Coastal Erosion
Management
Strategy

Coastal Erosion Management Studies in Puget Sound Washington: Executive Summary

Coastal Erosion Management Studies, Volume 1

WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

January 1995
94-74

printed on recycled paper

Coastal Erosion Management Studies in Puget Sound, Washington: Executive Summary

Coastal Erosion Management Studies, Volume 1

January, 1995

Prepared by:

Douglas J. Canning and Hugh Shipman
Washington Department of Ecology

Report 94-74

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

Coastal Erosion Management Strategy

This report is one in a series or reports commissioned or completed by the former Shorelands and Coastal Zone Management Program of the Washington Department of Ecology in fulfillment of the Coastal Erosion Management Strategy project. The project is dedicated to seeking answers to questions on appropriate technical standards for coastal erosion management, the environmental impact of shoreline stabilization techniques, and the assessment and development of policy alternatives. The reports in the series are listed on page iii. Inquiries about the Coastal Erosion Management Strategy project should be directed to the project manager and series editor:

Douglas J. Canning
Shorelands and Water Resources Program
Washington Department of Ecology
P. O. Box 47600
Olympia, WA 98504-7600
360.407.6781 (telephone)
dcan461@ecy.wa.gov (Internet)

The Coastal Erosion Management Strategy was funded in part through a cooperative agreement with the National Oceanic and Atmospheric Administration with funds appropriated for the Coastal Zone Management Act of 1972 through a grant to the Washington Department of Ecology. The views expressed herein are those of the authors and do not reflect the views of NOAA or any of its sub-agencies.

The Department of Ecology is an equal opportunity agency and does not discriminate on the basis of race, creed, color, disability, age, religion, national origin, sex, marital status, disabled veteran's status, Vietnam Era veteran's status or sexual orientation.

If you have special accommodation needs or require this document in alternative format, please contact Tim Gates at (360) 407-7256 (Voice) or (360) 407-6006 (TDD).

Recommended bibliographic citation:

Canning, Douglas J. and Hugh Shipman. 1994. *Coastal Erosion Management Studies in Puget Sound, Washington: Executive Summary. Coastal Erosion Management Studies Volume 1.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Coastal Erosion Management Studies

Volumes in the Coastal Erosion Management Studies series will be published over a period of time. At the time of publication of this volume, the printing schedule was as follows.

Volume	Title	Status
Volume 1	Coastal Erosion Management Studies in Puget Sound, Washington: Executive Summary	Published January 1995
Volume 2	Coastal Erosion Management: Annotated Bibliographies on Shoreline Hardening Ef fects, Vegetative Erosion Control, and Beach Nourishment	Published June 1994
Volume 3	Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993	Not published
Volume 4	Engineering and Geotechnical Techniques for Coastal Erosion Management in Puget Sound	Published June 1994
Volume 5	Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound, Washington	Published August 1994
Volume 6	Policy Alternatives for Coastal Erosion Management	Published June 1994
Volume 7	Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington	Published August 1994
Volume 8	Management Options for Unstable Coastal Bluffs in Puget Sound, Washington	Published August 1994
Volume 9	Regional Approaches to Address Coastal Erosion Issues	Published June 1994
Volume 10	Coastal Erosion Management in Puget Sound: Final Environmental Impact Statement	Not published
Volume 11	Coastal Erosion Management in Puget Sound: Technical and Policy Guidance for Local Government	Not published

Contents

List of Figures

List of Tables

1. Introduction

The shores of Washington's inland coast—greater Puget Sound—undergo both shoreline erosion and landsliding. The overall rates of shoreline retreat are usually minor, maybe an inch or two a year, but in some areas may average as much as half a foot per year. This is usually due to a combination of bluff undercutting and failure of steep slopes, resulting in landslides. At any particular location, landslides occur infrequently, often decades apart. Simple shoreline wave erosion *by itself* is not often the problem in Puget Sound.

Marine shoreline erosion is a concern to both coastal property owners and the users and managers of coastal public resources. Coastal property owners are naturally concerned with protecting their investments in land and buildings. Unfortunately, houses and other buildings are often built dangerously close to the shoreline. Most property owners react to incidents of erosion or landsliding by erecting erosion control structures such as concrete or rock bulkheads. If properly constructed, these shoreline armoring structures can slow most forms of wave induced shoreline erosion for a period of time, but will probably do little to prevent continuing landsliding. Many shoreline property owners consider shoreline armoring critical to the protection of their real estate investment.

Resource managers are, of course, concerned about any adverse effects on the habitats which support biological resources such as fish and shellfish, and are charged with protecting the public property right in those resources. As we began designing the CEMS project in 1992, the scientific literature seemed to indicate that shoreline armoring (and the associated vegetation clearing) had a variety of adverse effects on shoreline resources, but there was little unequivocal documentation of those impacts, especially for Puget Sound. Throughout the course of this study we have learned that wide spread shoreline armoring typically results in the following adverse effects:

- Sediment supply to nearby beaches is cut off, thus leading to "starvation" of the beaches for the sand and other fine grained materials that typically make up a beach.

- The hard face of shoreline armoring, particularly concrete bulkheads, reflects energy back onto the beach, thus exacerbating beach erosion.

- In time, a sandy beach is transformed into gravel or cobbles, and may even be scoured down to bedrock, or more commonly in the Puget Sound basin, a hard clay. The footings of bulkheads are exposed, leading to undermining and failure.

- Vegetation which shades the upper beach is eliminated, thus degrading the value of the beach for spawning habitat.

- Any transformation of the character of the beach affects the kind of life the beach can support.

Request for Investigation and Assessment

The Thurston and Mason County Commissioners, and the Pierce County Executive, in 1991, requested that the Department of Ecology (Ecology) investigate the effects of wide spread shoreline armoring and prepare a programmatic environmental impact statement on the cumulative effects of bulkheading and other forms of armoring. These elected officials were reacting to the large numbers of bulkhead permit applications in recent years, and were voicing concern over their uncertainty about the wisdom of permitting large scale unmitigated shoreline armoring.

Legislative Action

In an action unrelated to the local government requests, the Washington State Legislature in 1992 passed *Engrossed Senate Bill 6128* which amended the Shoreline Management Act to provide for the following:

- Local governments must have erosion management standards in their Shoreline Master Programs. While most local governments have erosion sections in their SMP, these existing regulations may not be as comprehensive as ESB 6128 requires.

- These standards must address both structural and non-structural methods of erosion management. Structural methods are typically bulkheads or rip rap. Non-structural methods include building setbacks and other land use management approaches.

- The standards must give a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment." This implies no preference for protection measures first occupied after January 1, 1992.

- ESB 6128 expands erosion protection from just a residence to "single family residences and appurtenant structures."

- Permit application processing by local government must be carried out in a timely manner. Shoreline property owners testifying for the bill cited local government delays in permit approval as onerous. Local governments report that most permit delays are caused by incomplete or inaccurate information on the permit application.

The Coastal Erosion Management Strategy

The legislature was unable to provide local governments or Ecology with the funds necessary to carry out the intents of ESB 6128 because of reduced tax revenues. Fortunately, Ecology was successful in obtaining a grant under the federal Coastal Zone Management Act to carry out a comprehensive Coastal Erosion Management Strategy.

CEMS—the Coastal Erosion Management Strategy—is a four year, multi-task program aimed at (1) satisfying local elected officials' requests for assessment of the cumulative effects of shoreline armoring, (2) developing the standards for shoreline erosion management mandated by ESB 6128, and (3) assessing regulatory alternatives for erosion management. Tasks 1 - 4 were completed in 1992-93. Tasks 5 - 7 were completed in 1993-94, and tasks 8 and 9 in 1994-95.

Task 1. Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993. Thurston County was selected as the study area for a pilot project because of the availability of large amounts of relevant information already in data management and GIS (geographic information system) computer file formats. This study was designed to provide quantitative answers to questions on the rate and character of new and replacement shoreline armoring which are not readily available for most of Puget Sound.

Task 2. Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound. The generally accepted engineering and geotechnical techniques for selected erosion management alternatives (bulkheading, revetments, wave attenuation, beach nourishment, etc.) appropriate to the tidal range, wave energy, and geologic conditions characteristic of Puget Sound are assessed. This report provides the basis (in part) for development of State guidance recommendations to local government for adoption of standards for appropriate erosion management measures.

Task 3. Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound. The key assumptions and questions about the effects of shoreline armoring on coastal processes were evaluated based on the technical literature, and sensitized to Puget Sound conditions. Selected local case examples are provided.

Task 4. Coastal Erosion Management Regulation: Case Examples and Critical Evaluation. Regulatory approaches to coastal erosion management in Puget Sound and other states are evaluated, and policy alternatives for Washington are assessed. This report will provide the basis (in part) for development of State guidance recommendations to local government for adoption of coastal erosion management procedures.

Task 5. Shoreline Armoring Effects on Biological Resources and Coastal Ecology in Puget Sound. Following on from Task 3, the direct effects of shoreline armoring and the secondary effects of changes to coastal processes and conditions upon biological resources are assessed. Selected local case examples are provided.

Task 6. Coastal Bluff Management Alternatives for Puget Sound. A large measure of bulkheading is in reaction to slope failures (landslides), not shoreline erosion *per se*. Slope instability is caused by a combination of inherent geologic weaknesses, ground water loading, and toe erosion. Following on from tasks 2 and 4, this task addresses coastal bluff management alternatives.

Task 7. Regional Approaches to Coastal Erosion Management. Traditionally, shoreline management and erosion control permitting has been on a case-by-case basis. Many "soft" approaches to erosion management (e.g. beach nourishment) or mitigation for adverse effects must be carried out on a regional basis to be effective. Both the technical and political feasibility of regional erosion management is assessed.

Task 8. Coastal Erosion Management Environmental Impact Statement. This task will integrate the special study reports and other information into a programmatic environmental impact assessment.

Task 9. Coastal Erosion Management Recommendations for Puget Sound. Based largely on the foregoing studies, this task will formulate specific model elements which can be recommended as amendments to local Shoreline Master Programs. The guidance will be published as a chapter in Ecology's *Shoreline Management Guidebook*.

Task 1, Inventory and Characterization, was completed by Thurston Regional Planning Council. Tasks 2 through 7 were completed CH2M Hill and Battelle Memorial Laboratories under contract to Ecology. Tasks 8 and 9 will be completed by Ecology.

Tasks 1 through 7 are each designed to answer a relatively narrow set of questions, therefore each task completion report presents only a very limited portion the study. Until the entire project has been completed, the analytical studies have been integrated (Task 8), and Ecology has developed its guidance to local government (Task 9), no conclusions should be drawn from the individual study reports.

Remarks

We have chosen the terminology 'shoreline armoring' for this report series because it is a broad enough term to encompass most structural techniques for shoreline erosion protection commonly practiced in Puget Sound: concrete bulkheads, vertical rock walls, wood bulkheads of various designs (plank-and-piling, pilings, stacked logs, etc.), gabions, and riprap (rock) revetments. We also learned that there is considerable inconsistency in the use of terminology. To an engineer, there is a distinct difference between a rock wall (which is vertical) and a rock revetment (which is sloped). Planners, however, often do not make that distinction, leading to very confused dialogues.

This report volume in the Coastal Erosion Management Studies is an executive summary of the reports prepared by the Department of Ecology's contractors. Unless explicitly stated and cited to the contrary, all information in this volume was drawn from those reports.

The CEMS study was designed to address the focus of ESB 6128: residential shoreline armoring on the shores of Puget Sound. From a policy perspective, the study does not address commercial and industrial land uses. The CEMS project is a balancing of concerns and mandates. The Shoreline Management Act (SMA) has goals of both "planning for and fostering all reasonable and appropriate uses" while at the same time "protecting against adverse effects to the public health, the land and its vegetation and wildlife, and the waters of the state and their aquatic life." ESB 6128, in amending the SMA, gave a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment."

The study area for the CEMS project within Washington state was Puget Sound (Figure 1.1). While case examples were limited to Puget Sound, the scientific, resource management, and policy literature examined was nation-wide, and to a lesser degree, world-wide.

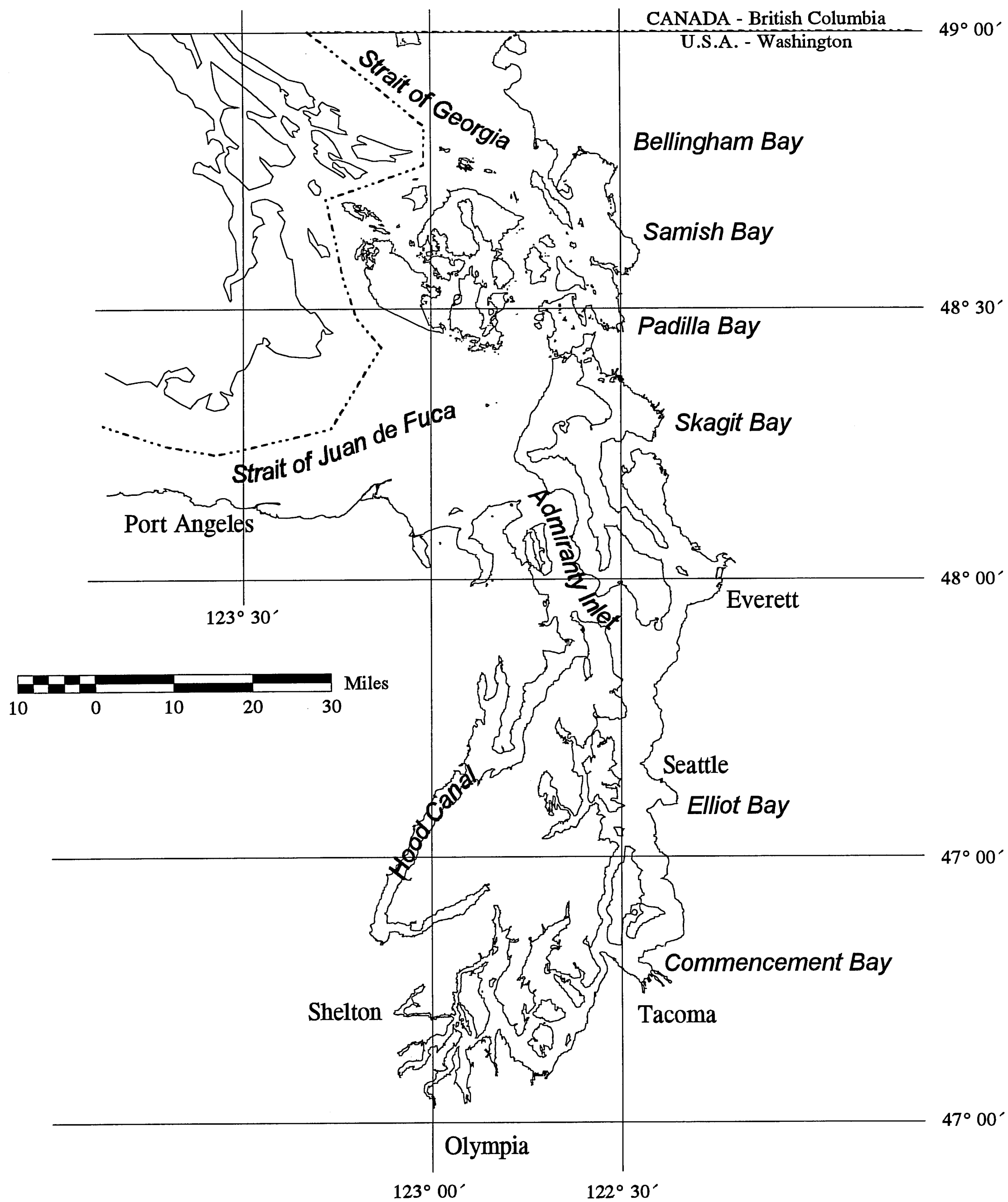


Figure 1.1. Puget Sound Study Area.

