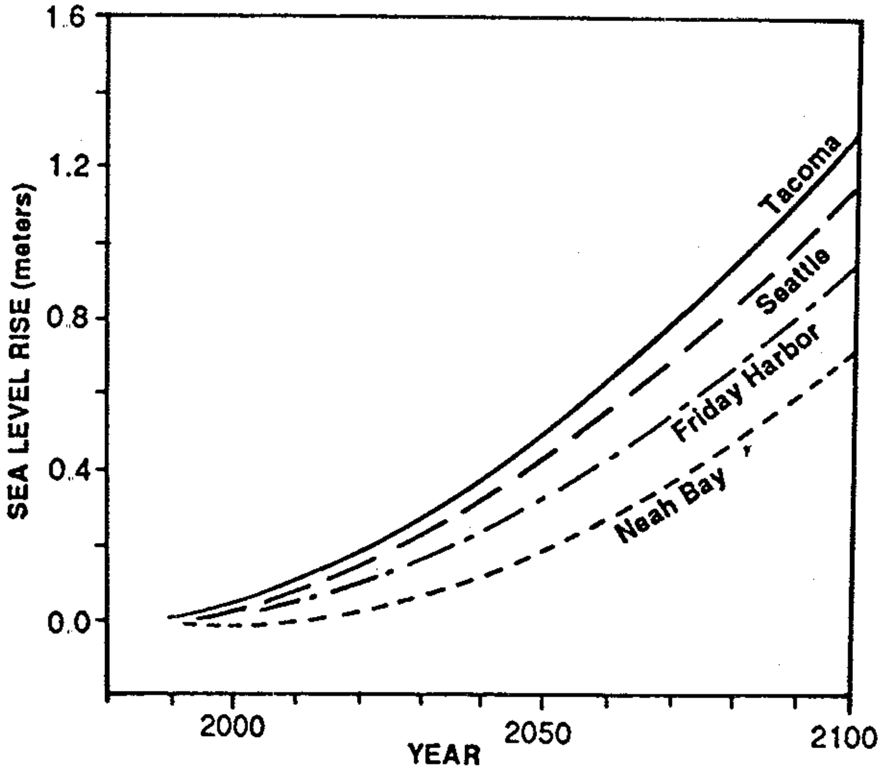


Figure 5. 1 meter sea level rise scenario at Tacoma, Neah Bay, Seattle, and Friday Harbor. Curves are based on a global sea level rise of 1.0 meter (3.3 feet) by 2100. The differences between the curves result from the difference rates of vertical land movement at each location.

POTENTIAL IMPACTS AND POLICY ISSUES

The scenarios outlined here address impact chains (primary, secondary, tertiary, etc., impacts) originating primarily as a direct effect of sea level rise. Global climate change will create ecosystem impact chains which will likely interact with effects induced solely by sea level rise. The analyses in this report, therefore, are simply a generic, "first cut" effort.

> Climatic change in the Northwest might result in annual increases in precipitation of up to 30%. Regardless, the higher temperatures will result in more rainfall and less snowfall, and a higher snowline and therefore less snowpack. The net result will be a shift in the timing of peak runoff in the snow-fed rivers from about May or June, to as early as December or January. This is expected to have profound effects on the productivity and survival of salmon, as well as upon flooding patterns in the lower river valleys.
>
> On a more speculative note, climatic change in the central part of the nation—higher temperatures and lower rainfall—is expected to accelerate the existing migration of Americans to coastal areas, thus possibly aggravating the existing population growth problems in western Washington.

The best references known to us which discuss the effects of sea level rise are *Greenhouse effect and sea level rise: A challenge for this generation* (Barth and Titus, 1984), *Greenhouse effect, sea level rise, and coastal wetlands* (Titus, 1988), *Responding to changes in sea level: Engineering implications* (National Research Council, 1987), and the proceedings of a *Workshop on sea level rise and coastal processes* (Mehta & Cushman, 1989). There is also a growing body of professional literature, much of it published in the journal *Coastal Management*. This report compiles information from these and other studies and professional papers.

The relative significance of the scenarios in this report depends, of course, partly on which sea level rise scenario occurs, as well as the planning horizon one is considering. The San Francisco Bay Conservation and Development Commission (BCDC) now requires that all projects which come under their licensing authority to be engineered and constructed for existing sea level rise, and that the conceptual design include an evaluation of accelerated sea level rise (*Bay Plan Amendment No. 3-88 Concerning Sea Level Rise* adopted January 5, 1989). The US Army Corps of Engineers now also includes an evaluation of existing and accelerated sea level rise in their design of coastal works (Circular 1105-2-186; April 21, 1989) but this policy does not apply to civil works which are licensed under Section 404 of the Clean Water Act. The state of Washington has not yet set policy in this area, but does require that beginning in 1990, all Coastal Zone

Management grants to local government for planning, land acquisition, and construction include a requirement consider sea level rise where appropriate. Projects must be engineered and constructed for the existing rate of sea level rise, and conceptual planning for response to accelerated sea level rise must be carried out.

Planning horizon refers to the term or time for which a plan is developed or for which analyses are being performed. The planning or analysis horizon for a structure might be limited to its useful economic life which might be measured in terms of the duration of a mortgage or purchase loan, or in terms of how long the structure is expected to be functional.

Planning and analysis horizons for land use decisions or commitments might as well be perpetual for all practical purposes. Once a site has been "committed" to a use, that use becomes established by tradition or legal fact. The site of the Brooklyn Bridge connecting Brooklyn on Long Island with Manhattan, for example, was the locale of Native American canoe traffic between the two islands to which "all trails lead." After the area was occupied by Caucasians in the 15th century, they too used the traditional trails leading to the canoe crossing. Trails became roads and the canoe crossing became a ferry crossing. Once that crossing of the East River became fixed it was inevitable that a bridge would be built there.

This report assumes no planning horizon or sea level rise acceleration scenario; the analytical discussions are therefore generalized. Site-specific or project-specific analyses can assume a scenario as well as an analysis horizon and therefore produce quantitative or semi-quantitative predictions.

The existing sea level rise described in the preceding section, in combination with subsidence in the Puget Sound basin, has and is having effects upon the shores of the Sound. These effects may be imperceptible over the few decades of a human life, but the effects are occurring. Clearly then, the first effects of accelerated sea level rise will be an increase in the frequency or intensity of these existing effects.

Among the first effects of accelerated sea level rise will be changes in shoreline accretion and erosion patterns, most noticeably accelerated erosion. There will also be an increase in the frequency and intensity of coastal flooding. In time, as sea level rise forces a rise in coastal water tables, saturation will affect the character of soils and the ability of soils to support agriculture or onsite sewage disposal. High water tables may lead to a corrosion problem for underground structures. Coastal biology and ecology will be affected, particularly wetlands. Over longer periods of time, coastal facilities and land uses will be at risk from not just greater flooding but from inundation.

Erosion and Accretion Patterns

Existing Status: Along much of Washington's southwest coast uplift presently exceeds eustatic sea level rise. Historically, the sand beaches of southwest Washington were strongly accretional at lateral rates of up to 20 feet per year (Phipps & Smith, 1978). Since 1978, the rate of accretion on the Long Beach Peninsula has slowed to maximum rates of 5 to 10 feet per year and ceased in some limited areas (Phipps, 1990). Historical accretion rates have continued on the Ocean Shores peninsula and the beaches to the north. Between 1978 and 1988 up to 400 feet of erosion occurred between the Columbia River North Jetty and North Head; however, the rate of this erosion appears to have slowed (or even ceased) in recent years.

Puget Sound shorelines have evolved to conform with rising sea levels since the end of the last glaciation about 14,000 year ago (Downing, 1983; Burns, 1985; Terich, 1987) as shown in Figure 6. Between the close of the last glaciation and about 6,000 years ago, sea level rose about 70 m (230 feet) at an average rate of nearly a meter per century (about 2.9 feet per century). As sea level rose, the Puget Sound shorelines eroded, producing the high banks and bluffs which are so common in most areas. The eroded material formed the present day beaches and sand spits.