Washington's inland coast, Puget Sound, is defined differently for different purposes. Originally, Puget Sound included only those waters south of The Narrows at Tacoma, and Admiralty Inlet stretched from Commencement Bay north to the Strait of Juan de Fuca. For the purposes of the Coastal Erosion Management Study, Puget Sound is defined as Washington's inland waters from Olympia north to the Canadian border, including Hood Canal, and the Strait of Juan de Fuca east of Port Angeles.

2. Coastal Erosion in Puget Sound

This chapter was prepared by CEMS (Coastal Erosion Management Strategy) staff originally as a paper for delivery at the Coastal Zone 93 symposium held in New Orleans, Louisiana in July 1993 (Shipman & Canning, 1993). Due to Washington state travel restrictions, the paper was not delivered, but was published in the symposium proceedings.

2.1 Introduction

A property owner's standard response to erosion of a marine bluff on Puget Sound is the construction of a concrete bulkhead or vertical rock wall. In many cases, such structures protect the toe from further erosion and may reduce bluff failures that occur from over-steepening and undercutting. As the shoreline of Puget Sound becomes more developed, and as the scale and value of development increases, we see an increase in the amount of shoreline armoring. This raises questions about the less desirable side-effects of such large-scale shoreline hardening[1].

Shoreline hardening can alter wave regimes, cross-shore and longshore sediment transport, and coastal sediment supply. Although each of these is relevant in Puget Sound, the latter is particularly critical as the region's beaches are derived almost exclusively from the erosion of adjacent bluffs. The armoring of these bluffs to protect shoreline property reduces the supply of sediment to the littoral system and may result in negative consequences downdrift. These consequences may include narrower, coarser beaches, increased downdrift erosion, and may result indirectly in significant changes to nearshore habitats.

The adverse environmental impacts associated with a single shoreline stabilization structure are, in many cases, not great. On the other hand, much of Puget Sound's shoreline is eroding to some degree, and can legally be bulkheaded. Planners and natural resource managers are becoming more concerned about the cumulative impact of shoreline armoring on both physical processes and on ecological conditions.

This problem has not been addressed rigorously, although Washington State has recently initiated a multi-year project to better understand the potential environmental consequences related to shoreline armoring. This Coastal Erosion Management Strategy is addressed in a companion paper at this symposium (Canning and Shipman, 1993). The following paper summarizes the relevant coastal geology of Puget Sound and the nature of shoreline armoring. We propose a number of potential environmental problems that may result from shoreline armoring. We anticipate that future work will help better define these problems and allow

---

[1] For example, the request from Thurston, Pierce and Mason county elected officials that the Department of Ecology investigate the cumulative effects of shoreline armoring.

coastal managers to make informed, balanced decisions regarding protection of both coastal property and of coastal environments.

2.2 Geologic Setting

The inland waters of Washington State include Puget Sound, the Strait of Georgia, and numerous smaller bays and passages (Figure 1.1). The Puget Lowland, in which these bodies of water lie, is separated from the Pacific Ocean by the Olympic Peninsula and Vancouver Island, and is connected to the Pacific through the Strait of Juan de Fuca. For simplicity, we use the term Puget Sound to refer to all marine water in the Puget Lowland.

Puget Sound contains approximately 3000 kms (2000 miles) of shoreline, much of which consists of poorly consolidated marine bluffs of glacial sediments. Rocky shorelines are found in the San Juan Islands, the western Strait of Juan de Fuca, and in isolated pockets throughout the remainder of the Sound. The remaining shoreline consists of several river deltas, shallow bays with low banks, and numerous spits, cuspate forelands, and small barrier beaches.

The Puget Lowland was shaped by repeated glaciations, the most recent of which ended approximately 12,000 years ago. The north-south fabric of the topography results from glacial scouring. The geology of the region consists predominantly of glacial outwash, till, and glacial-marine drift, along with coarse fluvial deposits and some lake beds.

2.2.1 Waves and Tides

With the exception of the outer parts of the Strait of Juan de Fuca, open ocean wave conditions do not influence Puget Sound significantly. Wave size within Puget Sound depends on fetch and local storm conditions. Maximum wave heights occur during winter storms in locations with fetches of several tens of kilometers. The largest waves can reach heights of 2 m (5-6 ft). In many restricted inlets and shallow bays, wave heights rarely exceed 0.5-1.0 m (2-3 feet).

Puget Sound has mixed semidiurnal tides (e.g. two high and two low tides of unequal heights daily), which range from less than 3 m in the north to over 5 m in the southern sound. The Puget Lowland is subsiding as a result of tectonic movements and thus relative sea level is rising. The Sound is actually tilting southward, resulting in more rapid sea level rise in the southern Sound (3.4 mm/yr [1.12 ft/century] in Tacoma) than in the northern Sound (0.6 mm/yr [0.20 ft/century] in the San Juan Islands) (Shipman, 1990).

2.2.2 Coastal Geomorpholgy

The present shoreline of Puget Sound has formed since the rate of post-glacial sea level rise slowed about 5000 years ago. The existing shoreline consists of a notch cut into the glacial topography, with an eroded shore platform from a few tens to several hundred meters wide and bluffs from 0 to 150 m (0-450 ft) high. Eroded material forms beaches on the upper portion of the platform, although this beach may consist only of a thin veneer of sediments (1 m or less thick) on many bluffed shorelines (Downing, 1983).

Flooding of the post-glacial landscape resulted in a highly convoluted shoreline. This combined with local wind variations has resulted in the division of the shoreline into hundreds of discrete littoral transport cells (drift sectors, longshore sediment cells), ranging in length from a few hundred meters to several tens of kilometers (Schwartz and others, 1989).

Sediment budget

Sources. Puget Sound beaches consist predominantly of sediment eroded from local bluffs. Fluvial inputs are restricted to isolated areas near river mouths. Offshore sources of sediment are limited to seasonal bars that may form in lower intertidal or shallow subtidal zones. The size composition of beaches reflects the composition of local bluffs, which are typically composed of poorly sorted glacial sediments with significant coarse grained components (coarse sand, gravel, and cobble). Cobbles and boulders characteristically form a lag deposit on the shore platform due to insufficiently high wave energy. Fine sands and silts are rapidly winnowed from eroded deposits and transported to deeper water offshore and into protected coves. What remains are highly variable and often poorly sorted beaches composed of sand, gravel, and small cobble.

The volume of sediment provided to the beaches by bluff erosion depends on the rate of shoreline recession, the height of the eroding bluff, and the composition of the bluff material. Keuler (1988) found that volume rates of erosion in central Puget Sound were closely related to wave energy and ranged from less than 1 m^3/m/yr in sheltered bays to more than 10 m^3/m/yr on exposed shorelines (0.4-3.3 yds^3/ft/yr).

Transport. Beach sediment is transported along the shoreline by longshore drift. Volumes of transport range from 30 m^3/yr to 14,000 m^3/yr (39-18,000 yds^3/yr), based on studies of dredging records and accretion updrift of jetties by Wallace (1988). These rates correlate strongly with fetch.

Sinks. Sediment movement is largely confined to the upper foreshore on Puget Sound beaches and offshore transport of coarse sediment is limited. A bulk of beach sediment is transported to one of many small accretion landforms. In the case of bay barriers this may be the ultimate sink of material for a littoral cell. In the case of spits and cuspate forelands, sediment may eventually be transported to deeper water or into the shallow waters of small coves and stream mouths. In rare circumstances sand is carried a short distance inland by aeolian action and removed from the littoral system. Finally, a portion of beach sediment is trapped updrift of small jetties, is lost to artificial channels at marina entrances, or is locked up under bulkheads and fills that extend waterward of the shore.

Erosion

Marine bluffs on Puget Sound erode through a combination of wave erosion of the toe and mass-wasting of the overlying units. Although wave erosion ultimately sets the pace of shoreline recession, many cases of "erosion" are the result of upland slope failures, often caused by groundwater conditions. The evolution of consolidated Puget Sound bluffs is illustrated in Figure 2.1.

Mass-wasting of coastal bluffs may occur gradually through soil creep or may occur in a single event. Slope failures depend on the geology and hydrology of the bluffs but may occur as small sloughs that only involve surface layers of soil and vegetation, as larger landslides that carry large amounts of upland debris to the beach, or as large rotational slumps that may involve several kilometers of shoreline.

Rates of bluff recession on Puget Sound depend primarily on three factors: wave environment, geology, and beach characteristics. Wave environment depends on fetch, storm size and duration, and nearshore bathymetry. The most dramatic wave energy is recorded on the western side of Whidbey Island facing the Strait of Juan de Fuca, and on Whatcom County shorelines facing the Strait of Georgia.

Erosion rates are also affected by the geology of the bluffs. Glacial materials erode one to two orders of magnitude more rapidly than bedrock. Among glacial materials, unconsolidated outwash sands and gravels are less resistant to wave action than compacted tills (Keuler, 1988).

The width and elevation of the beach may influence significant control over the degree to which waves can attack the base of the bluff. Schwartz and others (1989) have noted that beaches tend to widen downdrift within individual littoral drift cells. This in turn provides greater protection to downdrift bluffs. Whereas bluffs near the origin of littoral cells may be near-vertical as a result of active wave erosion, bluffs downdrift may be more gradual and more heavily vegetated.

Keuler (1988) found that typical long-term erosion rates in central Puget Sound were about 10 cm/yr (0.3 ft/yr) and that maximum rates of 30 cm/yr (1.0 ft/yr) could be documented on the exposed west side of Whidbey Island. Schwartz (1971) documented a recession rate of 15 m (50 ft) over a 76-year period (20 cm/yr, or 0.7 ft/yr) west of Anacortes, but noted that an adjacent shoreline, with similar characteristics, had eroded negligibly.

The rate of shoreline recession can be constrained by the width of the shore platforms observed around the Sound. Assuming that these platforms have developed since sea levels slowed their rise in the late Holocene (the last 6000 years) and that the maximum width of these erosional platforms is no more than 300 meters (1000 ft), we can estimate long-term shoreline recession to have occurred at 20 cm/yr (0.7 ft/yr). Not only is this rate unusual, since most shore platforms are much narrower, but it is also an overestimate if one assumes that erosion rates have slowed as the platforms have widened, reducing wave energy.

Erosion rates in Puget Sound are highly episodic. Even rapidly eroding bluffs may remain stable for years, decades, or even centuries prior to a slope failure. Often property owners fear disaster when several feet of their bluff slides, failing to note that a 200-year old fir tree had been growing from the bank. The distinction between long-term averages and short-term events is crucial, but not often made.

2.3 Shoreline stabilization

The predominant land use on Puget Sound's marine shoreline is low-density residential housing. Traditionally, most homes were for weekend or vacation use, but increasingly primary residences are being located on the shoreline. Much of the shoreline is within commuting distance of major metropolitan centers. Bluff shorelines are popular for their outstanding views and traditional drawbacks such as beach access are frequently overcome with elaborate stair towers and tramways.

Shoreline protection is installed with the goal of protecting upland property from erosion. Often there is a perception that the shore is retreating rapidly and that a house or lot is in jeopardy of being lost. This perception is reinforced by the sudden and episodic nature of bluff failures. Ironically, property owners also attempt to maximize views by building their homes extremely close to the bluff edge.

The rationale for constructing shore protection devices is confounded by many non-geologic motivations. Bulkheads are often viewed as landscape improvements or as convenient ways to improve beach access on otherwise difficult sites. On a bluff shoreline, the bulkhead and the terrace behind it provide an excellent place to store a small dinghy, to place a picnic table, or to serve as the foundation of a stairtower.

Concrete bulkheads and rip rap are the most common forms of shore protection on Puget Sound. Rip rap may be installed either as a rubble revetment or as a placed-rock wall. Bulkhead and seawall construction reflects the experience of individual contractors, with the choice of rock or concrete largely determined by expertise and availability of suitable rock. Shore protection structures are rarely engineered for specific site conditions. Although older bulkheads were often built over the foreshore, present regulations discourage construction of structures below MHHW (mean higher high water). Still, bulkheads on bluff shorelines are typically built six or more feet from the toe of the bluff, largely on practical and safety grounds.

The effectiveness of shoreline stabilization has been mixed. Failures have occurred where structures were constructed poorly or were improperly designed for the site. Often walls designed to limit wave erosion are overtopped by landslides. This results from a common tendency to attribute bluff erosion to wave action alone and to ignore upland land practices or inherent weaknesses in the bluff. Walls are often undermined as a result of chronic lowering of the beach surface or during extreme storms.

Alternatives to traditional bulkheads and seawalls are unusual in Puget Sound. Breakwaters, although applied to traditional uses near marinas and harbors, have not been applied to erosion reduction. Groins proliferated in several shoreline communities prior to the state's Shoreline Management Act (1971), but have been generally prohibited since.

Beach nourishment has been used to protect shorelines and rebuild eroding beaches at several locations, including Ediz Hook at Port Angeles (Galster and Schwartz, 1989) and Lincoln Park in Seattle (Chu, 1985), and artificial gravel beaches have been constructed at several additional sites, but nourishment has not been applied to more traditional erosion problems or to bluff shorelines. Beach nourishment often encounters stiff resistance from regulatory agencies as a result of the high biological productivity of beaches and nearshore zones in Puget Sound and historical concerns about artificial filling of tidelands.

Shore protection is guided under Washington's Shoreline Management Act (SMA) and the Hydraulics Code, in addition to local regulations and building codes. The SMA (administered at the state level by the Department of Ecology) generally exempts residential bulkheads from Shoreline Substantial Development Permits, although local jurisdictions may require the permit if the applicant does not meet specific criteria. In general, if an existing structure is threatened by erosion, bulkheading is allowed. The Hydraulics Project Approval (HPA), which is required for any project in the waters of the state, establishes the maximum waterward extent of structures and seasonal windows in which construction can occur. The Department of Fish and Wildlife administers the Hydraulics Code.