Puget Sound shorelines are still affected by existing sea level rise. A slow, almost imperceptible, chronic erosion of unconsolidated and poorly consolidated shorelines is common. In recent centuries, sea level rise has averaged 12 cm (0.4 foot) per century. The rate of erosion is therefore very slow in most places, and can be measured in inches or more likely, fractions of an inch per year. The common response to shoreline erosion—real or apparent—has been a proliferation of bulkheading and other "hard protection" techniques.

Landslide episodes occur along many Puget Sound shoreline bluffs. Not all landsliding is caused by sea level rise; much landsliding is due to slope failures caused by inherent geologic weaknesses, vegetation removal, and other factors. A more detailed discussion is available in the Shorelands

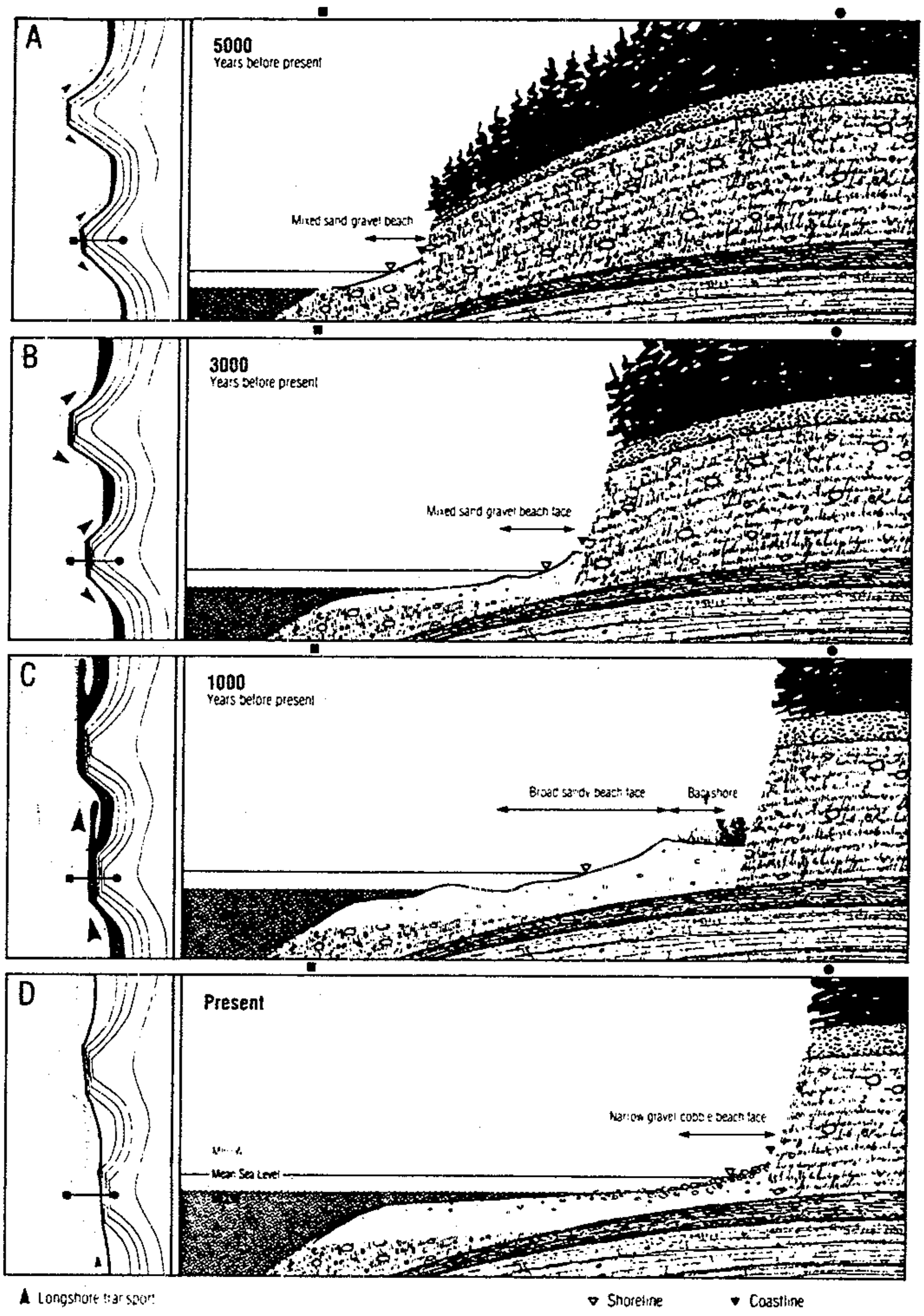


Figure 6. Evolution of Puget Sound gravel and cobble beaches. Reproduced from Downing, 1983:52.

report *Shoreline bluff and slope stability: Technical management options* (Canning, 1985).

Potential Effects: An alteration of accretion - erosion patterns on southwest coast beaches is likely. If accelerated sea level rise over takes uplift in the third or fourth decade of the 21st century as projected, accretion rates can be expected to slow, and possibly reverse. Effects are likely to be seen first on the Long Beach Peninsula.

The shorelines most susceptible to erosion due to accelerated sea level rise are sandy accretion beaches. Although erosion rates are difficult to predict, applications of the Bruun (1962) rule and similar evaluative procedures suggest that a 1 foot rise in sea level would erode the shore 50-100 feet in New Jersey (Kyper & Sorenson, 1985) and in Maryland (Everts, 1985); 100-200 feet in South Carolina (Kana, et al., 1984); 200-400 feet in California (Wilcoxen, 1986); and 100-1,000 feet in Florida (Bruun, 1962). No similar evaluation has been developed for Washington beaches, but even the minimal range, 50-100 feet, is substantial. Washington's accretion beaches are found along the southerly Pacific Ocean coast, and as small spits within Puget Sound.

Divergent opinions exist as to whether future Pacific Ocean beach erosion would result in (1) a simple change in beach topography and bathymetry with no inputs to longshore drift, or (2) that eroded materials would enter the longshore drift system to be deposited elsewhere. Thinking leading to development of the first scenario is based on Atlantic coast research which may not be applicable on the Pacific coast. Further research is necessary to resolve this question. A major policy issue in other states addressing sea level rise is whether shoreline protection will be allowed and under what circumstances. Regardless, erosion rates would be highly variable, with the rate of retreat dependent on a number of factors including the rate of sea level rise, the local shoreline wave energy, and the relative consolidation or "competence" of the shoreline materials.

Puget Sound semi-consolidated shorelines will suffer lower rates of erosion than unconsolidated sandy beaches. To the extent that sea level rise acceleration occurs, coastal bluffs which are now subject to landsliding caused by shoreline erosion and undercutting will experience an increased rate of slope failures. Erosion and undercutting may be extended to other areas. As discussed in *Shoreline bluff and slope stability: Technical management options*, much coastal landsliding is not caused by erosion and undercutting, but rather by various kinds of slope failures.

River deltas are maintained in equilibrium with existing sea level rise by means of sedimentation. With accelerated sea level rise, the sedimentation rate of only the largest rivers (e.g. the Fraser and the Skagit) is expected to be sufficient to maintain an equilibrium (Hutchinson, 1989). The deltas of the smaller rivers will be subject to erosion and inundation.

The degree to which erosion takes place is problematical, and will also depend on the degree and nature of shore protection. Extensive shore protection will minimize shoreline erosion and retreat, but will also eliminate the source of materials which would other wise be available to maintain beaches and accreting shorelines.