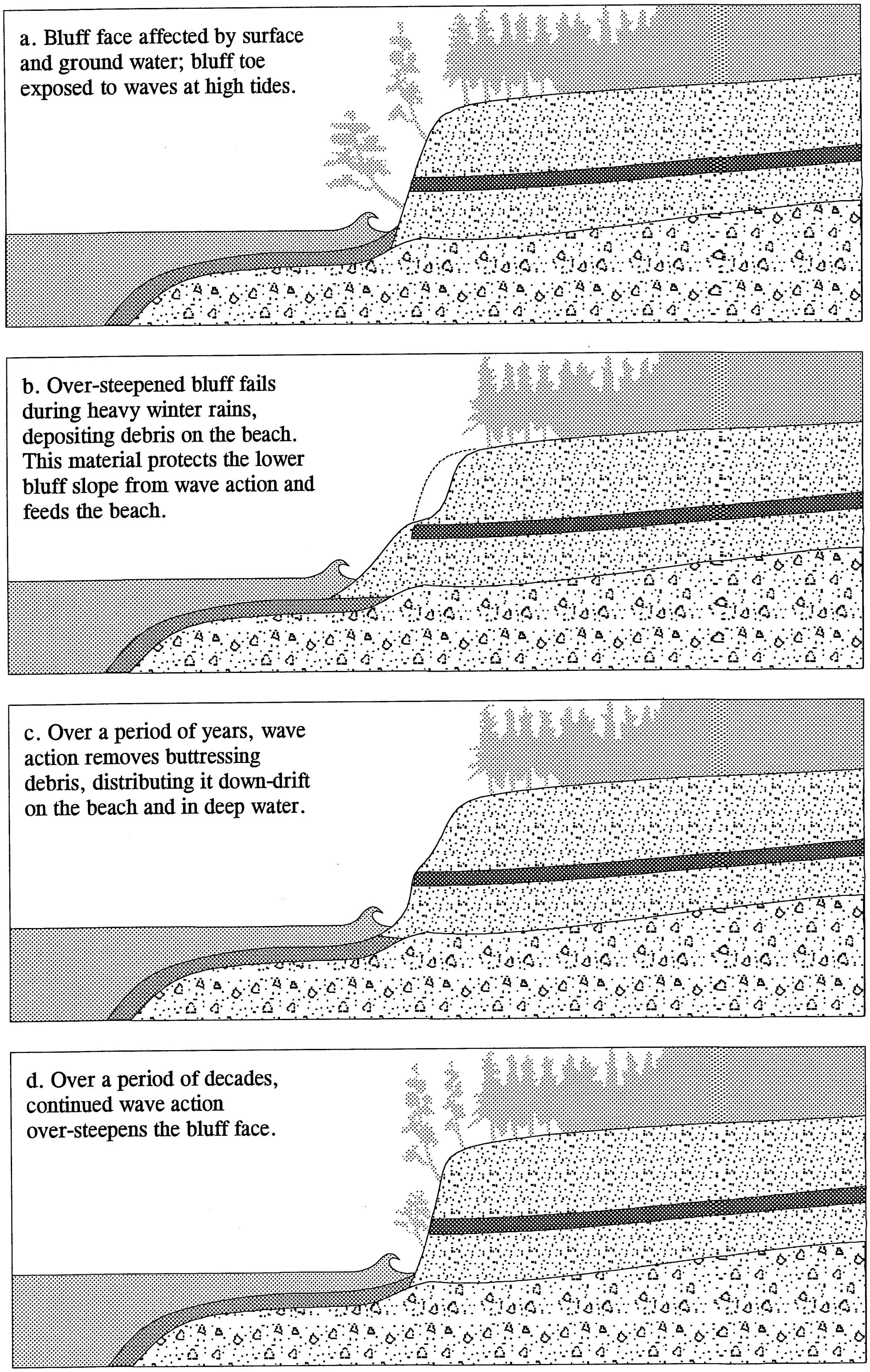


Figure 2.1 Evolution of Consolidated Puget Sound Bluffs

3. Shoreline Armoring in Thurston County

At the onset of the Coastal Erosion Management Strategy project, some of the fundamental questions that were prominent in discussions on shoreline erosion control were:

What portion of the shoreline is now armored?

Where is the existing armoring concentrated?

What types of shoreline protection is employed? Concrete bulkheads? Vertical rock walls? Rock revetments? Other techniques?

What portion of the current construction work is for new armoring and what portion is repair or replacement work?

Why is repair work being proposed?

At the time there was no definitive information, only informed speculation. The cost of answering these questions for all of Puget Sound would have been prohibitive. Thurston County was chosen as a representative locale for a study on shoreline armoring characteristics for a number of reasons:

Thurston County was thought to be representative of the still-developing, suburban Puget Sound shorelines;

Thurston County's shoreline permit records were thought to be relatively accessible;

Thurston County possessed a relatively advanced geographic information system (GIS) which already included some of the information necessary for an inventory and characterization;

Thurston Regional Planning Council staff were capable of carrying out the proposed study; and

the Thurston County Commissioners were one of the groups of local government elected officials which had requested that the Department of Ecology conduct an assessment of the cumulative effects of shoreline armoring.

The following sections of this chapter are a summary of the Thurston Regional Planning Council report (Morrison, Kettman & Haug, in press) to the Department of Ecology.

3.1 Introduction and Methods

The main objective of this pilot study was to document the extent and nature of shoreline armoring present in 1993 along the marine shorelines of Thurston County, and to analyze shoreline armoring permits and other data sources to assess the rate of change since the implementation of the Shoreline Management Act in the early 1970s. The study also contemplated the possibility of developing a model for documenting marine shoreline armoring or other shoreline developments.

Data characterizing shoreline armoring were gathered from shoreline armoring permits granted from 1985 through 1992; oblique and vertical aerial photographs taken in 1977 and 1992; the *Coastal Zone Atlas of Washington*; and a boat survey of the shoreline in January, 1993. Data characterizing shoreline properties were obtained from the Thurston County Assessor's 1992 property tax roll database; and data characterizing other natural features of the County's marine shore and nearby uplands were obtained from various existing maps. All data were either digitally mapped or linked to map coverages as tabular attributes in Thurston County's Geographic Information System, creating the Thurston County Shoreline Armoring Inventory Database. The organization of the database is depicted in Figure 3.1.

3.2 Methods Recommendations

Thurston County Planning Council team made the following recommendations as a result of their experiences in carrying out the pilot project.

3.2.1 Shoreline Armoring Permit Data

The main difficulty with this task was that the data in the permit files were inconsistent, both in form and content. Some files included information about the dimensions of the armoring proposed, but not enough of them did to be able to draw conclusions about average armoring length, for example. Some files included site characteristics, like evidence of slope failure, and vegetation type, or distance of nearest structure to the shore. If such data were consistently included in permit files, they would have contributed greatly to the study.

Recommendation: Standardize permit record-keeping: decide what information should be included in every permit file and provide a form for consistency and ease in entering and retrieval.

Recommendation: Better yet, include permit information in a computerized database of permit information, and attach land use permit file numbers as an attribute to the parcel in the Assessor's GIS parcel base for automated data retrieval.

Recommendation: As always, database design is critical. Utilize the skills of an experienced database designer in determining database structure and data entry protocols.

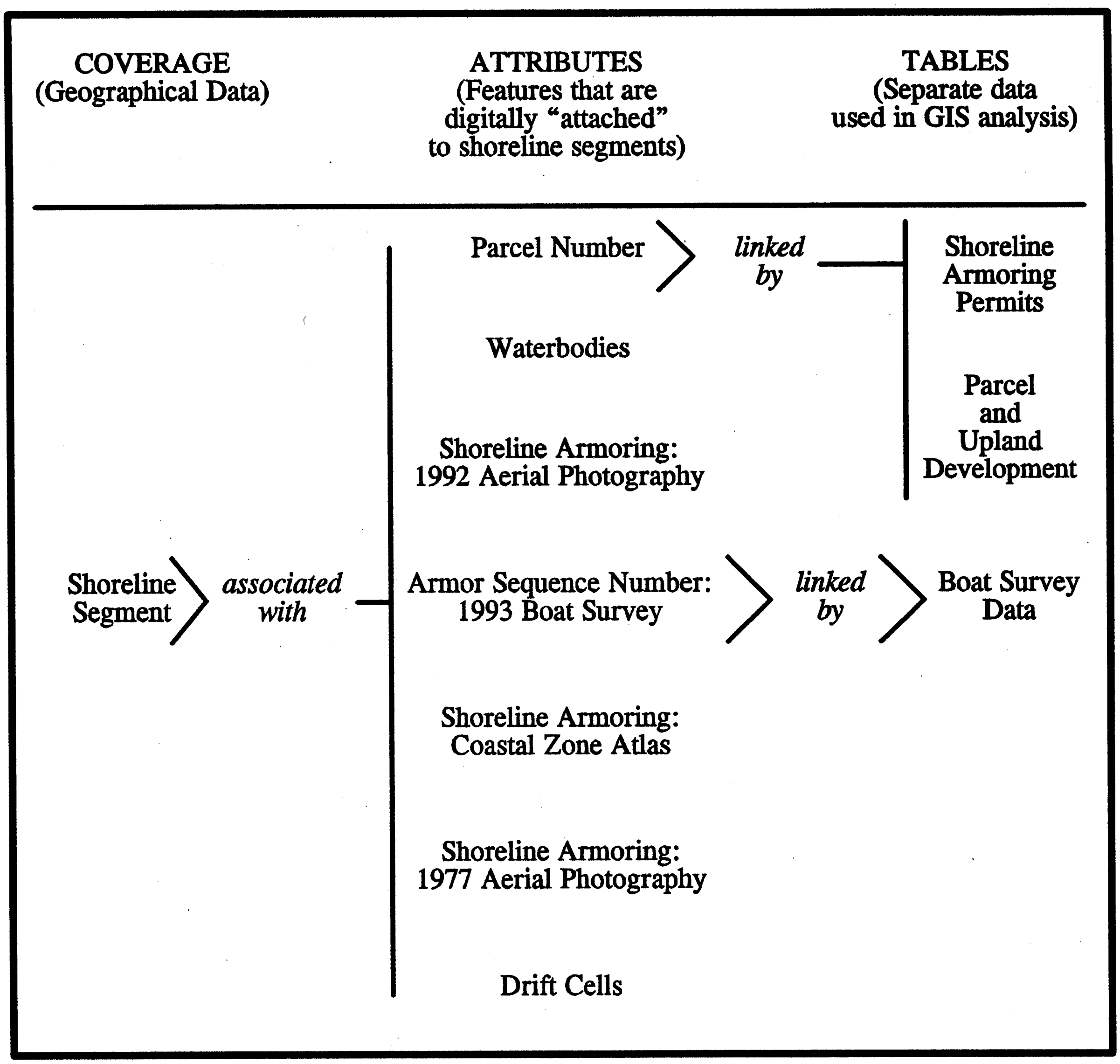


Figure 3.1 Thurston County Shoreline Features Database Organization

3.2.2 Parcel and Upland Development Data

The automated process of transferring data from one computer database to another using GIS to limit the data by area (200 feet upland of the shoreline) worked successfully.

Recommendation: Use automated data transfers whenever feasible.

3.2.3 Aerial Photo Interpretation

Difficulties with aerial photo interpretation include photo quality, photo angle, sun angle and beach shadows, time of year that photos were taken, and difficulty in mapping armoring on the correct parcels using landmarks on the photos in conjunction with vertical aerials and clear parcel map overlays of the same scale.[2]

Recommendation: Consider having oblique aerial photos taken during winter months.[3]

Recommendation: Get the best oblique photos possible: close range from shore, with appropriate sun position for minimal shadowing, at the lowest angle possible.

Recommendation: Conduct at least a partial field verification survey to estimate range of error on aerial photo interpretation.

Recommendation: Prepare a place name and landmark index for oblique photos with participation from staff most familiar with the shoreline, to aid parcel identification.

Recommendation: Use permit data, if necessary, to help eliminate false negatives.

3.2.4 Field Survey Data

The field survey was conducted in January, which caused great discomfort to the crew, who at times endured snow while collecting the data, and had difficulty focusing on the task. The difficulties in identifying parcels from landmarks, mentioned above, also occurred during the field survey, and relevant recommendations apply here as well. In addition, the boat used for the survey was sometimes too big to get close to the shore (generally at the heads of inlets), and a smaller boat had to be employed in a return trip to the site.

Recommendation: Conduct boat surveys during the summer.

Recommendation: Plan to use a small boat for shallow water areas.

---

[2] Department of Ecology staff note that north facing shorelines will almost inevitably be shaded, thus making difficult accurate photo interpretation of those shorelines. Further error analysis should be done to determine if significantly greater interpretation error did occur on north facing shorelines.

[3] The Department of Ecology conducts its aerial oblique photography during spring and summer months [1] when flying weather is more stable, [2] when day-time low tides enable more expansive photodocumentation of the intertidal zone, and [3] light levels are more reliable for better photography.

3.2.5 Geographic Information System

The most difficult task in approaching a project such as this is relating data of different types together. The questions asked of this database included "Are steep slopes near this shoreline area?" and "How built-up is that section of shoreline?" Responses to such questions need be very clear about the subject being quantified. Those difficult-to-quantify questions were supplemented by simple linear questions such as, "How much shoreline is armored?" The approach taken in this project was to answer all of these questions in one database and to limit most of the data to linear features tied to the shoreline. Some of the linear features provide a link to data subjects not precisely on the shoreline, and thus can help answer some of those difficult-to-quantify questions.

To be aware of potential problems early in the project, a pilot area was created and used to test each data attribute, coverage, and table link. Sample queries were applied and a demonstration of the data presented to the project team. Although this testing scheme did not identify all of the problems that arose, (because not enough queries were tested) it did provide critical information early enough to adjust the project work, and continue to produce useful data.

Recommendation: Make liberal use of the linear data format in GIS to provide versatility of the data and cost-efficiency.

Recommendation: Digitize and test a small area using all data types and sources to be included in the final product, before completing the coverage or attribute data entry.

3.3 Results

A comparison of 1992 aerial photograph interpretation and field survey data reveal a 34% error rate in the aerial interpretation data: 26% from false negative reports of armoring and 8% from false positive reports of armoring. When both 1977 aerial photograph data and *Coastal Zone Atlas* data are compared with field survey data, and then against each other, the *Coastal Zone Atlas* data show 27% false positives and the aerial photo data show 24% false positives. Thurston Regional Planning chose the 1977 Aerial Photograph Interpretation data for use as a 1977 baseline data source.

Within the entire study area, there were 2,590 marine shoreline parcels in 1992. For the purpose of comparison, both 1992 and 1977 data are measured against that total figure. Based on the January 1993 Field Survey, 56% of all parcels are currently armored. This represents 29% of the total shoreline length, compared to 14% that was armored in 1977 (see Table 2.1).

The number of shoreline parcels armored increased by 78% over the past 15 years. The cumulative armor length during this same time period rose by 110%. These rates of increase represent roughly 1% of the shoreline per year becoming armored, slightly more than 1 mile per year. The numbers shown on the tables above and throughout this report will be slightly high, due to the recording of entire parcels' frontage lengths as armored, although a few of those structures do not extend the entire length of the shoreline parcel's frontage.

The data (see Table 3.1) reveal that relative change over the fifteen-year period measured was by no means consistent throughout Thurston County. On Budd Inlet, where 44% of the parcels were already armored in 1977, showed a relatively moderate increase, to 66% of the parcels becoming armored by 1993. In comparison Nisqually Reach showed a larger increase: from 27% of parcels armored in 1977, to 63% armored by 1993. On Dana Passage, 17% of the parcels were armored in 1977, and 53% were armored in 1993. Although the numbers differ when shoreline lengths are compared instead of numbers of parcels, the variation in relative change persists. The Thurston County study area and its marine water bodies is mapped in Figure 3.2.

Comparing each of the water bodies for percent increase in both total shoreline-armored parcels and total length between 1977 and 1993 shows that Dana Passage and Nisqually Reach had the highest percent increase in shoreline armoring count and armor length.

Budd Inlet has the highest percentage of armored length in 1993 (see Table 3.2), as it did in 1977 as well. Budd Inlet[4] is also the most intensively developed shoreline. Conversely, the least intensively developed shoreline, Totten Inlet, has the smallest percentage of parcels armored. Although Henderson Inlet shows slightly less shoreline length armored than Totten, It also contains the Woodward Bay Conservation Area, which covers several thousand feet of shoreline, and is largely un-armored. Totten Inlet currently has no such shoreline protection.

During the eight years from 1985 through 1992, a average of 16 permits per year for new shoreline armoring and 32 permits for repair or replacement armoring were approved (see Table 3.3). The annual length of new armoring ranged from 1,079 feet to 4,952 and averaged 2,590 feet, or approximately 0.5 mile. On average, about two-thirds of the shoreline armoring applications are for repair or replacement work.

[4] Shorelines on Budd Inlet within the City of Olympia were not included in this study. The Coastal Erosion Management Strategy project was designed to address residential shoreline armoring. While there are residential uses on Olympia's portion of the Budd Inlet shoreline, much of the Olympia waterfront is industrial.

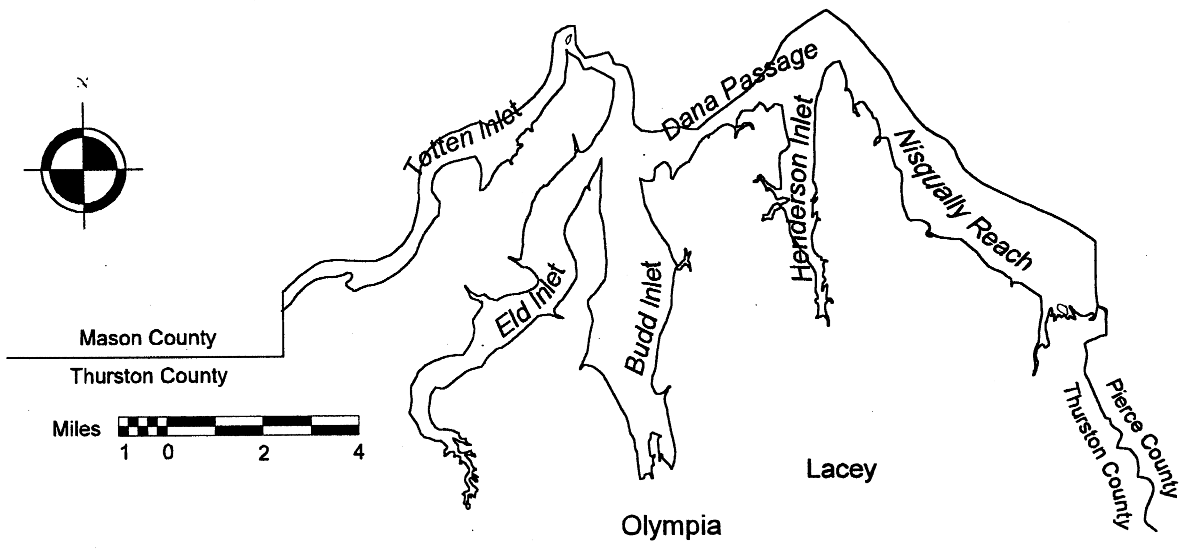


Figure 3.2 Thurston County Marine Shorelines

Table 3.1 Shoreline Armoring: 1977 – 1993

Characteristic	Budd Inlet	Dana Pass	Eld Inlet	Hend'n Inlet	Nisqually Reach	Totten Inlet	Total
Parcels Armored in 1977	217	27	313	104	69	86	816
Parcels Armored in 1993	330	86	559	164	171	139	1,449
Number Change	113	59	246	60	102	53	633
Percent Change	52%	219%	79%	58%	148%	62%	78%
Shoreline Armored in 1977, Feet	20,735	2,767	29,977	9,996	5,970	6,604	76,049
Shoreline Armored in 1993	34,108	8,485	63,701	19,177	19,594	14,388	159,453
Number Change	13,373	5,718	33,724	9,181	13,624	7,784	83,404
Percent Change	65%	207%	113%	92%	228%	118%	110%

Table 3.2. Thurston County Shoreline Armoring in 1993

	Budd Inlet	Dana Passage	Eld Inlet	Hend'n Inlet	Nisqually Reach	Totten Inlet	Total
Parcels Armored, 1993	330	86	559	164	171	139	1,449
Percent of Parcels	66%	53%	60%	43%	63%	40%	56%
Shoreline Armored, 1993	34,108	8,485	63,701	19,177	19,594	14,388	159,453
Percent of Shoreline	47%	33%	35%	19%	21%	20%	29%

Table 3.3. Comparison of New and Repair Armoring Permits, 1985 to 1992.

Year	Permits, New Armoring	Permits, Repair/ Replace	% Permits Repair/ Replace	% Permits Multiple Parcels	Feet, New Shoreline Armoring	Feet of Repair/ Replace	% Length Repair/ Replace
1985	7	14	66%	31%	1,073	1,175	52%
1986	12	44	79%	19%	2,229	9,228	81%
1987	14	38	73%	29%	2,611	6,445	71%
1988	12	40	77%	11%	1,892	13,394	88%
1989	36	25	41%	9%	4,952	3,750	43%
1990	18	34	65%	10%	4,399	7,8544	64%
1991	11	29	73%	14%	2,050	6,107	75%
1992	15	28	65%	3%	1,510	3,858	72%
Total	125	252	67%	16%	20,716	52,011	72%
Average	16	32	67%	16%	2,590	6,501	72%

In the comparing the change in the amount of armoring to the change in the amount of shoreline development, armoring outpaced development at twice the rate of increase (78% versus 39%). Since a significant number of parcels with existing development were adding armoring during this period, a closer look at the numbers of developed but non-armored parcels is called for. Unfortunately, such analysis could not be included in this study due to resource limitations, but the data is available in the database for future study.

County-wide, 42% of the shoreline is undeveloped and un-armored, but in certain areas, like Budd Inlet and the eastern shore of Eld Inlet, the percentage is much lower, indicating a higher build-out of the shoreline. Unfortunately, those high build-out areas generally coincide with some of the County's smelt spawning areas. Other major smelt spawning areas are in Henderson Inlet and Totten Inlet. The vacant and un-armored shoreline property includes the Nisqually National Wildlife Refuge, and local and state parks which will skew any projections about future build-out.

4. Coastal Erosion Management Techniques

This chapter consists of a summary of the engineering and geotechnical techniques addressed by the CEMS consultant team in two separate reports. The first report, *Engineering and Geotechnical Techniques for Shoreline Erosion Management in Puget Sound* (Volume 4 in this report series), addresses responses to wave erosion at the base of banks and bluffs. The second report, *Management Options for Unstable Coastal Bluffs in Puget Sound, Washington* (Volume 8 in this report series), addresses problems and solutions associated with development on and near unstable steep slopes on the shoreline. The Department of Ecology is not necessarily endorsing the information provided by the consultant team as a general solution to coastal erosion and landslide problems. Policy guidance to local governments and individual property owners will be developed in a later phase of the CEMS project.

4.1 Engineering and Geotechnical Techniques for Shoreline Erosion Management in Puget Sound

Many techniques are available for reducing shoreline erosion or minimizing its consequences, ranging from traditional engineered seawalls to the artificial nourishment of natural beaches. In general, bulkheads, seawalls, and riprap revetments are classified as "hard," whereas beach nourishment and vegetative erosion control are viewed as "soft." As environmental concerns have risen and our understanding of coastal geologic processes has grown, there has been an increasing emphasis on solving erosion problems with "soft" methods.

The technical feasibility and effectiveness of any erosion management technique will depend on both the physical setting and on the objectives of the landowner. Solutions that may be appropriate for one location may be unacceptable in another. Methods that are ineffective for a broad, sandy ocean beach may be well suited to the narrow, gravel beaches of Puget Sound.

This element of the Coastal Erosion Management Strategy addresses the wide variety of erosion control techniques that might be applicable in Puget Sound and presents a methodology for selecting appropriate alternatives. The emphasis is on engineering suitability given the geology and wave regime at the site, and the operational needs for the project (for example, protection from wave attack, slope stabilization, or protection of the beach itself). No comprehensive effort has been made to assess cost, economic risk, regulatory constraints, or environmental impacts.

Erosion control measures by property owners on Puget Sound are often driven by slope stability problems—and those problems may not be adequately addressed with the shoreline stabilization methods outlined here. Stabilization of coastal slopes is discussed in section 4.2 of this report.

4.1.1 Erosion Processes

Shorelines are dynamic, constantly changing environments. Waves continually erode material in one location, only to deposit the same material somewhere else. On Puget Sound, the beaches act as conveyor belts, moving sand and gravel from source areas, such as eroding bluffs and stream mouths, to depositional beaches or to deep water. As a result, erosion is not necessarily "bad" and is actually critical to the preservation and maintenance of some of our beaches. Beaches themselves can provide valuable protection for a bluff from wave attack, since they limit both the intensity and frequency with which waves can erode the toe of the slope.

Puget Sound shorelines consist largely of steep, unstable bluffs fronted by narrow beaches. These shorelines have evolved over several thousand years through a cyclic process of wave erosion, slope failure, and further wave erosion. Because shoreline erosion involves both wave process and upslope mass-wasting, both must be considered when searching for an explanation or solution. The evolution of consolidated Puget Sound shorelines through this interaction of wave erosion and slope failure is illustrated in Figure 2.1. Awareness of the inevitability of coastal erosion, its episodic nature, and its natural function, provides a basis for wise management of both natural resources and of shoreline development.

4.1.2 Identification of the Problem

Several factors influence the selection of an appropriate erosion management technique. Clearly the goals of the property owner are a significant determinant. A large industrial port facility may need erosion protection, but in the context of docks and cargo handling facilities. On the other hand, a public park may desire to reduce erosion, but without compromising shoreline access or losing a recreational beach. In this study, we have concentrated on the typical residential property owner whose goals may include landscaping improvements and beach access, but whose primary concern is to prevent the retreat of the shoreline or to reduce sliding of a marine bluff.

An equally important determinant of an appropriate erosion management technique is the physical nature of the shoreline. Both the geologic character of the beach or bluff and the wave conditions at the site are crucial in this evaluation.

Geologic Landform

The geologic form of the shoreline is strongly related to the nature of the erosion problem. High, steep bluffs often indicate more rapid erosion than do gradual, heavily vegetated banks. In addition, the form of the shoreline may affect the choice of an appropriate erosion management technique. What works to reduce sliding on a high bluff may not be a proper choice on an eroding sand spit. Puget Sound shorelines can be characterized to five general types:

Marshes are characterized by quiet water and are often found at mouths of streams and rivers or in protected bays and lagoons. They are sites of abundant aquatic vegetation and may be flooded at the highest tides.

Beaches are found on virtually all marine shorelines, but here we refer to beaches with wide berms or backshore areas as typically found on sand spits and other "no bank" waterfront. These shorelines are composed of unconsolidated sediments (sand and gravel) and are subject to periodic flooding. The backshore area may be a low marsh or a lagoon.

Banks are defined as low, steep shorelines less than 10' in height. These can occur anywhere the shoreline is cut into an upland of low relief. They may or may not indicate areas of low erosion.

Bluffs are steep shoreline slopes greater than 10' in height, typically composed of layers of sand, gravel, clay and glacial till. They may be bare or heavily vegetated and their slope may range from moderate to vertical. Bluffs are probably the single most abundant shoreline type within Puget Sound.

Rocky shorelines (bedrock) can be found in the San Juan Islands and a few other locations, primarily in the northern Puget Sound. Their resistant nature typically makes erosion protection a minor issue and are generally not addressed here.

Wave Energy
Wind-generated waves are the primary source of energy driving erosion and impacting shoreline structures on Puget Sound. The influence of waves on the shoreline may be significantly moderated by the presence and condition of the beach, but in general, maximum wave height provides a simple basis for delineating low, medium, and high energy shorelines. In Puget Sound, wave height is closely related to the local fetch (distance across open water). The following table illustrates this basic three-way division of wave-energy regimes.

Wave Energy	Wave Height	Fetch
Low	0 - 2 feet	less than 1 mile
Medium	2 - 4 feet	1 - 5 miles
High	over 4 feet	over 5 miles

4.1.3 Feasible Shore Protection Techniques

The *technical* feasibility of a particular erosion protection technique depends on the factors or criteria discussed in the previous section: the objectives of the property owner, the geologic landform, and the wave energy of the site. A wide range of options exist to prevent or reduce erosion, including what are generally categorized as hard solutions, soft solutions, and composite solutions. In addition, their are numerous nonstructural activities (building setbacks, upland drainage management, etc) that may result in reduced erosion or reduced threat from erosion.

The following table summarizes a large number of approaches that might be technically feasible in Puget Sound (the more commonly used armoring structures are illustrated in Figure 4.1). Some of these are described in more detail below.

Hard Structures	**Soft solutions**	**Composite Systems**
Bulkhead	Sand fill	Headland/pocket beach
Zero-clearance bulkhead	Gravel fill	Perched beach
Seawall	Beach strands	Groin systems
Revetment	Beachface watering	
Riprap	Shoreline vegetation	***Manufactured systems***
Gabions	Bluff vegetation	Linked blocks, Seascape
Grout-filled bags	Groundwater drainage	
Floating attenuators	Slope regrading	***Nonstructural activities***
Breakwaters		Setbacks, runoff control

Hard structures are designed to deflect or absorb wave energy and to retain natural banks or artificial fill. They are usually located parallel to and immediately adjacent to the shoreline and generally refer to bulkheads, seawalls, and revetments. Breakwaters and wave attenuation devices are also considered hard structures, but instead are placed offshore and designed to reduce wave energy before it reaches the beach.

Soft structures are also designed to dissipate wave energy, but do so more flexibly. They are generally intended to simulate a natural beach or shoreline. Typically examples include sand or gravel beach fills and beach nourishment or the use of vegetation to absorb wave energy and retain easily erodible soils.

Composite systems are combinations of the above. Hard structures may be combined with beach fills to improve their compatibility with the natural environment without sacrificing protection. Vegetation may be used in conjunction with a hard structure to maintain ecological values. Examples of composite solutions include groin systems, headland/pocket beaches, buried revetments, and bioengineering.

A number of manufactured systems have been developed, including an artificial seaweed to absorb wave energy and a variety of interlocking concrete block systems designed to armor shoreline slopes. These are not described specifically since they fall broadly under the categories above.

Nonstructural activities include measures such as construction setbacks—for homes or drainfields, for example—that either reduce human-induced erosion or that reduce the potential for erosion to cause harm.

The appendix to the full report presents technical descriptions of many specific erosion management techniques, including general construction information, design issues, and examples. The descriptions include rankings of appropriateness for various landforms. Although the descriptions evaluate the techniques from an engineering perspective, they do not assess the methods from the perspective of costs, regulatory concerns, or adverse impacts on either neighboring properties or on the natural environment. The following is a summary of this information.

Bulkheads and Seawalls

Bulkheads are the most common form of erosion protection used in Puget Sound and are generally designed to deflect wave energy and to retain soil. They may be constructed of concrete, rock, wood, or steel. A commonly used bulkhead on Puget Sound is the vertical rock wall or rockery, constructed from two or more tiers of large boulders. For the most part, there are no engineering design criteria for vertical rock walls used as bulkheads. Seawalls are massive bulkheads, designed for more energetic environments, and often incorporating features such as recurves or stepped walls.

Revetments

Revetments are sloped structures designed to dissipate wave energy and are often built of large rock (riprap). The rip rap may be placed on an existing shoreline slope, or may be built up to form a sloped structure.

Wave Attenuators and Breakwaters

These structures are designed to reduce or block incoming wave energy and thereby limiting erosion. They are placed offshore and may be floating or built on the bottom.

Beach Fills

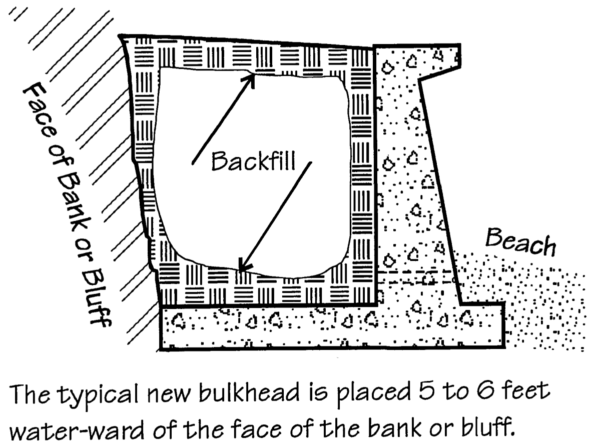
Sand and gravel fills can be placed to replace eroded material on a beach or to increase the protection provided by the beach. These systems may be highly effective at absorbing wave energy, but are designed to be flexible, and may require periodic renourishment. Coarse material can provide more protection than fine material and forms a steeper natural beach. Most beach fills closely approximate the natural beach and may be considerably less intrusive visually or ecologically.