Secondary effects of large-scale erosion might include:

- Increased chronic input of materials to longshore drift, with tertiary effects:
    - Accelerated accretion at shoals and spits. This effect may moderate or mitigate the inundation of shoals and spits by sea level rise).
- Increased shoreline bulkheading for the protection of real property, with tertiary effects:
    - Decreased input of sand, gravel, and other materials into the shore system, leading to:
        - Beach scour in the vicinity of the shore protection structures and accelerated erosion of distant accretion shoreforms dependent on a continual supply of material.
    - Alteration of physical shoreline processes and degradation of shoreline fisheries habitat; see Plants and Animals: Habitat/Numbers/Diversity.
    - Creation of a demand for shoreline protection materials and for beach nourishment materials

> Under a sea level rise acceleration scenario, simple bulkheading alone will not be sufficient as a shoreline property protection measure. As sea level rises, the bulkhead or other hard protection will have fixed the shoreline in place. The base of the bulkhead will be subjected to increasing erosive forces which will tend to undermine the bulkhead. To counteract these forces, beach nourishment with imported sand and gravel will be necessary to maintain the proper topographic and geometric relationship between beach levels and profiles, and tide levels. The demand for sand and gravel could be substantial.

Undercutting (erosion) of shoreline bluffs, a special case of unconsolidated shoreline erosion, would trigger secondary effects:

- Increased bluff and slope instability, thus a greater frequency of landsliding, leading to:
    - Greater frequency of building damage and loss.
    - Increased chronic input of materials to longshore drift, leading to:
        - Accelerated accretion at shoals and spits (Note: this effect may moderate or mitigate the inundation of shoals and spits by sea level rise).
- Increased shoreline armoring, leading to the same effects noted above for bulkheading of eroding shorelines.

Policy Commentary: There is great potential for a clash of interests over the appropriate way to address shoreline erosion control. There are three fundamental responses to shoreline erosion: (1) "hard" protection, e.g. bulkheads and riprap; (2) "soft" protection, e.g. beach nourishment or sand replenishment; and (3) retreat and abandonment. A summary of common erosion abatement techniques is provided in Table 5.

Upland property owners, both private and public, will be concerned with protecting their financial investments in land and structures. In the past, this has lead to extensive shoreline property protection in the form of bulkheading, rip rapping, and other forms of shoreline hardening. The long term effect of extensive shoreline hardening would be a diminishment or elimination of the shoreline beaches and habitats, with a consequent adverse effect upon fisheries and general ecologic habitat values, as well as to public access rights.

Conversely, resource managers are concerned with protecting shore resources, be it public access rights, or fish and shellfish and their supporting habitat.

Clearly, a policy which addresses the needs of one interest group to the exclusion of others will not be acceptable. Shoreline hardening is too destructive of the shore and its resources over the long term. Retreat and abandonment is rarely politically popular, even when funds are available for fee or development rights purchase. Soft approaches such as beach nourishment are increasingly the preferred choice.

To the extent that beach nourishment is practiced as a "soft" protection measure for shoreline properties and structures, there will be created a higher demand for sand and fine gravel. Shoreline property protection by "hard" methods will create an increased demand for rip rap materials such as boulders and quarry rock, and concrete (itself composed of sand and cement. Any substantial increase in sea level rise cannot be resisted by bulkheading alone; beach nourishment will be necessary in addition to bulkheading to protect bulkhead footings from scour. No studies on the quantities of materials required have been completed, but the cumulative demand could easily run into the hundreds of thousands of cubic yards.

> The proliferation of seawalls and other hard erosion protection structures has prompted researchers to study their possible impacts to beaches. A review of the contemporary literature (Terich, Schwartz & Johannessen, 1991) shows that a majority of the published work on the subject finds seawalls in some way aggravate the pre-existing erosion of beaches. Researchers commonly concluded that seawalls change a dissipative beach into a reflective beach leading to increased wave reflectivity and beach scour. The presence of seawalls was found to double the applied littoral energy to the sedimentary bed leading to increased scour both in front of the wall and some distance downcoast. The beach in front of seawalls all but disappears due to increased wave scour in some circumstances. Other research indicates a one to one relationship between the depth of toe scour and incoming wave heights.
>
> Increased littoral zone turbulence and beach scour leads to a general lowering of the beach profile and possibly a narrowing of the beach as well. However, narrowing might also result from a reduced sediment input due to the presence of a protective structure. Up to 70% of the natural beach sediment supply had been reduced due to seawalls along a stretch of the English coast.
>
> Seawalls also appear to have adverse impacts to adjacent beaches. Wave reflection and scour transfers energy stresses and reduced sediment inputs to nearby unarmored beaches. Laboratory data revealed that the length of coast affected by erosion to be approximately 70% of the structure length.
>
> Rock rip rap is also a commonly used erosion protection structure. Unlike a seawall, rip rap tends to reduce wave reflectivity by dispersing the wave energy over the sloping, multifaceted face of the rock. It appears that less work has been conducted on the effects of rock rip rap to beaches. However, one study reported rip rap to lead to a greater frequency of wave overtopping.

Table 5. Summary of erosion abatement techniques.

Construction setback	Vegetation	Beach nourishment	Bulkhead or seawall	Revetment	Groin
Advantages					
Reduces threat of destruction	Shelters and binds soil and substrate	Often makes beach more suitable for use	Shields the land from wave attack	Least expensive	Quick trap of beach sediment
Allows natural shore processes to operate	Reduces soil creep and rain/gully wash	Does not affect down stream beaches	Low maintenance	Individual units allow settlement and replacement	Builds beach on updrift side
No impact on beach life	No impact on beach life				
Disadvantages					
Does not stop erosion	Does not stop erosion	Does not stop erosion in all situations	Limits access and recreational use of beach and scenic view	Subject to settling	Downdrift beaches subject to erosion
Area must be available for relocation	Vegetation may reduce views	Cost and accessibility of borrow materials varies	Complex design	Underlying material lost through joints	Unsuitable in low littoral transport areas
May reduce views	Reduces access	Adversely affects beach life	Special equipment needed	Adversely affects beach life	Legal problems may result
Special moving skills required			Subject to failure if improperly designed	Limits recreational use of beach and scenic value	Adversely affects beach life
			Adversely affects beach life		Limits recreational use of beach
Costs					
$3.00 to $5.00 per sq. ft.	Minor	$2.50 to $3.00 per cu. yd.	wood: $30 to $50 per lin. ft.; concrete: $60 to $100 per lin. ft.	$30 to $80 per lin. ft.	wood: $10 to $25 per lin. ft.; concrete: $60 to $100 per lin. ft.

Adapted from Terich, 1987, *Living with the shore of Puget Sound and the Georgia Strait.*

Flooding

Existing Status: Coastal flooding is presently a periodic risk in low lying coastal areas. No data are collected and published on the actual frequency and magnitude of the events. The Federal Emergency Management Agency publishes maps depicting the areas at risk.

Potential Effects: A higher mean sea level will create a higher base from which storm surges can sweep inland causing flooding. Therefore an increased frequency and intensity of periodic flood events can be expected. Another way of stating that is to say that the magnitude of the 10-year, 100-year, etc. events will be greater. The secondary effects include:

- Increased damage to private and public property, with tertiary effects of:
    - Greater demands on National Flood Insurance Program.

> The foregoing brief outline belies the seriousness and complexity of the flooding issue. While sea level rise itself will create opportunities for an increased frequency and intensity of periodic flood events, other greenhouse effect climatic factors will further aggravate coastal flooding. While these climatic factors are beyond the intent of this report, they are important factors to consider in evaluation of responses to future flooding potential.
>
> Warmer oceans will result in more frequent formation of large storm systems (tropical depressions, cyclones, hurricanes); the intensity of these storm systems may also be affected. The heat and moisture from warm ocean waters are the driving force of large storm events. Thus, warming seas will impact existing and future coastal development in two ways: more frequent, possibly more intense storm events; and, greater storm surges due to rising sea levels. This effect has been predicted for the Atlantic and Gulf coasts; the situation on the Pacific coast is less certain. Additional research is necessary, but research of this nature is probably best carried out at the national rather than the state level.
>
> The effects of climate change and warmer, rising seas on the periodic *El Nino* events along the Pacific Coast are difficult to predict given the current state of understanding of *El Nino* formation. *El Nino* effects on the Washington coast are discussed by Phipps (1990) in his report on accretion, erosion, and flood hazards on the southwest Washington coast. Damage from previous *El Nino* events has been so significant that research into the relationship between greenhouse effects and *El Nino* should be a national priority.

Policy Commentary: Existing coastal hazard maps and mapping methodology are not adequate to cope with sea level rise. For example, maps indicating areas subject to storm surge (coastal high hazard areas or velocity zones as mapped by the Federal Emergency Management Agency), assume a static sea level plus storm frequencies and intensities based on historic records. These assumptions and maps will likely prove to be increasingly inadequate—dynamic natural conditions cannot be depicted on a static map. Possible solutions include a regular revision process for coastal hazard area maps or a new approach to risk assessment of coastal hazards. Again, these are issues best addressed at the national level.

Ground Water

Ground Water Levels

Existing status: Ground water levels near the coast are known to fluctuate with the tides. This has been demonstrated through the monitoring of wells a mile or more from the shoreline. No long term well monitoring in correlation with sea level is known to have been carried out.

Potential Effects: Sea level rise will force a rise in water table in coastal aquifers near sea level. Where a water table is forced to an elevation at or near the surface, soils become permanently saturated. The chronic or periodic saturation of coastal soils due to a water table rise forced by sea level rise may alter the fundamental character of those soils. Saturated soils will impede surface and subsurface drainage. Saturated agricultural soils will have diminished value for growing crops; see Agricultural Land Uses section below. Saturated soils are less effective (or ineffective) for filtration and treatment of septic tank effluents; see Ground Water Quality section below. Saturated soils have lower load bearing strength for structures and roadways. This situation appears to have occurred at the Skokomish River delta, possibly as far upstream as the US 101 bridges (Canning, et al., 1988).

The secondary effects include:

- Impeded subsurface drainage. Subsurface drainage rates are a function of the ability of storm water to infiltrate the soil and then move either laterally to discharge into a surface water body, or to infiltrate to a lower aquifer. A higher water table will raise the zone of saturation, impeding this process. Under extreme circumstances, the practical meaning of this is impediment of surface drainage translates into increased duration of flooding in the lower reaches of coastal rivers.
- Saturated soils possess decreased load bearing strength for building construction and roadways. Existing structures may be subject to differential settlement.
- Saturated soils are also less effective for onsite sewage disposal. Under extreme conditions, existing conventional installations may have to be abandoned, and be replaced with mound systems.
- Saturation of some soils can be expected to lead to increased corrosion of underground utilities, foundations, storage tanks, etc. Different soils possess different corrosion

potentials for metals and concrete. Site specific analyses can be developed through reference to US Soil Conservation Service soil surveys.

- A water table rise into some solid and hazardous waste sites can be expected to lead to a greater leaching of contaminants into the ground water stream and eventually into surface waters.
- In extreme situations, where the water table rises to the surface, wetlands may be created. This situation appears to have occurred over portions of the Skokomish River delta on the Skokomish Indian Reservation. Anecdotal reports by Tribal members that present day wetlands were formerly orchards or hay fields (Canning, Randlette & Hashim, 1988) might best be explained by a combination of sea level rise and subsidence.

Ground Water Quality

Existing Status: There are three fundamental coastal ground water quality issues. First, sea water intrusion is a potential problem in any coastal area, and is presently a concern in Island and San Juan counties and along the shores of Hood Canal. Excessive ground water withdrawals for domestic and other kinds of wells leads to an inland migration of sea water, or intrusion into fresh water aquifers. The process is the result of long term cumulative effects, and therefore often difficult to detect. Ecology's Water Resources Program is developing a sea water intrusion response plan.

Second, leachates from coastal solid and hazardous waste sites can migrate through the ground water an discharge into coastal bays. This is more of a problem with old waste sites which were operated and closed before the present regulatory and management programs were in effect.

Third, leachates from onsite sewage disposal systems are a widespread problem which has lead to the closing of shellfish beds throughout Puget Sound and even in Willapa Bay. The generally accepted design standard for septic tank leach fields requires at least three feet of undisturbed soil separation between the bottom of the leaching trench and the top of the water table to provide adequate treatment and adsorption of contaminants before the leachate reaches the water table. Once the leachate reaches the water table little or no additional treatment occurs.

Potential Effects: A rising sea level will aggravate the sea water intrusion problem, but will likely not, by itself, cause problems where none yet exists. The magnitude of the problem will vary with the geologic and hydrologic characteristics of particular locales, as well as the intensity of development and ground water withdrawal.

The potential for adverse effects of higher water tables on old, inadequately closed solid waste disposal sites can be substantial. Prior to the 1970s it was not an uncommon practice in some coastal communities to use high marshes and tidal mud flats as solid waste disposal sites. As the rising water table envelopes an old, unprotected solid waste site, leachates will more readily be swept into the ground water stream and transported to coastal bays. Part of the problem lies in incomplete knowledge of the location of pre-1970 solid waste disposal sites.

The effect of a ground water table forced upward to envelop an onsite sewage disposal leaching field will be two-fold. First, as the leach field becomes saturated, the treatment efficiency decreases to the point where no treatment is taking place and the system "fails." The owner of the system will eventually be required to take remedial action. On an individual basis, this could mean a mound system; on a neighborhood basis, this could mean hooking up to a sewerage system. Second, until remedial measures are taken, higher loadings of contaminants will be transported to coastal bays.

Under certain circumstances there could be a greater transport of contaminants into urban bays by ground water transport. The failure of onsite sewage disposal systems could be induced by a rising water table forced upward by a rising sea level. Similarly, rising water tables could envelop old hazardous and solid waste sites or underground storage tanks, leading to a leaching of contaminants into the ground water stream and thence into urban bays.

> Water quality concerns in marine bays and estuaries are presently focused on contaminants. Salinity and temperature are water quality components, but not ones which have been of concern in the past with respect to marine waters. It is difficult to address water quality issues without considering the cumulative effects of the full range of water quality changes due to all aspects of global climate change. Because many if not most marine organisms are limited in their range by temperature, any increase in water temperature will tend to shift the range of native species to the north, and to make possible the survival of exotic or introduced species. Salinity might increase as a result of sea level rise, and temperature would increase (1 to 3°C) in marine bays as a result of general climate change, with secondary effects of:
>
> - Species and population shifts to an unknown degree; see Plants and Animals section.
> - Salt water wedge migration upstream in estuaries (due both to increased salinity and to higher mean sea level).

Public Water Supplies

Potential Effects: Sea water intrusion of aquifers will lead to degraded water quality, with secondary effects of:

- Greater reliance on alternate, more distant, or deeper water sources, with a tertiary effect of:
    - Greater energy and cost demand.
    - Greater need for conservation.

Biology and Ecology

The principal coastal habitats of concern are wetlands, accreted shoreforms, and intertidal and shallow subtidal habitats. Clearly, the effects upon habitats and species by sea level rise will be difficult to separate from the broader effects of climate change in general. While it is beyond the intents of this report to address climate change generally (see Reid & Trexler, 1991 for a discussion of coastal biodiversity, global warming, and public policy), an illustrative discussion bears inclusion.

> *Spartina alterniflora*, Smooth Cordgrass, is an introduced species from the Atlantic Coast. First introduced to Willapa Bay in c. 1895, it appears to have been held in check by the relatively adverse summer climate in western Washington as well as by a "natural" lag in expansion (Sayce, 1988). During the 1980s, *Spartina* had noticeably colonized larger areas. At the expansion was partly attributed to the abnormally warmer summer temperatures of this period. Over the long term, greenhouse effect climatic warming will aggravate this warming trend, and possibly the expansion of *Spartina*.
>
> If present conditions continue, *Spartina* is predicted to expand from its present 680 acres to 31,000 acres—66% of the total intertidal mudflats of Willapa Bay—by 2025. *Spartina* is more invasive in Willapa Bay than in its native habitat where a barnacle limits its range to above mean sea level, and insect predators limit its vitality within its range. In Willapa Bay *Spartina* grows from about the 3 foot tide level (2.5 feet below mean sea level) to the upper limits of the mud flats, and has no predators.
>
> *Spartina* is extraordinarily efficient at capturing sediments and tolerating sedimentation. Spartina can tolerate sedimentation rates of up to 4 to 6 inches annually. *Spartina* is an aggressive colonizer; during the past decade the characteristically circular colonies increased their radius by 1/5 meter annually. As a result, *Spartina* can not only rapidly cover native mudflat habitat, but also rapidly raise the elevation of the area it is colonizing if adequate sediment is available.
>
> The ecological implications of a *Spartina* invasion are the replacement of the native, mid-tide, diverse, mudflat habitat and associated species, with a high intertidal *Spartina* monoculture. *Spartina* colonies eventually succeed to a high intertidal Salicornia marsh when sedimentation raises the marsh elevation above the tidal range in which *Spartina* competes most effectively.