Shoreline and Bluff Vegetation

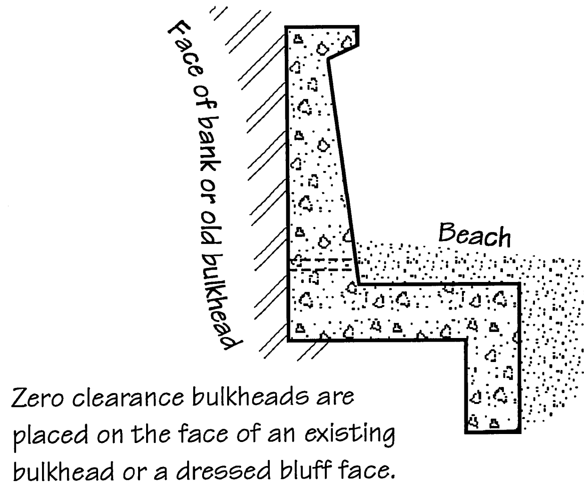
Vegetation can be used to absorb wave energy in lower energy environments and can be used to retain soils on berm/dune systems and on coastal bluffs.

Groundwater and Surface Water Drainage

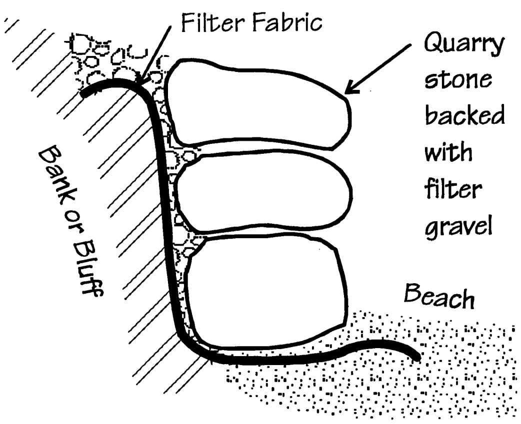
The stability of coastal bluffs is often strongly related to groundwater or to surface runoff. Drainage systems can reduce the saturation of a bluff, increasing its stability, and divert runoff away from the bluff face, reducing surface erosion.



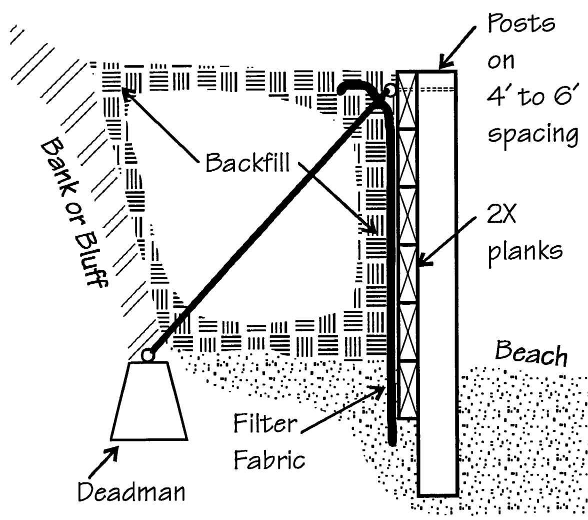
a. Concrete Bulkhead



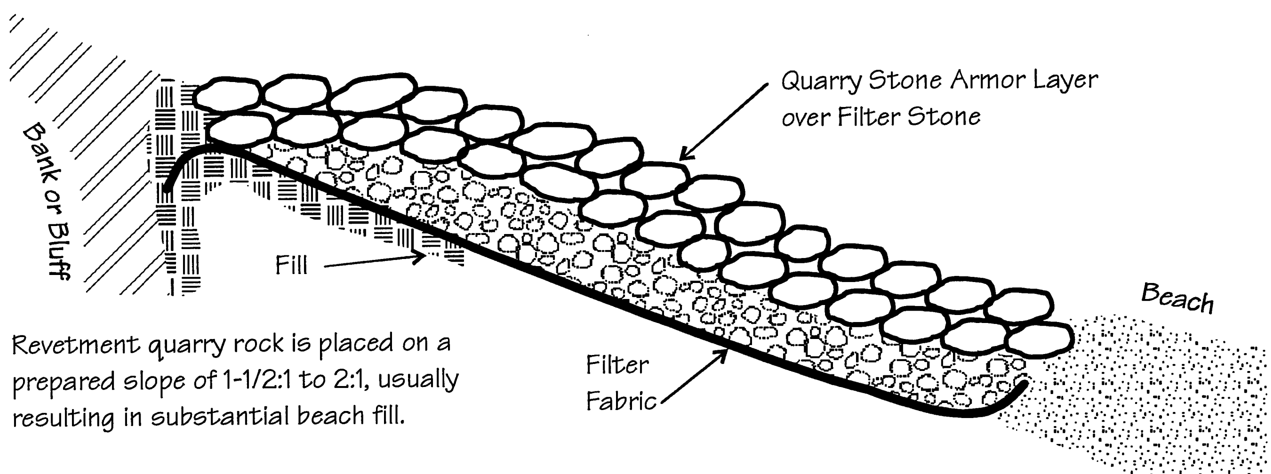
b. Zero Clearance Bulkhead



c. Vertical Rock Wall



d. Post and Plank Bulkhead



e. Rock (Riprap) Revetment

Figure 4.1 Common Types of Shoreline Armoring

4.1.4 Application to Specific Sites

Each of the shore protection techniques was evaluated to determine its compatibility with the selection factors described earlier: landowner's objective, geologic landform, and wave exposure. The following is a brief summary of findings.

Objective
A bulkhead or seawall may be the technically appropriate solution for a property undergoing significant wave attack, but drainage measures and revegetation may be a better choice if bluff erosion is largely related to upland hydrologic problems. A hard structure may do little to protect the beach itself and may actually exacerbate its loss, whereas a beach fill or breakwater may actually lead to increased beach area.

Landform
Landforms can affect the selection of an erosion protection structure either because of construction considerations or because of the compatibility of the structure with the site. A marshy soil may not form an stable foundation for a bulkhead. Similarly, large rock placed on beach may ultimately sink into the beach or shift waterward. A bulkhead may be effective on a steep slope where both wave protection and buttressing are necessary, but a gravel fill may be more appropriate on an eroding spit or barrier beach. An offshore breakwater might provide protection for an eroding marsh, without adversely impacting the waterward edge of the marsh itself.

Wave Energy
Some solutions, such as shoreline vegetation, may not be appropriate for high energy environments, whereas structures deigned for high-energy wave conditions, such as seawalls or large revetments, may be unnecessary in protected regimes such as small bays or lagoons. Composite solutions may allow a more natural solution such as a small beach fill or bioengineering techniques to succeed, despite a higher wave energy environment.

4.1.5 Site-specific Decision Model

The full report includes a model aimed at helping shoreline regulators and property owners determine the appropriate methods for a given site, based the protection goals, the geologic setting, and the wave exposure. The model allows decisions to be made on the basis of a minimum of critical information about the site.

The decision model is presented as a flow chart. The first step is to determine the nature of the problem. Does the erosion present a serious threat, or is a property owner reacting to a relatively minor or infrequent event? Is the problem related to wave action or to upland instability? Next, provided the site can be characterized by landform (bluff or beach) and by wave exposure, a list of available and appropriate options can be compiled. Finally, the property owner or regulator can evaluate the aesthetics, costs, and relevant regulatory constraints (usually based on resource value of the shoreline and potential adverse impacts of the structure) and select the best technique for the site.

4.1.6 Conclusions

This portion of the Coastal Erosion Management Strategy outlines a wide range of available techniques for reducing, preventing, or otherwise managing an eroding shoreline. These techniques range from traditional engineered structures such as seawalls and revetments to more natural methods such as beach nourishment or the planting of shoreline vegetation. These techniques are evaluated based on their appropriateness and effectiveness for given shoreline conditions (geology ad wave regime) and in the context of the landowner's objectives. No attempt is made in this report to assess the impact of these structures on adjacent shorelines or their cumulative impact on shoreline resources.

Although an effort was made to draw the techniques from shorelines similar to Puget Sound's, experience suggests that some techniques will prove inappropriate in the Sound, for either physical reasons or because of unacceptable environmental impacts. On the other hand, the list may include valid alternatives that simply have not been tested in Puget Sound.

Currently, decisions about preferred erosion management techniques are influenced by concerns about risk. Concerns about contractor liability or about worst-case failure may drive a decision to build a structure that is substantially more robust, and potentially more expensive or more environmentally damaging, than would normally be needed. This issue tends to discourage soft solutions such as vegetation and beach fills which are inherently less predictable. (Note that even "hard" solutions often fail prematurely, often for the very reason that they are not sufficiently flexible to adapt to dynamic beach conditions).

4.2 Management of Unstable Shoreline Slopes on Puget Sound

Coastal bluffs are the dominant landform along Puget Sound shorelines. These bluffs are erosional features by their nature, gradually receding through the action of waves and mass-wasting, however, bluff stability is a complex issue related to geology, hydrology, vegetation, as well as wave-action.

Residential development pressure is high along these bluffs and often structures are built sufficiently close to the shoreline to be threatened by erosion or landsliding. To protect these properties, erosion control structures such as concrete or rock bulkheads are typically built, yet many of the erosion problems on these coastal slopes are the result of bank and bluff failures, and not due to shoreline erosion per se. Bulkheads may slow wave erosion at the foot of a bluff, but they cannot halt surface erosion and sliding occurring farther up the bluff caused by geologic weakness, poor drainage, or poor vegetation management practices.

The approach of this task was to generally describe Puget Sound coastal bluffs and common forms of slope failure, to identify the principal causes of slope failure, to outline the range of techniques available to address slope failure, and to identify areas where additional work is necessary. The emphasis, as with other tasks in this study, was on single-family residential shoreline development.

4.2.1 Regional Overview

Puget Sound is a series of fjordal estuaries, comprised of numerous straits, bays, and small coves. Major and minor rivers form deltas where they enter the Sound. Because shoreline areas are generally steep, the most common landform is a high bluff, sometimes vegetated, and usually fronted by a coarse sand or gravel beach. These bluffs generally consist of glacial sediments and the beaches derive primarily from the erosion of these bluffs, except in certain locations where local stream and river inputs are relatively more important.

Recent glaciations dominate the geologic setting of the Puget Sound region, creating many of the topographical features of the area and deposited most of the sediments now exposed along the shoreline. The highly variable nature of glacial action, combined with other factors, has led to a highly diverse shoreline that includes major bays with extensive tidal flats, small tidal inlets, river deltas, rocky headlands, low-lying sand spits and barrier beaches, and most commonly, eroding bluffs with fronting beaches. Every county displays a different range and mix of these landforms and therefore, a different exposure to coastal hazards.

Marine bluffs are a significant regional hazard, subject to active erosion and landsliding. Erosion control measures are often not a reaction to shoreline erosion *per se*, but are rather a response to slope instability and bluff failures. At least half the Puget Sound shoreline is subject to these hazards. Although local Shoreline Master Programs give attention to coastal flooding and erosion, they often do not adequately address hazards associated with the bluffs themselves.

Puget Sound shorelines have undergone a number of major historical modifications, the earliest of which was the large-scale logging of the readily accessible timber. The remnants of this activity can still be seen in large stumps and abandoned mill sites along the shoreline. The most significant modification of the physical shoreline, outside of the major urban/industrial areas, was the establishment of the Great Northern railroad grade along the eastern shore of Puget Sound between Seattle and Everett.

Development initially concentrated in low-lying areas with easy water access and marine bluffs underwent only limited low-density residential development. As population increases in the region, the bluffs are now becoming high-value real estate, largely due to their expansive views. Some of the region's highest growth rates are occurring in rural counties with extensive marine bluff shorelines (for example: Island, Kitsap, and Jefferson).

4.2.2 Types of Slope Failure

Slope failures can be generally classified as soil and rock falls, shallow slides and flows, and deep-seated slumps and flows. Although most failures can be described by a combination of these types, the most typical slope movement on Puget Sound bluffs is the shallow slide (soil creep is pervasive on steep slopes, but is generally not as serious a hazard).

Soil and rock falls are characterized by rapid downslope movements of blocks of material and might be found on rocky shorelines or in areas dominated by coherent units of fine-grained sediments such as glacial till or lake deposits. They generally occur following undercutting by wave action or sapping of underlying sediments by groundwater.

Deep-seated slope movements generally include rotational slumps and associated earth flows. They are usually related to specific geologic circumstances and in many cases may represent areas of ancient slumping that first occurred soon after the glaciers retreated. They may be subject to reactivation following modification of slopes or hydrology. These features may be large, encompassing several properties. Many, but not all, are indicated on the Slope Stability maps of the *Coastal Zone Atlas of Washington* (Washington Department of Ecology, 1978).

Shallow slides and debris flows are probably the most common form of slope failure on Puget Sound bluffs. They typically involve only the upper few feet of material on a slope - usually the weathered soil layer. An initial slide may turn into a debris avalanche as it progresses downslope. Slides are often precipitated by saturated soils, that add to the weight and decrease the strength of the soils. This commonly occurs in association with human activities that result in concentration of drainage or other hydrologic changes.

4.2.3 Causes of Slope Instability

Slope stability is a function of geologic, topographic, climatic, and hydrologic factors, but ultimately a slope failure occurs when the stresses to move material downslope exceed the resistance of the materials to sliding. Three primary reasons for slope failure are: removal of lateral support at the toe or sides of a slope, loading of upper portions of the slope, and changes in the hydrology of the slope.

Topography

The height and steepness of coastal bluffs affect their stability, though this relationship is strongly dependent on the geology of the bluff. Bedrock will generally remain stable on much steeper slopes than will unconsolidated glacial sediments. Dry soils will generally support much steeper slopes than wet soils. Similarly, a fully vegetated bluff may be stable at substantially steeper angles than the same bluff when cleared of vegetation. (It should be noted that bluff topography is a function of stability and erosion rates, and not the other way around!)

Toe Erosion
Slope failures are often triggered or contributed to by the removal of support at the base of the slope. This may occur as a result of erosion of lower portions of slope by waves or runoff, or by excavation by humans. Wave-induced erosion is a primary cause of toe erosion and ultimately of shoreline recession on most marine bluffs.

Shorelines evolve and recede through a cyclic process: waves remove support at the base of the bluff, the oversteepened slope slides and deposits material at the toe of the slope, protecting the base from waves, and the process repeats itself. As a result, slope failures are episodic and short-term erosion rates may be substantially higher or lower than the more relevant long-term rates. The evolution of typical Puget Sound consolidated bluffs is illustrated in Figure 2.1.

Wave-induced erosion depends on the wave energy of the site and the geology of the material at the toe of the bluff. The ability of waves to erode the toe of a bluff also depends greatly on the character of the fronting beach, which can substantially limit the frequency and vigor with which waves and runup can reach the bluff. Ironically, the beach's ability to buffer wave action depends on the continued supply of sediment, and in the case of Puget Sound, the continued erosion of the bluffs. While armoring the toe of a bluff to stabilize a slope may be effective for a given piece of property, the ultimate effect of such armoring is to reduce the supply of sediment to the beach and to destabilize adjacent portions of the shoreline.

Local Geology
Local geology is a critical factor in determining slope stability. The strength of a geologic unit will help determine the slope at which it can stand, its susceptibility to failure due to loading, and its resistance to erosion. The geology of a unit also controls its hydrologic properties which may bear directly on a bluff's stability.

As discussed previously, Puget Sound bluffs consist primarily of recent glacial and interglacial sediments. There is considerable variation in the geology of the shoreline from one location to a another and significant variation can even occur within individual formations. The layering, or stratigraphy, of these sediments is also important. Landslides in the Puget Sound region commonly occur where a permeable outwash sand overlies an impermeable layer of lacustrine clays (Tubbs, 1974). Downward moving groundwater collects at this boundary, increasing pore pressure and leading to the development of a zone of weakness. The relatively weak, overlying sands can then slump or slide.