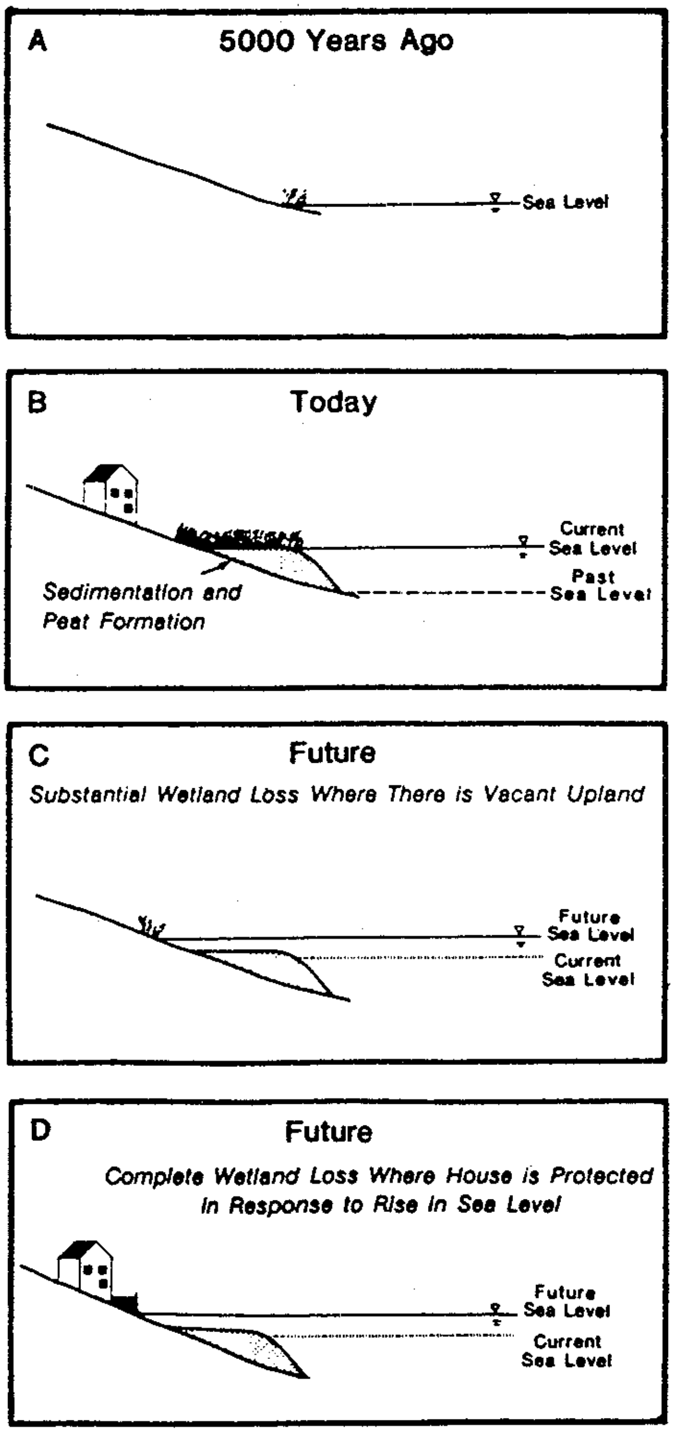
The economic implications of a *Spartina* invasion in Willapa Bay is the loss of habitat for rearing and holding oysters, the principal aquaculture business in Willapa Bay.

Wetlands

Existing Status: Wetlands are critical to estuarine ecosystem functioning, and have suffered substantial losses in past. In some areas of Puget Sound, up to 90% of coastal and estuarine wetlands have been lost to various land use practices through filling or diking Bortleson, et al., 1980). More detailed information on the status and functions of Washington's wetlands may be found in two *Environment 2010* reports, *Washington's wetlands at risk: Loss and degradation* (Canning, 1990), and *Wetlands of Washington: A resource characterization* (Canning & Stevens, 1990).

Potential Effects: A substantial body of thought has been devoted to sea level rise and coastal wetlands at the national level; much of this research has been compiled in a US EPA document, *Greenhouse effect, sea level rise, and coastal wetlands* (Titus, 1988). There are three principal pathways whereby sea level rise can alter coastal wetlands: inundation; erosion; and salt water intrusion. Inundation can "drown" existing wetlands, or can create new wetlands of existing uplands or transition zones. The potential loss of wetlands to sea level rise-induced inundation and erosion will depend on the maximum rate at which wetlands can migrate inland, relative to the rate of sea level rise which is controlled by: (1) the amount of sedimentation occurring in the wetland; (2) the coastal slope (topography) inland of wetlands; and (3) whether coastal developments obstruct the migration of wetlands. A typical scenario whereby accelerated sea level rise eliminates existing wetlands is depicted in Figure 7. Salt water intrusion will act to convert coastal freshwater wetlands to salt marshes.

The range of salt marshes is normally from about the mid-tide level to about ordinary high water (OHW). Ordinary high water varies in tidal elevation throughout Washington; in southern Puget Sound it is about one foot above mean higher high water (MHHW). Coastal wetlands inundated by salt water once or twice a day support "low marsh" plants; areas inundated less frequently support "high marsh" species (see Figure 8). Above the high marsh is a transition zone to upland vegetation. The transition zone may be a freshwater wetland.



Coastal marshes have kept pace with the slow rate of sea level rise that has characterized the last several thousand years. Thus, the area of marsh has expanded over time as new lands were inundated, resulting in much more wetland acreage than dry land just above the wetlands (A and B). If in the future, sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of bulkheads to protect economic development may prevent new marsh from forming and result in a total loss of marsh in some areas (D).

Figure 7. Evolution of a coastal marsh as sea level rises. Source: Titus, 1987:12.

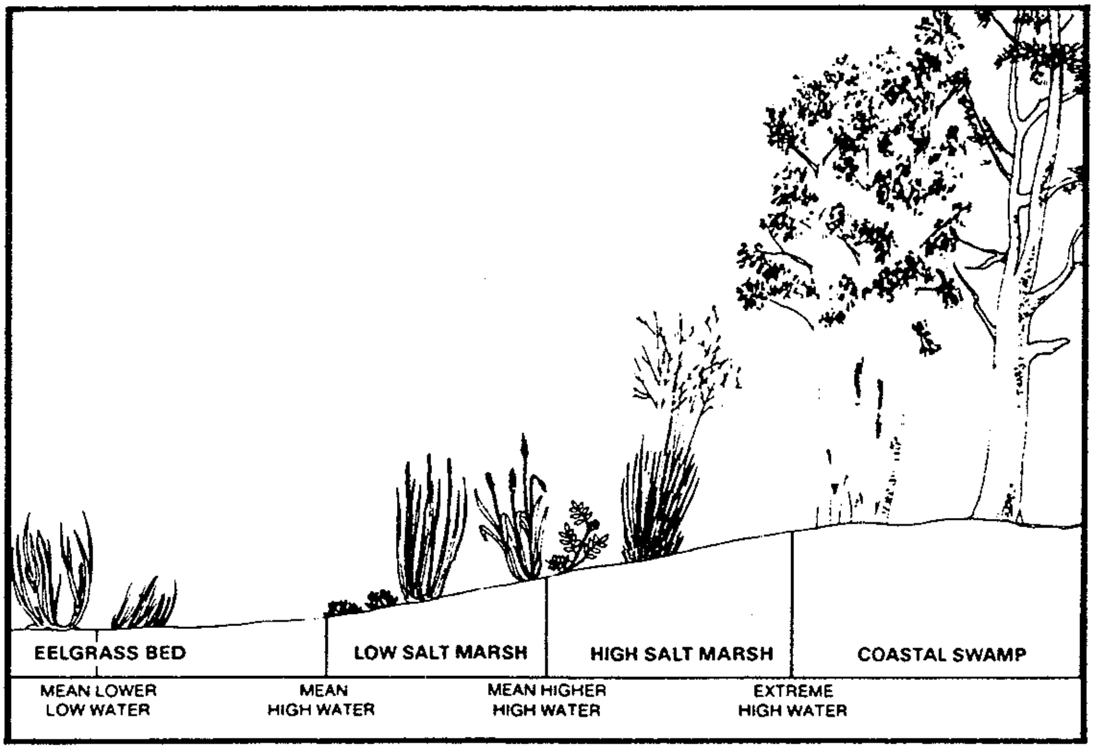


Figure 8. Idealized cross sectional view of coastal wetland types. Source: *Wetland plants of the Pacific Northwest.* US Army Corps of Engineers, Seattle District.