The Washington Coastal Zone Atlas (Department of Ecology, 1978) contains slope stability maps for much of the Puget Sound shoreline. In addition, county soil surveys or other geologic mapping may contain information that can help identify unstable areas. Such maps are not intended to be used to determine the characteristics of a particular site but rather to indicate a general condition that might lead to instability or the need for further evaluation.

Vegetation
Vegetation is an important factor in bluff stability. Although vegetation may occasionally lead to slope failure - by adding weight to the slope, by stressing soils during wind storms, or by

root wedging - it generally increases the stability of the slope. It provides root strength to the soil, protects the soil from surface erosion, and helps remove water from the soil. Woody vegetation may significantly stabilize slopes through buttressing, soil arching, and the formation of substantial root systems.

Groundwater and Surface Water
Hydrologic factors are also a major factor in bluff stability - as already mentioned in discussions of local geology and vegetation. Rain and surface runoff can erode soils. Groundwater seepage may sap individual layers of soil, undermining upper portions of the bluff, and saturated layers may weaken and lubricate potential failure surfaces. Water can add substantially to the weight acting on the bluff.

Human Modification
Humans can significantly affect slope stability - both in negative and positive ways - primarily through modification of the various factors mentioned above. We may undercut slopes, load the top of the bluff, or significantly alter the hydrology or vegetation on a site. These impacts are particularly likely during initial site development when vegetation is removed, grading leads to loading of the bluff top, soils are disturbed, and runoff and drainage are concentrated.

4.2.4 Managing Unstable Shoreline Slopes

A wide variety of techniques exist for reducing the hazards associated with marine bluffs, ranging from avoidance of erosion-prone areas to major regrading of slopes and structural stabilization. In this section, a survey of approaches is presented, moving from the least intrusive to the most intrusive techniques. In general, the cost of the technique increases in this same order as does the level of habitat loss and environmental impact.

Because public and private costs, along with environmental damage, may be considerably reduced for the less intrusive measures than for extensive stabilization works, it may be appropriate to view the choice of slope management technique in the following sequence: 1) avoid impacts, 2) minimize impacts, and finally, where the previous options are not viable, 3) mitigate for impacts.

Some approaches, such as avoidance and vegetation management, are easiest applied during initial site development, whereas the more sophisticated structural techniques may be more appropriate when dealing with older, inadequately set-back structures. This suggests that a management strategy for unstable coastal slopes might treat existing structures and sub-standard lots differently than future development.

Regardless of the slope management approach chosen, there is a clear need to identify potentially hazardous areas and to make decisions based on high quality geologic or geotechnical information. Existing geologic mapping may indicate the potential for stability problems on a site. Such information might be used to determine the need for more detailed, site-specific evaluation, which in turn would help guide appropriate site development and slope management options. Such geologic evaluations can be extremely useful to both property owner and to the local jurisdiction, if there is adequate review of both the content and quality of the study.

Avoidance

Slope problems are typically much less expensive to avoid than to repair. Avoidance may take the form of avoiding a site altogether, avoiding portions of a site that are subject to slope instability, or avoiding activities that may exacerbate problems. In general, avoidance would apply to initial decisions about site development, but avoidance might also be the rationale for relocating an existing structure rather than attempting to stabilize a hazardous slope.

Setbacks and Construction Requirements

Construction setbacks can be useful for guiding activities out of particularly hazardous locations or locations where development may increase stability problems. The actual distance should reflect the stability of the soils, the long-term erosion rate, the sensitivity of the area, and possibly the type of development. Determining an appropriate setback given this broad list of factors may be difficult, although numerous jurisdictions have established setbacks based on general conditions.

Setbacks can apply to the structures themselves, to outbuildings or decks, to impermeable surfaces, or to septic drainfields. Setbacks that apply to vegetation modification or grading activities might be better classified as buffers, though their purpose remains the same. In addition to setbacks, restrictions may be placed on the type of construction that may occur - such as requirements that drainfields be placed landward of the house or that fills or impermeable surfaces be avoided near the bluff.

Vegetation Management

Extensive vegetation removal often accompanies development of Puget Sound bluff property, but this practice can often exacerbate slope problems. Vegetation provides strength to soils , reduces surface erosion, and may prevent bluff material from becoming saturated. Wise vegetation management practices are described in detail in *Vegetation Management: A Guide for Puget Sound Property Owners* (Menashe, 1993).

Surface water Runoff

Poor management of surface runoff from developed properties may cause serious erosion of the bluff face or increased saturation of bluff materials, which can in turn lead to serious slope failures. Careful management of surface runoff, particularly from large impermeable surfaces such as roofs and driveways (and compacted lawns), can reduce the likelihood of problems. Solutions include careful planning, source reduction (decreased use of irrigation systems and less impermeable surface), and diverting runoff from sensitive areas with drains. Efficient infiltration should generally be encouraged, though not immediately adjacent to the bluff.

Groundwater Management

Groundwater is also crucial to slope stability, but is much more difficult to control than surface water. The same basic approaches, careful planning, source reduction, and drainage, apply, but the techniques vary. Management of surface water is an important step in managing groundwater, since excessive runoff can cause rapid infiltration and weakening of bluff soils. Drainfields can be a significant source of groundwater and should be located away from the bluff. Subsurface drains can be used to intercept water flowing toward the bluff face, or to reduce the water in subsurface horizons.

Biotechnical Slope Protection

Bioengineering methods are gaining wider recognition as viable means of providing stability to slopes, particularly in sites where costs or environmental concerns preclude more traditional engineering structures. These methods may rely entirely on vegetation or may incorporate vegetation into built structures. Techniques include intensive seeding, live staking of woody plants, and a variety of wattling and layering methods. The entire range of alternatives is provided in *Slope Stabilization and Erosion Control Using Vegetation; A Manual for Coastal Property Owners* (Myers, 1993).

Conventional Structures

A number of structural methods exist to stabilize steep slopes and eroding bluffs. Traditionally, the most common approach to managing bluff erosion on Puget Sound has been to construct bulkheads or place riprap to reduce wave-induced erosion at the toe of the slope, but these are only a subset of a broader range of structures that can be used to stabilize unstable slopes.

Well-designed bulkheads and riprap revetments may provide protection from wave action, but are generally not designed to buttress or otherwise stabilize the bluff itself (for more on wave-erosion protection methods, see Volume 4). More substantial retaining structures can also be built, either at the toe of the bluff, or on the slope itself. Basic types include gravity walls, cantilevered structures, tieback walls, and flexible walls. Reinforced earth fills can also be used to stabilize portions of unstable slopes. In the case of large rotational slope failures, it may be possible to stabilize the slide with a large buttress fill at the toe of the slope.

It is important to note however, that many of these solutions are expensive, difficult to construct (particularly on sensitive and cramped shoreline bluffs), and may be either impractical or unacceptable on many residential shorelines. All require significant modification of the shoreline and some require extensive coverage of the beach itself.

Structural solutions may suffer from three major limitations: 1) they may not be engineered properly for the situation, 2) they may not address the full range of destabilizing factors and 3) they address only a single property and fail to adequately address an entire reach of shoreline. As is discussed elsewhere, structures may actually exacerbate erosion and stability problems on adjacent or downdrift shorelines.

Reshaping of Slopes
In some situations, the most effective way of stabilizing a slope is through regrading and changing the contour. This normally involves flattening the slope. Where space is limited, as it usually is, terracing may be incorporated through the use of retaining walls. Slides can be stabilized by reducing the weight at the top of the slope, or increasing it at the base. Clearly, one major characteristic of slope regrading is that it fundamentally changes the natural slope and cannot be done without extensive removal of existing soils and vegetation.

4.2.5 Summary: Selecting Appropriate Solutions

A number of conclusions can be drawn from this study:

- Steep bluffs composed of poorly consolidated glacial deposits are common landforms on Puget Sound, but the bluffs vary greatly, even within fairly short distances.

- Shallow debris slides are the most common form of slope failure on Puget Sound coastal bluffs. These slides are on a scale that typically affects no more than a single home site.

- Slope instability is due to a number of factors, including geology, topography, hydrology, vegetation, and wave action. Actions to limit the role of any one factor may not prevent slope failures and erosion.

- Site development is a major cause of increased slope instability, through vegetation and hydrologic changes, construction activity, and slope disturbance.

- There are numerous ways of managing shoreline bluffs, though there is clear hierarchy of techniques ranging from simple avoidance of unstable sites to major structural stabilization. For both economic and environmental reasons, it is generally preferable to avoid or prevent slope problems through less intrusive means, before resorting to complex and expensive control measures such as engineered structures.

A framework for selecting appropriate solutions should be based on these conclusions, along with careful site-specific analysis. Site analysis may begin with a simple homeowner's questionnaire coupled with a review reconnaissance level information such as that found in the Coastal Zone Atlas of Washington, but might also extend to a detailed geotechnical examination of the site.

A number of factors should be given special attention. Evidence of past instability is a sure sign of potential hazards and can often be assessed based on existing maps or on a simple site evaluation. Attention should be paid to site development practices that may exacerbate unstable conditions, such as drainage changes or large-scale vegetation removal.

5. Impacts of Erosion Management

This chapter addresses the direct and cumulative effects of shoreline armoring in Puget Sound. The first section is a brief discussion on impact analysis and cumulative impacts prepared by Department of Ecology CEMS staff.[5] The second and third sections are summaries of reports prepared for the Department of Ecology by the CEMS consulting team.

5.1 Introduction

Environmental impact analysis was first mandated by the National Environmental Policy Act (NEPA) and Washington's State Environmental Policy Act in 1970 and 1971. In the intervening years a large body of legislative amendments, regulatory interpretation, quasi-official guidelines, and research literature has been published to explain the nature and methodologies of impact analysis. Its fundamental purpose remains to predict the impact upon the environment of specific actions undertaken or authorized by government. The goal of NEPA and SEPA was to integrate "the natural and social sciences and the environmental design arts into the planning and decision-making process." Environmental impact analysis was originally viewed as an artifact of that process; a report on the success of the desired integration.

The types of impacts to be analyzed are generally categorized as direct (or primary), indirect (or secondary), and cumulative. The definition of these types of impacts varies of necessity with the type of project or program under analysis.

Cumulative impacts were not explicitly mentioned in the 1971 SEPA or in the unofficial guidelines published by the Department of Ecology in 1972. In 1973, however, a state Court of Appeals decision (Juanita Bay Valley Community Association v City of Kirkland; Wash. App., 510 P.2nd 1140) cited cumulative effects as one of its reasons for overturning a grading permit issued by the City:

> Environmental impact of total project, rather than of grading project alone, must be weighed and environmental impact statement must be prepared before first governmental authorization of any part of project or series of projects which, when considered cumulatively, constitute major action significantly affecting quality of environment.

Direct impacts are most often the impacts associated with the construction of a proposed project.

---

[5] The original version of the essay in Section 5.1 was prepared by one of the CEMS staff (DJC) in 1982 for the Washington State Forest Practices Board's Cumulative Effects of Forest Practices Study Team.

Indirect impacts are most often the impacts associated with occupation and operation of the facility proposed for construction. They are also the 'down stream' effects created by, or set in motion by direct impacts. For example, sheet erosion as a result of construction activities is a direct impact; the secondary impacts are stream sedimentation, degradation of salmon spawning habitat, and reduction of salmon populations.

Cumulative impacts are generally regarded as some form of a large scale accumulation of impacts through time. The most widely referenced definition of cumulative impacts is the one set forth in the Council on Environmental Quality (CEQ) regulations for implementing NEPA. It defines cumulative impacts as:

> the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (federal or non-federal) or person undertakes such other actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time. (Section 1508.7)

Beyond this, there is little agreement as to a precise definition. In fact, most teams addressing major cumulative impact analysis tasks seem compelled to redefine cumulative impacts for their particular needs. Davies (1993) proposes that:

> To a large extent all environmental effects can be seen as cumulative in that all environmental effects occur in environments that are already stress by either natural activities and events, or human activities.

For the purposes of the CEMS project we concerned about the cumulative impacts of shoreline armoring on discrete segments of the Puget Sound shoreline and bodies of water within Puget Sound. To that end, throughout the project we were asking the following questions:

> Does shore protection cause sediment impoundment that has down drift effects?
>
> Can modification of the groundwater regime impact beach erosion?
>
> Does shore protection cause narrowing of the beach?
>
> Does shore protection cause lowering of the beach profile?
>
> Does shore protection cause coarsening of the beach substrate?
>
> Does shore protection cause loss of large organic debris at the shore?
>
> If the foregoing physical impacts are significant, what secondary effects on biological resources and ecological processes are caused?

The purpose of environmental impact analysis carried out under SEPA is to aid the decision-makers who must judge the merits of applications and determine what mitigation measures are appropriate.

The CEMS project was instigated primarily by an amendment of the Shoreline Management Act by the 1992 Legislature, and a request for assistance by certain local governments regarding the cumulative effects of wide spread shoreline armoring.

Under the SMA, "construction of the normal protective bulkhead common to single family residences" is exempt from the requirements of the Shoreline Substantial Development Permit (RCW 90.58.030 (3) (e) (ii)) but bulkhead construction must other wise comply with the basic legislative intents of the Act:

> It is the policy of the state to provide for the management of the shorelines of the state by planning for and fostering all reasonable and appropriate uses. This policy is designed to insure the development of these shorelines in a manner which, while allowing for limited reduction of rights of the public in the navigable waters, will promote and enhance the public interest. This policy contemplates protecting against adverse effects to the public health, the land and its vegetation and wildlife, and the waters of the state and their aquatic life, while protecting generally public rights of navigation and corollary rights incidental thereto. (RCW 90.58.020)

ESB 6128 requires local government to amend their shoreline master programs to give preference to shoreline erosion protection for residences occupied prior to January 1, 1992, where the shoreline protection measure "is the least harmful to the environment."

Therefore, the goal of impact analysis conducted under the CEMS project should be to aid decision makers to the extent possible:

> 1) in evaluating the SMA's fundamental goal of balancing "planning for and fostering all reasonable and appropriate uses" with "protecting against adverse effects to the public health, the land and its vegetation and wildlife, and the waters of the state and their aquatic life" with respect to shoreline protection proposals, and
>
> 2) by providing information to evaluate the shoreline protection measures that are "the least harmful to the environment."

Erosion control structures are purposely intended to modify physical characteristics of the shoreline. Specifically, they are designed and built to reduce wave-induced erosion, to retain unstable banks, and to limit flooding due to wave runup. Because the interaction of waves, beaches, and shore bluffs fundamentally defines the morphology and processes that affect the shore, it is reasonable to expect that shoreline armoring may lead to physical changes to beaches and shorelines beyond those for which the structure was actually planned.

The purpose of this part of the study was to identify the range of impacts that erosion control methods might have on the physical shoreline environment. This work has been based on a comprehensive review of published literature, an investigation of several well-documented shoreline sites within Puget Sound, and a careful application of fundamental coastal geologic principles and knowledge.

The wave dynamics and sedimentary processes that shape Puget Sound shorelines have already been described in detail and are crucial to understanding the findings of this section. In particular, readers should understand the significant role of longshore drift on Puget Sound beaches, the importance of bluff erosion as a source for beach sediment, and the predominance of coarse sand and gravel beaches in the Sound.

5.2 Physical Impacts

The subject of seawall and beach interactions has received considerable attention in recent years. Several comprehensive literature reviews have been published that summarize the results of laboratory, field, and theoretical research. These studies indicate that seawalls may indeed have significant adverse impacts on beaches, but that the effects are highly site specific. Quantitative studies have been rare and the studies are marked by considerable speculation. Many of the results are ambiguous or inconclusive due to the large number of variables involved.

A bulk of this research concentrates on open ocean systems, where shorelines are characterized by broad, sandy beaches and ocean wave and swell conditions. Beach changes may be associated with hurricane strength storms that are accompanied by extreme storm surges. Supplies of beach sediment may be largely offshore, dune systems, or rivers, as opposed to seacliff erosion.

Estuarine shorelines are distinctly different. Nordstrom (1992) provides an excellent review of research on the subject and makes it clear that estuarine beaches are not simply scaled-down versions of ocean systems.

Tidal ranges are higher and the wave environment is less severe (but waves are more likely to break directly on the bluff and to approach the shore at more oblique angles). Beaches are narrow, generally coarse grained, and often sediment-limited. Beach processes are more closely connected to bluff erosion, upland hydrology, and to the presence of upland vegetation and large organic debris along the shore.

Little scientific work has been done on Puget Sound beaches, and much of this has been qualitative. Where such work has been done, the circumstances are often unique, and extrapolation to general Puget Sound conditions is difficult.

5.2.1 Types of Impacts

Shoreline armoring can lead to a variety of physical impacts—see Table 5.1. Direct impacts include construction disturbance, burial of the beach or bluff toe by the structure, and the impoundment of sediment behind the structure. Indirect impacts include downdrift beach starvation due to sediment impoundment, changes in hydraulic action, and modifications to the groundwater regime. Cumulative impacts include incremental increases in the above impacts, the development of downdrift sediment deficits, and the possibility of exceeding threshold conditions that lead to acceleration of adverse impacts.

Table 5.1 Shoreline Armoring Impact Categories

Impacts to Physical Processes

1. Direct Impacts
   a. Temporary Construction Impacts
   b. Permanent Impacts
      - Placement of Structures/Loss of Beach Area
      - Impoundment (Loss) of Sediment Source Behind Structures
2. Indirect Permanent Impacts
   a. Downdrift Impacts from Sediment Impoundment
   b. Modifications of Groundwater Regime
   c. Hydraulic Impacts from Armoring
      - Increased Energy Seaward of Armoring
      - Reflected Wave Energy From Other Structures
      - Dry Beach Narrowing/End Wall Effects
      - Substrate Winnowing/Coarsening
      - Beach Profile Lowering/Steepening
      - Potential "During Storm" Impacts
      - Sediment Storage Capacity Changes
      - Loss of Organic Debris (inc. LOD)
      - Downdrift Impacts of the Above
3. Cumulative Impacts
   a. Incremental Increases in All Impacts
   b. Impacts to Single Drift Sectors
      - Downdrift Sediment Starvation
   c. Potential Threshold Effects

Note: Adapted from Table 3-1, *Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound Washington (Coastal Erosion Management Studies, Volume 5)*

In this study, several specific impacts were evaluated, including sediment impoundment, beach lowering and narrowing, substrate coarsening, groundwater changes, and the loss of large organic debris.

Sediment Impoundment

Impoundment of sediments by shore protection structures may be the least controversial and possibly most significant physical impact of shoreline armoring. Impoundment occurs when sediment that normally would have been supplied to the littoral system is blocked or impeded by a structure. This may happen in either of two ways: first, a structure designed to prevent erosion prevents upland sediment from reaching the beach; and second, a structure that projects any distance onto the beach may act as a groin, blocking longshore sediment movement.

Three factors determine the impacts of sediment impoundment on a shoreline. The most important is the local rate of shoreline retreat. A rapidly eroding shoreline provides substantial volumes of sediment to the beach, and therefore any successful effort to prevent erosion will have a larger effect than stabilization of a less-rapidly eroding shoreline. [This impact is modified, however, by the proportion of coarse sediment in the eroding bluff, since fine material is rapidly moved offshore and does not provide substantial beach material].

Also, on eroding shorelines, waves are continually cutting into the upper beach, the dune system, or the shore bluff, and a structure clearly removes this material from the system. On a stable or accreting shoreline, wave action may only affect this material during extreme storm or erosional events, and the impact of impoundment might be less. On the other hand, the need for an erosion control structure in this situation might be less in the first place.

A second factor affecting the significance of impoundment is the waterward position of an erosion control structure. The further a structure projects onto the beach, the greater the volume of beach material immobilized behind the structure and unavailable to the littoral system. The greater projection also increases the groin effect, trapping sediment on the updrift side and resulting in a sediment deficit downdrift.

It should be noted, however, that although a structure may initially be built far back on the beach, ongoing erosion of adjacent shorelines and continued downcutting of the beach will result in the structure effectively moving into deeper water and projecting further onto the beach. Therefore, the structure's impact on littoral transport may increase with time, particularly on rapidly eroding shorelines.

Finally, the significance of sediment impoundment at any given site depends on the volume of sediment impounded, relative to the local sediment supply. A minor impoundment of sediment on a broad beach with a voluminous updrift sediment supply should result in less impact than a large impoundment on a sediment-poor beach. One implication of this is that as the littoral system is progressively starved of sediment by armoring, the impacts of subsequent structures becomes relatively greater.

Beach Narrowing and Lowering
Another potential physical impact of shoreline armoring is the narrowing and lowering of beaches, either in front of structures or on adjacent shorelines. This may result from changed hydraulic action due to waves interacting with the structure itself or from changes in the volume of sediment on the beach resulting from local or updrift impoundment of littoral material. In general, beach narrowing refers to the loss of high tide beach width.

Beach lowering and narrowing are intimately related because both occur together as a beach profile shifts landward, assuming no fundamental changes in the slope of the profile. Under natural (no structures) conditions, the width and profile of the beach remain similar, despite this landward translation, but if a retreating shoreline is fixed in one location by a seawall, then the beach will narrow and drop over time.

In general, the hydraulic impacts associated with shoreline structures may be expected to increase as the structure is located farther waterward, simply because wave-wall interactions occur more frequently and because water depths are greater during this interaction (greater water depths lead to larger waves and greatly increased wave energy). In addition, the further a structure projects, the greater the possibility of waves reflecting or diffracting off of the ends of the structure and causing erosion of adjacent shorelines.

One conclusion of this is that structures located high on the beach may have minimal impact on the beach, however, although hydraulic impacts may in general be less for such structures, severe impacts may still occur during extreme storm and tide events. In addition, if the structure is located on an eroding shoreline, it will still impound sediment, regardless of its waterward projection.

Coarsening of the Beach Substrate
The particle size of beach sediment depends on the wave environment and on the source of the sediment. The wave regime determines the maximum size of material that can be moved and controls the distribution of particle sizes across the beach. The source of beach sediment determines the range of material available in the first place. In Puget Sound, there are systematic variations in sediment size that can be related to the lithology of the local bluffs and the location of the site within a littoral drift sector. Typically, the origins of drift sectors are characterized by coarse-grained gravel and cobble beaches, whereas the distal portions of drift sectors often consist of finer gravel and sand.

When waves interact with shoreline structures, the wave regime in front of the structure is modified, and changes in sediment size might be expected. Structures reflect wave energy back onto the beach that otherwise would have been dissipated during runup and by the movement of beach sediment. The increase in wave energy in front of a bulkhead or seawall may change the natural distribution of sediment sizes.

Coarsening of beaches may also result from sediment impoundment. Wave action and littoral drift will continue to winnow the finer sediment from a beach and without the input of new sediment from bank erosion or from updrift sources, the beach will become coarser. Sediment starved beaches often consist of a coarse lag of gravel or cobble.

Groundwater Impacts

Considerable volumes of groundwater emerge from coastal formations at the shoreline. A shoreline bulkhead or seawall may raise the water table behind the wall which in turn will result in higher pore pressures in the beach sediment. Higher pore pressures are known to lead to increased beach erosion, particularly of sand-sized material. This increase in beach erosion may occur on either a bluffed shoreline or on a depositional beach.

Changes in the hydrology of the toe of the bluff and of the beach itself are in themselves physical changes that can have direct ecological consequences. They can affect quantity of freshwater reaching the beach and the nature of the fresh water to salt water transition.

Loss of Large Organic Debris

Puget Sound shorelines are often marked by the abundance of large organic debris in the form of drift logs and eroded upland vegetation (fallen trees). One source of this material is natural shoreline erosion, although much of the material is cut logs that may have escaped from log rafts earlier in the century. This material is viewed as important habitat but also serves to provide substantial protection to beaches during storms.

The accumulation of L.O.D. on beaches depends to a large extent on the presence of a sufficiently shallow profile or wide berm to allow material to become beached. If the beach is steepened or narrowed by shoreline armoring (either directly or indirectly) the LOD will not become beached.

Armoring has several potential impacts on the presence of this material. Armoring, by reducing natural erosion, may reduce the supply of LOD from natural erosion of vegetated shorelines. In addition, the loss of high tide beach and the increase in wave energy waterward of structures makes accumulation of this material less likely.

Physical Impacts by Method and Location

There is an extensive literature on the design and construction of erosion control structures, but very little work has been done on the types of impacts associated with different types of structures or of different methods of shore protection.

Impacts associated with changes in hydraulic action would be expected to vary depending on the reflectivity of the structure. Research generally indicates that sloping structures or structures that due to their shape or roughness decrease wave reflectivity will have fewer impacts on the shorelines. Based on this relationship, the study suggests that in general, impacts (due to hydraulic changes)will be higher for vertical seawalls than for rock walls, which in turn will be higher than for riprap revetments. Gradually sloping beach fills or artificial beaches would have the least impact.

Sediment impoundment, on the other hand, is related to the effectiveness of the structure in preventing erosion of the upland or to the structure's tendency to block longshore sediment movement. In this regard, any erosion control method that successfully prevents erosion may lead to downdrift impacts, so the specific shape or construction of the structure may make little difference [the tendency of the structure to block littoral drift, however, will depend on its construction, since different methods may result in different degrees of projection onto the beach].

The location of a structure within a drift sector is also relevant to its impact on the shorelines. Based on a general understanding of Puget Sound shoreline processes the study suggests that the impacts of structures due to impoundment will generally be higher for armoring located near the origin of a drift sector, largely because these more rapidly eroding areas supply a much greater proportion of sediment to the littoral system.

Hydraulic impacts may depend much more on the type of structure than on its location. Impacts from structures located downdrift may be reduced as long as there is an ample supply of sediment from updrift locations. Groundwater impacts, on the other hand, may be related to structures anywhere within the drift sector.

Of course, there are few general rules that can be applied, and each site will ultimately need to be addressed on an individual basis.

5.2.2 Case Studies

A thorough review of Puget Sound projects was carried out to identify sites within the Sound where data on impacts and shoreline changes could be documented. Sites were selected based in part on interviews with shoreline experts in the region.

Few beaches on Puget Sound have been monitored systematically to evaluate beach changes that might be associated with shoreline armoring. Those that have are generally larger projects where significant shoreline modification has occurred, and therefore results may not be readily extensible to other more typical Puget Sound areas. Sites where abundant, useful data exist include Ediz Hook near Port Angeles, Sunnyside Beach in Steilacoom, and Lincoln Park in Seattle (see map, Figure 5.1). A number of other sites were also examined.

Ediz Hook
Ediz Hook is a large spit located across the entrance of Port Angeles Harbor. As a result of dams built on the Elwha River and the armoring of coastal bluffs located updrift, almost 88% of the supply of sediment to the spit was eliminated. As a result of this sediment impoundment, and despite many efforts to stabilize the shoreline with riprap, the spit continued to erode. The spit underwent progressively more severe erosion until a comprehensive solution was implemented in 1978 that included replenishment of the beaches with coarse gravel and cobble.

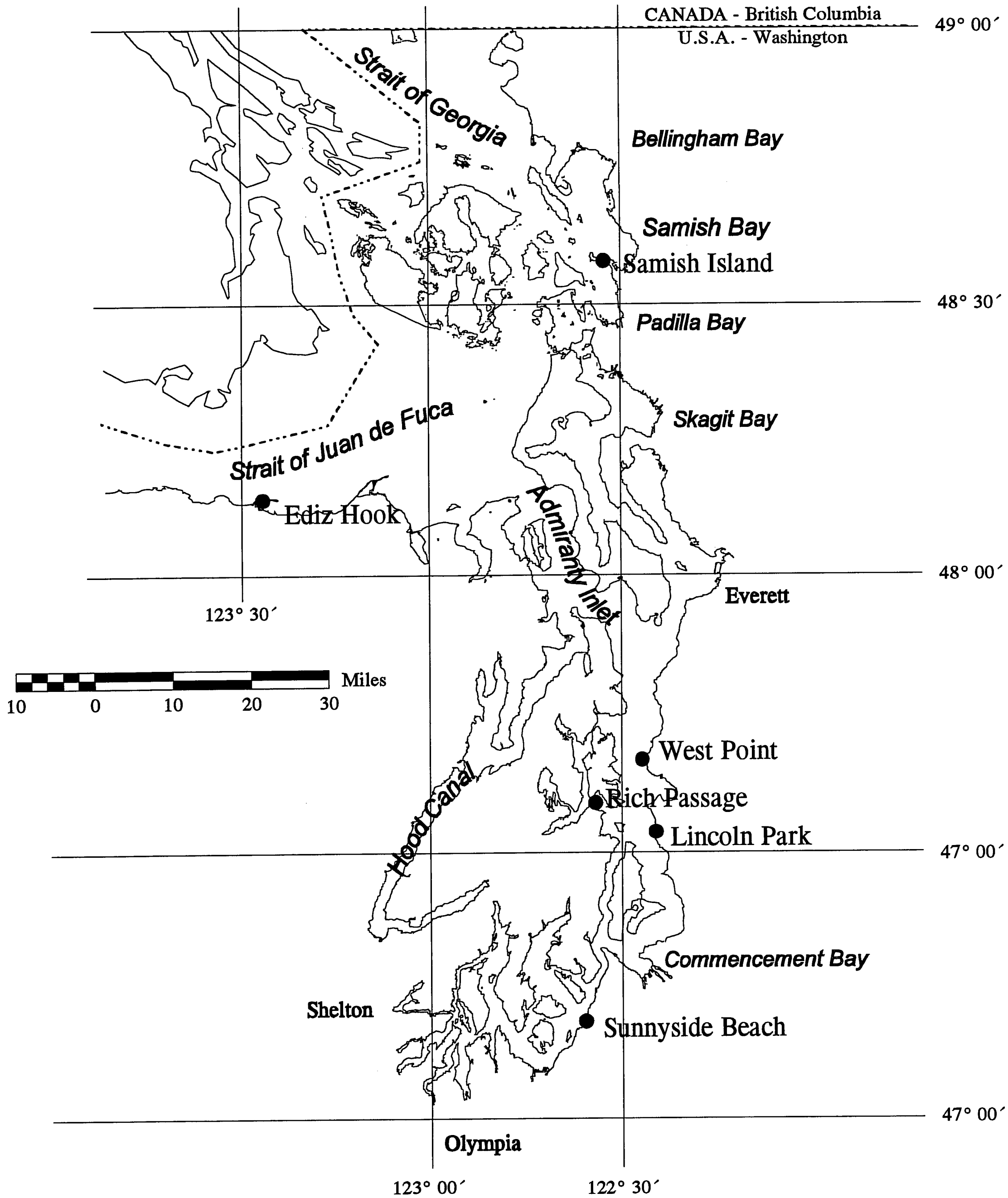


Figure 5.1. Case Study Sites in Puget Sound

Few formal studies on the effects of shoreline armoring have been carried out in Puget Sound. The sites identified on this map (●) are discussed in Chapter 5 at Section 5.2.2 (Case Studies) and in Chapter 7 at Section 7.3.3 (Observations).

Ediz Hook provides the best documented example in Washington of the impact of updrift sediment impoundment on littoral sediment movement and downdrift erosion. The anticipated removal of the dams has led to speculation about the beneficial impact on the spit, but the majority of the sediment deficit is due to the bluff armoring, not the loss of river gravels.