Everything else being equal, the effect of sea level rise upon coastal wetlands is to force a migration of the wetland inland (Figure 7). If the topographic gradient landward of the wetland is constant—that is, of the same topographic gradient as the wetland—then the wetland would simply shift landward with no loss of area or change in character. Topographic gradients along the coast are not ordinarily constant. Landward of coastal wetlands the topographic gradient ordinarily increases. Therefore, as sea level rises and the wetland migrates landward, the topographic zone between the mid-tide level and ordinary high water narrows, and the extent or area of the wetland decreases.

Where uplands landward of coastal wetlands are protected from inundation, wetlands migration will be prevented, and there will be an even greater loss of wetlands habitats (Figure 7).

The effects on Washington's coastal wetlands will be varied. No definitive studies have yet been completed, so only qualitative or semiquantitative judgements can be offered. There will be both losses and gains at specific locations; the net effect state-wide is not certain. In areas such as the Willapa Bay coastal plain, there might well be a net increase in wetlands due to both inundation and water table rise. Similar effects could occur at some river deltas such as the Skokomish where the delta is now marginally above ordinary high water. Here, inundation and a rising water table could combine to convert uplands to wetlands. The small wetlands along the bluffs of Puget Sound would likely be eliminated.

Preliminary computer modeling of selected Washington quadrangles (7.5 minute US Coast and Geodetic Survey map quadrangles) for a US Environmental Protection Agency nation-wide study of the effects of sea level rise upon coastal wetlands (Park, et al., 1990) has been completed by Holcomb Research Institute. In general, the study projects net gains in coastal wetlands, but there are anomalies in the projections which make the results suspect. The projects for specific Washington state locales are summarized in Tables 6 through 10.

The modeling is conducted through computer digitization of map and aerial photography data and images in 500m (1640 feet) square cells. The computer model of the coastal topography and habitat types is then "subjected" to sea level rise through the year 2100 for scenarios of 0.5m, 1.0m, 2.0m, and 3.0m increases, as well as a continuation of historic trends (0.12m/century). The results summarized in Tables 6 through 10 are net changes in existing habitat type by hectare.

Table 6. Shoreline habitat changes (hectares) in southern Willapa Bay through 2100. (Oysterville, Nemah, Ocean Park, and Long Island quadrangles.)

Sea Level Rise	Dryland	FW Marsh	SW Marsh	Beach	Water
Existing	18178	525	347	7873	23952
Historic	33	0	946	-815	-163
0.5m unprotected	-378	-320	816	-3301	3182
0.5m partially protected	-288	-294	722	-3314	3174
0.5m all protected	0	-244	459	-3367	3152
1.0m unprotected	-970	-433	1075	-5297	5634
1.0m partially protected	-739	-406	897	-5323	5572
1.0m all protected	0	-304	312	-5403	5395
2.0m unprotected	-2065	-485	1228	-6811	8133
2.0m partially protected	-1494	-456	951	-6881	7881
2.0m all protected	0	-339	41	-7062	7359

Source: Park, et al., 1990; Park, pers. comm., 1989.

Table 7. Shoreline habitat changes (hectares) in Commencement Bay, Colvos Passage, and East Passage through 2100. (Olalla, Vashon, Gig Harbor, and Tacoma North quadrangles)

Sea Level Rise	Dryland	FW Marsh	SW Marsh	Beach	Water
Existing	30792	0	0	0	20083
Historic	-149	0	154	116	-121
0.5m unprotected	-695	0	685	100	-89
0.5m partially protected	-388	0	384	94	-89
0.5m all protected	0	0	3	86	-90
1.0m unprotected	-1158	0	1027	175	-44
1.0m partially protected	-642	0	569	123	-51
1.0m all protected	0	0	2	57	-59
2.0m unprotected	-1865	0	1199	529	136
2.0m partially protected	-1019	0	653	313	54
2.0m all protected	0	0	2	47	-50

Source: Park, et al., 1990; Park, pers. comm., 1989.

Table 8. Shoreline habitat changes (hectares) in the Port Gamble area through 2100. (Port Gamble, Edmonds West, Suquamish, and Shilshole Bay quadrangles.)

Sea Level Rise	Dryland	FW Marsh	SW Marsh	Beach	Water
Existing	22306	0	0	411	273121
Historic	-19	0	29	-17	7
0.5m unprotected	-102	0	105	-55	51
0.5m partially protected	-49	0	55	-56	51
0.5m all protected	0	0	6	-57	51
1.0m unprotected	-173	0	153	-73	93
1.0m partially protected	-85	0	77	-83	91
1.0m all protected	0	0	4	-92	89
2.0m unprotected	-289	0	176	-58	171
2.0m partially protected	-145	0	91	-93	147
2.0m all protected	0	0	2	-127	125

Source: Park, et al., 1990; Park, pers. comm., 1989.

Table 9. Shoreline habitat changes (hectares) in the Discovery Bay area through 2100. (Gardiner quadrangle (partial).)

Sea Level Rise	Dryland	FW Marsh	SW Marsh	Beach	Water
Existing	6820	0	0	61	3184
Historic	-11	0	15	-16	11
0.5m unprotected	-38	0	39	-31	30
0.5m partially protected	-28	0	29	-32	31
0.5m all protected	0	0	3	-33	30
1.0m unprotected	-65	0	52	-35	48
1.0m partially protected	-48	0	39	-38	47
1.0m all protected	0	0	1	-46	44
2.0m unprotected	-111	0	52	-28	86
2.0m partially protected	-80	0	38	-36	78
2.0m all protected	0	0	1	-56	55

Source: Park, et al., 1990; Park, pers. comm., 1989.

Table 10. Shoreline habitat changes (hectares) in the Padilla and Samish Bay area through 2100. (Lummi Island, Eliza Island, Cypress Island, and Anacortes North quadrangles.)

Sea Level Rise	Dryland	FW Marsh	SW Marsh	Beach	Water
Existing	9405	127	257	0	38747
Historic	-167	0	104	31	31
0.5m unprotected	-634	0	432	82	120
0.5m partially protected	-532	0	342	75	115
0.5m all protected	0	0	-71	26	45
1.0m unprotected	-1049	0	526	165	359
1.0m partially protected	-877	0	407	144	328
1.0m all protected	0	0	-139	41	100
2.0m unprotected	-1574	0	351	314	992
2.0m partial protected	-1305	0	255	268	864
2.0m all protected	0	0	-161	55	187

Source: Park, et al., 1990; Park, pers. comm., 1989.

(One hectare equals 2.47 acres.) There are two concerns. First, the 500m square cell or pixel covers about 60 acres. Many Puget Sound shoreline features are too small or narrow to be detected by a pixel this large. Also, it is not easily possible to evaluate the accuracy of the predictions because no field checking has been conducted.

Analysis of southern Willapa Bay (Table 6) has produced results which intuitively seem valid. Here it might be expected that substantial losses of beach habitat would occur, and that salt marsh would be created through conversion of freshwater marshes and inundation of dryland. The features of the Willapa Bay area are relatively large in scale, and the 500m square pixel does a relatively good job of detecting and modeling them.

Analysis of the Commencement Bay, Colvos Passage, and East Passage area (Table 7), on the other hand, has produced results which are clearly suspect. The decrease in water area is counter intuitive as is the increase in beach area, and the supposed existing absence of salt marsh or beach habitats. This latter is likely due to the low sensitivity of the model.

Analyses of the Port Gamble and Gardiner areas (Tables 8 and 9) give results which are difficult to evaluate because the changes predicted are trivial. However, there are now coastal salt marshes in these areas contrary to the modeling; the model is not sufficiently sensitive to detect them. Therefore, the prediction of salt marsh gains is suspect. Analysis of the Padilla and Samish Bay area (Table 10) produces "mixed" results in the context of intuitive expectations. Here one might expect increases in salt marsh, but not of beach area.

In summary, sea level rise is expected to result in increases in the extent of wetlands in areas such as Willapa Bay, and will most like result in the elimination of some existing coastal wetlands within Puget Sound. More extensive computer modeling of selected Puget Sound shoreline areas was carried out during 1990-91 by Holcomb Research Institute as a part of the US Environmental Protection Agency's Pacific Northwest Global Climate Change Case Study. Many problems with earlier versions of the computer model were resolved, and results should be available in early 1992.

With a decrease in wetlands, the secondary effects include:

- Decreased primary and secondary productivity inputs to estuarine systems (i.e. decreased food availability to higher organisms in the wildlife food chain), with tertiary effects of:
  - Decreased productivity of fin fish, shell fish, and crustaceans.

Accreted Shoreforms

Accreted shoreforms have relatively less habitat importance and constitute only about 5% of the coastline. Many of these sand spits have been converted to highly valued residential uses. Losses can also be anticipated of accreted shoreforms, beaches and bars, due both to inundation and erosion. Erosion might be aggravated if large scale shoreline protection reduces or eliminates the sources of sand supply which build and maintain accreted shoreforms. These habitats are often used as haul out habitat for Harbor Seals and California Sea Lions. The Shorelands Program is carried out an inventory and characterization of the state's accreted landforms during 1990-91 (Shipman, 1991).

Intertidal and Shallow Subtidal

Existing Status: Intertidal and shallow subtidal habitats are important spawning areas for Pacific Herring and Surf Smelt, and migration corridors for young salmon migrating out to sea. Surf

Smelt (*Hypomesus pretiosus*) spawning takes place virtually year-round in Puget Sound, although any particular spawning area is used only for a period of 2 to 6 months. Spawning occurs throughout Puget Sound and has also been found on Pacific Ocean beaches near La Push and Kalaloch. Spawning can occur on any suitable beach. Spawn is deposited in the uppermost intertidal zone, generally on coarse sand and fine gravel of 1 to 7 mm grain size. In the Seattle area, spawn is found from tidal elevation 7.0 to 11.0, or roughly from a foot above mean sea level (MSL) to mean higher high water (MHHW). The incubation period is about 2 weeks. The principal causes of mortality are temperature extremes, desiccation, and other abiotic factors. Based on field research conducted in 1974 and 1975, the Department of Fisheries established supplemental bulkhead and land fill regulations under the Hydraulic Code (WAC 220-110). The lower limits of shoreline filling permitted by the Hydraulic Code varies through out Puget Sound depending on the tidal elevation regime and the fish species under protection. For Surf Smelt, the lower limit is mean higher high water. Surf Smelt has economic importance as a sports fish. (Penttila, 1978.)

Pacific Herring (*Clupea harengus pallasi*) spawn in protected bays and inlets from Alaska south to San Francisco Bay. Spawning has been documented throughout Puget Sound and the Gulf of Georgia. Eggs are deposited on marine vegetation in the intertidal and shallow subtidal zones. A variety of substrates may be used, including eelgrass (*Zostera marina*) and rockweed (*Fucus* spp.), the latter being particularly common in Puget Sound. Pacific Herring has economic importance as a bait fish. (Gonyea, Burton & Penttila, 1982.)

Pink and Chum Salmon fry migrate to sea almost immediately upon emerging from gravel and becoming free-swimming. Upon reaching the ocean, Pinks are usually 1.0 to 1.6 inches long and Chum may be as large as 2.7 inches. Other salmonids are a year or more old before beginning migration. This places Pink and Chum Salmon at a much greater risk from predation during migration than the other species. For this reason, Pinks and Chum are dependent on shallow water migration habitats to escape predation by larger fishes.

Potential Effects: Losses of intertidal and shallow subtidal habitats are anticipated due to potential sea level rise response strategies for protection of shoreline properties and structures. To the extent that "hard" protection is practiced—bulkheading and riprapping—intertidal habitat will be diminished and eliminated, and shallow subtidal habitat will be made deeper. Bulkheading will fix the shoreline and as sea level rises the intertidal area will become progressively smaller and may eventually be eliminated. Under extreme scenarios of sea level rise and bulkheading, shallow subtidal habitat would become deeper. Thus, there is great potential for the loss of Pacific Herring and Surf Smelt spawning habitat and salmon migration zones in highly developed areas.

Increased water depth (decreased shallows) along shorelines will be a chronic problem (with respect to fisheries) until sea level equilibrates and shoreline erosion ceases. Where bulkheads or other hard protection devices are used, there may be a permanent elimination of shallow water habitat. The secondary effects of an increased shoreline water depth are:

- An increased predation of out-migrating young salmon leading to decreased stocks.

> The effects upon salmon will be more complex and pervasive than simple sea level rise. First, as ocean temperatures warm, the southern limits of salmon habitat will move north. Of the salmonids of the Pacific Northwest, most (Pink, Chum, Coho, Chinook, and Cutthroat) find their southern most range at or south of San Francisco Bay. The Sockeye's southern limit is at Cape Mendocino. It is not certain the extent to which warming waters would move salmonid ranges north of Washington waters. (Scott & Crossman, 1973.)
>
> Changes in hydrologic regimes are likely to have adverse effects upon salmonid productivity and survival. Presently, most Pacific Northwest streams and rivers are dominated by a snow melt peak runoff in about May. With rising temperatures, less precipitation will fall as snow and more as rain. Also, the snow line will be at higher elevations. Both factors will combine to produce less snow pack. The result is expected to be a shift in the time of peak runoff from about May to maybe as early as December. (Vail & Lettenmaier, 1989.)
>
> Most salmonids migrate upstream to spawn in the summer or autumn after the spring freshet. (In some areas low summer flows impede upstream migration.) Nests are dug and eggs are laid in the fall; as winter ends the young salmonids emerge from the gravel and enter the rivers. After some time in the rivers—days to weeks for some species, and years for others—they migrate out to sea on the spring freshet. Salmonid life cycles have evolved in close synchronicity with the hydrologic cycle. Any substantial changes in the hydrologic cycle will upset salmonid life cycles and lead to decreased populations. (Neitzel, 1990.)

Shoreline Facilities and Development

Existing housing built on low lying areas will be first subject to increased severity and frequency of flooding; then as underlying water tables rise, onsite sewage disposal systems will begin to fail; ultimately the threat of erosion or inundation will mandate protection or relocation.

Coastal storm water outfalls and agricultural drainage outfalls are mostly above present tidal ranges, though many outfalls are below the upper tide levels and are equipped with tidal flap valves. Rising seas will inundate more coastal outfalls and for longer periods. This increased head on some coastal storm water outfalls—especially during high tides—will impede storm drainage.

Increased tide levels equate directly to an increased head on sewage treatment plant (STP) outfalls and trunk lines, with secondary effects including:

- Increased STP pumping capacity demand which might be met by means of:
  - Increased pumping duration requiring a greater energy demand.
  - Replacement with larger capacity pumps.
- Increased infiltration of older, subtidal trunk lines (new, tight joint sewer lines will likely not be affected.

Existing recreational facilities built on low lying areas will be first subject to increased severity and occurrence of flooding; then as underlying water tables rise, onsite sewage disposal systems will begin to fail; ultimately the threat of inundation will mandate relocation or abandonment. Shoreline public parks, accesses, and other recreational facilities will be subject to all the erosion, flooding, and inundation effects described throughout this report. The response will vary. In urban areas, protection will be likely. Conversely, the Parks and Recreation Commission has determined the most cost effective response to the rapid (5 - 10 feet per year) coastal erosion at Westhaven State Park (Westport, Pacific County) to be policy of periodic retreat.

Many archaeological sites are located on low lying shorelines or along easily eroded shores, and are therefore highly susceptible to loss or damage by erosion, or to inundation.

Lowlying coastal highways will experience greater frequency of flooding, greater destabilization of roadbeds due to soil saturation, and accelerated erosion. Where relocation is not practical, roadbeds will have to be raised and protected from erosion. Locales where this is most likely to occur include US 101 along portions of Willapa Bay and Hood Canal, and SR105 and SR109 along portions of Grays Harbor.

Port facilities and their associated waterborne traffic are not likely to be seriously affected by sea level rise. The useful economic life of most port facilities and the frequency of reconstruction necessary to keep up with technological change in cargo handling is such that incremental changes to port structures can be expected to keep pace with sea level rise.

Much of the eastern shore of Puget Sound is edged by major rail road lines. For the most part, road beds are well above any of the sea level rise scenarios, and are well protected against erosion with rip rap. As sea level rises, existing rip rap may have to be raised.

Washington is fortunate in having no major airport facilities built on coastal fill or low lying coastal uplands. However, local service facilities such as those at Ocean Shores, Hoquiam, and Westport may be subject to high water table impacts and increased flood frequency. Where relocation is impractical, protection by diking may become necessary. Additionally, special facilities such as the US Navy's Ault Field on Whidbey Island might also be subject to flooding or inundation.

Government at all levels—but particularly at the local level—will experience increased maintenance costs to address the effects of sea level rise.

Policy Commentary: The question of protect or retreat may become a fundamental and difficult public policy issue. Clearly, high density urban areas with a high level of public investment will be protected; protection will be less costly than relocation. The difficult decisions will be focused on low density developed areas where the cost of protection is greater than or close to the cost of relocation. To what degree will the general public be willing to dedicate general tax revenues for the protection of private shoreline property?

Agricultural Land Uses

Potential Effects: A rising water table in near coastal areas leading to impeded subsurface drainage and water logged soils (see Water: Ground Water Movement) includes the following secondary effects:

- Decreased agricultural productivity, or:
- Soil drainage efforts through private or public means (Diking and Drainage Districts), with tertiary economic effects:
    - Diking, ditching, and equipment installation
    - Increased energy costs for pumping.

CONCLUSION

It is clear that we don't yet know, and in the near term can't know with absolute certainly, when sea level rise acceleration will begin, or precisely how much sea level will rise over any given period in the future. We know that sea level is and has been rising at a rate of about 12cm/century. We have good reason to believe that the rate of rise may increase substantially in the future. Prudence, therefore, tells us that we must prepare for changes in our planning for coastal land uses and facilities while monitoring sea level rise.

The central dilemma for coastal planners and managers—acting in the face of uncertainty—is not in itself an insurmountable problem. We—that is, society and it's groupings—take action on no end of issues for which we have imperfect knowledge for decision-making. The real issue is more one of social consensus that the time for action has arrived. So, how then can coastal planners and engineers reasonably prepare for changes in our planning for coastal land uses and facilities without certainty as to the rate and amount of increase?

There are a number of models for planning and engineering design in the face of high uncertainty. One that has worked well in practice, and with which planners and engineers have become quite comfortable is the hydraulic design storm—the 50 year event, the 100 year event, etc. Other models might be design standards for seismic safety or projection of electric load demand.

Hydraulic design has evolved, through time, a generally accepted practice whereby hydraulic structures such as culverts and bridges are designed to withstand or pass storm discharges of varying volumes depending on what is at risk and how much risk we are willing to accept. For low risk (high-risk-tolerance) situations, a 25 or 50 year storm event is the design standard; for progressively higher risk (lower-risk-tolerance) situations the 100 year or 500 year storm event is the design standard. We accept this with little question, even in the face of weather records often spanning less than 100 years.

We will likely come to accept a similar approach to planning and designing for sea level rise acceleration when the social consensus develops that accelerated sea level rise is a significant coastal zone issue. For high-risk-tolerance situations, a sea level rise scenario of 0.5 m by 2100 may become the standard. For progressively lower-risk-tolerance situations, progressively greater sea level rise scenarios will be applied. For example, a coastal highway can be relatively easily raised if the sea level rise design projections are found to have been set too low. Conversely, repeated remediation of a coastal hazardous waste site may be judged too risky from a fiscal and public health stand point, thus warranting a higher design standard.

Regardless of greenhouse effects, there are present adverse effects of sea level rise—erosion, bluff landsliding, and wetlands modification—which should be addressed. The mechanisms and means to address these issues already exist. To some degree, response to sea level rise acceleration will involve little more than prudent coastal zone management—abstaining from development of and building in the coastal zone in imprudent ways.

In a broader context, there will likely arise some very difficult policy choices, particularly with respect to decisions regarding protection or abandonment of developed areas. Clearly we will choose to protect lowlying areas such as Harbor Island in Seattle, the Olympia central business district, and the Tacoma waterfront—the cost of relocation would be substantially greater than the cost of relocation. It is unlikely that we would choose to spend public monies protect private agricultural, timber, or rural residential lands—the cost of protection would likely exceed the value of the land and structures. The difficult choices will arise with respect to lowlying residential areas where the cost of protection slightly exceeds the value of the developed properties. To what extent will the general public be willing to subsidize shoreline property owners?

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Greenhouse effect and sea level rise, Van Nostrand Reinhold Company, 1984 (325 pp). Edited by Michael C. Barth and James G. Titus, this is the only major commercially published book on sea level rise. It is based on papers presented in the spring of 1983 at the conference on sea level rise sponsored by the US Environmental Protection Agency. Topics covered include sea level rise causes and future scenarios, economic analyses, and impacts regarding coastal erosion, hazardous waste sites, and disaster response to flooding and storms.

Projecting future sea level rise: Methodology, estimates to the year 2100, and research needs, US Environmental Protection Agency publication EPA 230-09-007 (121 pp). This 1983 document describes the scientific basis for US EPA's sea level rise scenarios, and includes a brief discussion of impacts. Four sea level rise scenarios above a 1980 base year for 2100 are projected: low, a 1.8 foot rise; mid-range low, 4.7 feet; mid-range high, 7.1 feet; and high, 11.3 feet. The scenarios have subsequently been reevaluated, but the scientific basis remains valid. Available from:

Mr. James G. Titus
OPPE (PM-221)
US Environmental Protection Agency
401 M Street, SW
Washington, DC 20460
202/381-7821

Greenhouse effect, sea level rise, and coastal wetlands, US Environmental Protection Agency publication EPA 230-05-86- 013 (152 pp). This 1988 document projects the impact of sea level rise on US coastal wetlands. Two case studies—Charleston, South Carolina, and New Jersey—provide specific examples. A national context is discussed based on computer modeling of impacts at 51 selected sites. Regionally, wetland losses due to sea level rise are estimated to be 30 - 80 percent. Available from James Titus, US EPA—see above.

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GLOSSARY

absolute sea level rise - commonly referred to simply as sea level rise; global average sea level rise due to oceanic warming and snow and ice melting; see relative sea level rise.

accelerated sea level rise - a present and future increase in the rate of sea level rise due to "greenhouse effects" resulting from industrial era additions of carbon dioxide and other greenhouse gasses to the atmosphere.

relative sea level rise - absolute sea level rise plus subsidence or minus uplift equals relative sea level rise.

CONVERSION FACTORS

Multiply	By	To Obtain
millimeters (mm)/year	0.32808	feet/Century
feet/Century	3.048	mm/year
meters	3.2808	feet
feet	0.3048	meters