Sunnyside Beach

Sunnyside Beach Park is located immediately north of the town of Steilacoom. The park is constructed on artificial fill associated with an abandoned sand and gravel operation. The site juts out from the original shoreline and is exposed to substantial wave action. In 1967, a timber pile bulkhead was constructed to chronic erosion, but the beach continued to erode. In 1975, and again in 1978, sand was placed to renourish the beach. As of 1994 a major shoreline restoration project is underway, with the primary elements being the removal of the failed bulkhead and renourishing of the beach with gravel. The site illustrates the ineffectiveness of a structural solution when beach sediment is continuing to undergo erosion.

Erosion at this site appears to be the result of significant wave action, combined with sediment starvation. Progressive erosion had led to significant lowering and narrowing of the beach in front of the bulkhead and coarsening of the beach material was observed in front of the bulkhead but not on adjacent unarmored shorelines. Large organic debris collected on the unarmored shorelines, but not on the bulkheaded portion.

Lincoln Park

Lincoln Park is located at Williams Point, south of Seattle. The southwest shore of the park consists of a low promenade protected by a seawall built in the 1930s. This seawall was progressively undermined following construction, ultimately causing failures of portions of the wall and exposure of the underlying erosion platform. In 1988, following numerous efforts to repair the seawall, beach nourishment was begun and more natural beach has been restored.

Lincoln Park is a case where progressive beach lowering and narrowing is well documented in front of a seawall. Beach erosion was accompanied by significant coarsening of the substrate and the loss of beached large organic debris. This loss of the beach is at least in part related to the loss of updrift sediment supplies. The degree to which the seawall itself may have aggravated the loss of the beach is unclear.

West Point

West Point is a cuspate spit located in Discovery Park, west of downtown Seattle, and is the site of Seattle's major sewage treatment facility. The southern side of the point is fed by littoral drift derived from erosion along bluffs to the southeast. In 1962, a sludge lagoon was built across the beach, effectively blocking longshore drift. The shoreline accreted updrift of the lagoon and eroded downdrift. In 1980, this structure was removed, and a gravel beach was built to restore the original shoreline.

There is good documentation of the West Point site, both before and after the removal of the sludge lagoon. The data provides limited insight into the character of shoreline changes following a perturbation to littoral drift, but may be difficult to apply to shoreline armoring situations in general. An interesting footnote to West Point is that a severely modified shoreline can be restored to functioning beach, if updrift sediment supplies remain intact.

Other sites

A recent study of bulkhead installations on the west side of Whidbey Island is being carried out by scientists at Western Washington University, specifically to address the impact of bulkheading on beaches. To date, the authors have found that beaches do indeed respond to seawall construction, but that the impacts depend on the availability of sediment and the location of the structure. At least over the short term, they confirm that structures built high on the beach have minimal impact on the beach. They also observed changes in adjacent shorelines attributed to the observed bulkheads. The sites are located on heavily developed depositional beaches and it is not clear whether this work can be directly applied to bluffed shorelines. (Terich & Schwartz, 1993.)

The Corps of Engineers undertook a study of shoreline protection methods at Forbes Point near Oak Harbor in 1979. The study was designed as a demonstration project to investigate the effectiveness of construction methods and designs, but did not assess beach or environmental changes resulting from the armoring. A study of ferry wakes on Rich Passage near Bremerton indicated numerous problems with bulkhead construction and design, but provided little information directly relevant to assessing the impact of shoreline structures on the beach.

Summary of Case Studies

Chronic lowering and narrowing of beaches in front of seawalls has been documented at both Lincoln Park in Seattle and at Sunnyside Beach in Steilacoom. In addition, coarsening of the beach in front of bulkheads was noted at each location, as was the loss of large organic debris. At these sites, as well as at Ediz Hook, beach erosion is clearly related to sediment starvation, and at the latter site in particular, to the armoring of eroding bluffs. Significantly, in each of these cases, hard structures proved ineffective at preventing continued shoreline retreat, and beach nourishment has been ultimately chosen to solve the erosion problem.

These and other sites document beach changes related to hard structures, but in each case, the specific characteristics of the sites make it difficult to generalize the results to all Puget Sound shorelines. There is clearly need for additional studies in this area.

5.2.3 Cumulative Physical Impacts

Cumulative impacts are those that result from the combined effect of numerous similar small actions. The impacts of the individual actions might be relatively small, but when the cumulative impact of many such small actions is considered, the consequences may be significant. An important concept in cumulative impacts is the threshold at which the combined impact becomes significant. Shoreline armoring appears to fit this description of an activity that would result in significant cumulative impacts.

An accurate assessment of cumulative impacts requires data on the status of the individual actions - the amount of shoreline armoring on Puget Sound, for example - and data on the environment from which to assess adverse changes. As discussed elsewhere, there is very little data on which to base these assessments.

A number of studies of shoreline modifications in other regions address cumulative impacts, but in general, are difficult to apply to Puget Sound due to differences in conditions. One well-supported conclusion is that shoreline protection measures tend to accelerate both in numbers and in engineering sophistication, particularly in a regional context.

5.2.4 Physical Impacts Summary

This study identifies a number of specific impacts associated with shoreline armoring, including:

- Sediment impoundment. As a result of shoreline armoring, the sources of sediment on Puget Sound beaches (eroding bluffs) are progressively lost and longshore transport is diminished. This may lead to lowering of downdrift beaches, the narrowing of the high tide beach, and the coarsening of beach sediment. Sediment starvation may lead to accelerated erosion in downdrift areas.

- Hydraulic impacts. Shoreline armoring generally increases the reflectivity of the shoreline and redirects wave energy back onto the beach. This may lead to scouring and lowering of the beach, to erosion at the ends of the structure, and to coarsening of the beach.

- Groundwater impacts. Erosion control structures often raise the water table on the landward side, which leads to higher pore pressures in the beach itself. In some cases, this may lead to accelerated erosion of sand-size material from the beach.

- Impacts on large organic debris. Changed hydraulic regimes and the loss of the high tide beach, along with the prevention of natural erosion of vegetated shorelines, leads to the loss of beached organic material. This material can serve as a stabilizing influence on natural shorelines.

Some of the impacts of bulkheading can be reduced by selecting the design or the location of the structure. Hydraulic impacts may be reduced by keeping the structure as high on the beach as possible, by sloping the structure, and by constructing the structure of rough materials. Impoundment impacts are more difficult to mitigate, except by using beach nourishment, but may be reduced by locating the structure as far landward as possible. Impacts on groundwater may be reduced by designing adequate drainage into the structures.

The impact of bulkheads is expected to be highest near the origins of drift sectors since the amount of sediment impounded is generally higher and because there is less sediment in the littoral system available to compensate for beach losses, whether due to impoundment or due to hydraulic action.

Shoreline armoring is an excellent example of an activity with significant cumulative impacts. A single structure may have little measurable impact on a shoreline, in part because its effects may be obscured by natural variability in shoreline processes, or because they are compensated for by small increases in erosion of other beaches. There may be a threshold, however, above which the adverse impacts occur rapidly and irreversibly.

Interest in the relationship between seawalls and beaches is relatively new, and a majority of the work done to date has focused on open ocean shorelines and sandy beaches that differ greatly from the gravel-dominated estuarine beaches of Puget Sound. Very little work has been done on Puget Sound shorelines and where data has been collected they are of limited value in evaluating the cumulative impact of shoreline armoring - particularly in the context of residential shoreline protection on bluffed shorelines.

On the other hand, the study confirms that beaches do change in response to armoring in many situations. In particular, impoundment of sediment by armoring can and often does lead to downdrift sediment starvation, changes to the profile and composition of the beach, and accelerated erosion. The case studies suggest that hard structures do little to prevent continuing erosion of the beach itself. As a result, the upper portions of the beach are gradually squeezed out and structures must be repeatedly repaired and enlarged.

5.3 Impacts to Biological Resources and Ecological Systems

The assessment of the ecological effects of shoreline armoring followed on from, and built upon, the assessment of the effects of shoreline armoring on coastal physical processes. Many of the effects of shoreline armoring on ecological processes and biological resources are independent of physical impacts, but many others are the result of habitat changes brought about by physical impacts which change the character of the beach. This summary of Impacts to Biological Resources and Ecological Systems consists largely of extensive direct quotations from Volume 7, *Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington* (Thom, Shreffler & Macdonald, 1994).

5.3.1 General Ecology of Puget Sound

Puget Sound proper is a fjordal estuary, which displays most of the coastal features found worldwide in temperate latitudes. Major and minor rivers form deltas at their junction with Puget Sound. Formed relatively recently by glaciation, most of the sediments along the shorelines consists of glacial drift. Because of its narrow profile and deep central basin (i.e., 600 ft), the shoreline is relatively steeply sloping in many areas. Beaches are nourished primarily by erosion of shoreline bluffs and secondarily by sediment from rivers and streams.

Puget Sound shoreline consists of an intertidal zone and a shallow subtidal zone (between -1m and -15m [-3ft and 49ft] mean lower low water [MLLW]). Together, the intertidal and shallow subtidal zones can be referred to as the *nearshore zone* of Puget Sound. High bluffs fronted by coarse sand and gravel beaches are the most common shoreline landforms around Puget Sound. Fine sand and mud occurs primarily at the mouths of larger rivers entering Puget Sound and in quiet bays. Shoreline boulder fields and rock benches are both relatively rare.

The habitats of Puget Sound have been characterized by Dethier (1990) in a comprehensive report for the Washington Department of Natural Resources titled *A Marine and Estuarine Habitat Classification System for Washington*. The Puget Sound intertidal and shallow subtidal habitat types are summarized in Table 5.2. The prevalent Puget Sound shoreline sediment type is coarse sand and gravel (Downing, 1983). This substrate equates with Dethier's (1990) habitat types of *mixed coarse-open* and *gravel-open habitats*.

Energy, in the form of organic matter, is produced in the habitats and may either be utilized there or transported to other habitats or communities within habitats. The communities within a habitat type are, therefore, connected by the transport of energy and resources. As tides and currents move water among the habitats, dissolved and particulate organic matter and nutrients also flow among the sites. In addition, fish and motile shellfish move among the communities as water covers these communities. Birds will often feed in one habitat (e.g., eelgrass) and rest in another habitat (riparian), which expands the range of energy flow among habitat types. Energy remaining within a community is recycled (remineralized) into inorganic substances including nitrates and phosphates. The four major ecological processes involving the food web are, then, *production* and *consumption* (plant and animal metabolism), *transport* and *cycling*. The primary productivity associated with representative habitats is depicted in Figure 5.2.

The beaches of Puget Sound are highly important areas for shorebirds, waterfowl, shellfish and finfish. Armstrong et al. (1976) found a range of 178 to 203 species of invertebrates in the intertidal zone on five beaches in central Puget Sound. Thom et al. (1976) listed a total of 157 species of algae at these same beaches. An extremely rich seaweed flora containing in excess of 600 species is found within the waters of Washington and British Columbia (Mumford, 1990). Community Profiles prepared for eelgrass (Phillips, 1984), saltmarshes (Selisker and Gallagher, 1983), tidal channels (Simenstad, 1983), and coastal sand dunes (Wiedemann, 1984) in the Pacific Northwest illustrate the vast array of species that use these habitats for part or all of their lives.

Table 5.2 Puget Sound Intertidal and Shallow Subtidal Estuarine Systems: Habitats, and Diagnostic and Common Taxa

HABITATS	PLANT TAXA EXAMPLES	ANIMAL TAXA EXAMPLES	SITE EXAMPLE	FINFISH SPAWNING HABITAT	JUV. FINFISH FORAGING HABITAT	JUV. FINFISH REARING HABITAT	JUV. SALMON MIGRATION HABITAT	HARDSHELL CLAM HABITAT	CRAB, URCHIN, ETC. HABITAT
INTERTIDAL									
BEDROCK, OPEN	*Fucus gardneri*	*Balanus glandula*	West Point	X	X		X		X
HARDPAN, OPEN	none listed	*Balanus glandula* *Zirfaea pilsbryi*	Alki Point		X		X		X
MIXED-COARSE OPEN	*Ulva*	*Macoma inquinata* *Protothaca staminea*	Salt Water State Park	X	X	X	X	X	X
GRAVEL, OPEN	none listed	*Exosphaeroma inornata* *Anisogrammarus*	Guemes Island		X		X		
GRAVEL, PARTLY ENCLOSED EULITTORAL	*Glaux maritima* *Salicornia virginica*	none listed	Quilcene Bay		X				
SAND, OPEN	*Zostera marina*	*Macoma secia*	Dash Point	X	X	X	X	X	X
SAND, PARTLY ENCLOSED EULITTORAL EUHALINE	*Salicornia virginica* *Jaumea carnosa*	none listed	Dungeness Spit		X		X	X	
SAND, PARTLY ENCLOSED EULITTORAL POLYHALINE	*Distichlis spicata* *Salicornia virginica*	none listed	Thorndyke Bay		X		X		
SAND, PARTLY ENCLOSED EULITTORAL MESOHALINE	*Scirpus americanus* *Carex lyngbyei*	none listed	Skagit Bay		X		X		
SAND OR MIXED-FINE LAGOON HYPERHALINE EUHALINE	*Salicornia virginica* *Jaumea carnosa*	*Macoma nasuta* *Transennella tantilla*	Foulweather Salt Marsh		X	X			
MIXED FINES PARTLY ENCLOSED	*Carex lyngbeyi* *Distichlis spicata* *Salicornia virginica* *Triglochin maritimum* *Zostera marina*	*Protothaca staminea* *Saxidomus gigantea* *Callinasa californica*	Dosewallips River Delta Skagit Flats	X	X	X	X	X	X
MIXED FINES & MUD, PARTLY ENCLOSED EULITTORAL MESOHALINE	*Scirpus maritimus* *Triglochin maritimum* *Carex lyngbyei*	none listed	Nooksack River Delta		X		X		
MIXED FINE LAGOON MESOHALINE OLIGOHALINE	*Scirpus maritimus* *Scirpus acutus* *Typha latifolia*	none listed	Foulweather Bluff Preserve		X		X		

Table 5.2 (continued) Puget Sound Intertidal and Shallow Subtidal Estuarine Systems: Habitats, and Diagnostic and Common Taxa

HABITATS	PLANT TAXA EXAMPLES	ANIMAL TAXA EXAMPLES	SITE EXAMPLE	FINFISH SPAWNING HABITAT	JUV. FINFISH FORAGING HABITAT	JUV. FINFISH REARING HABITAT	JUV. SALMON MIGRATION HABITAT	HARDSHELL CLAM HABITAT	CRAB, URCHIN, ETC. HABITAT
INTERTIDAL									
MUD	*Zostera* spp.	*Macoma nasuta* *Macoma balthica*	Dockton, Vashon Island	X	X	X	X		X
ORGANIC PARTLY ENCLOSED BACKSHORE POLYHALINE	*Deschampsia* *Distichlis spicata* *Salicornia virginica* *Potentilla pacifica* *Grindella integrifolia* *Juncus gerardii*	none listed	Nisqually River Delta		X		X		
ORGANIC, PARTLY ENCLOSED BACKSHORE MESOHALINE	*Deschampsia* *Juncus balticus* *Potentilla pacifica* *Carex lyngbeyi* *Festuca rubra* *Agrostis alba*	none listed	Nisqually River Delta		X		X		
ORGANIC, SAND MIXED FINE, MUD PARTLY ENCLOSED BACKSHORE OLIGOHALINE	*Juncus balticus* *Potentilla pacifica* *Calamagrostis nutkaensis* *Picea sichensis* *Typha latifolia*	none listed	Hamma Hamma River Delta		X		X		
MIXED FINES, MUD CHANNEL & SLOUGH	*Zostera marina*	chironomid larvae *Corophium salmonis* juvenile salmonids	Skagit Flats	X	X	X	X		
SHALLOW SUBTIDAL (LESS THAN 15m DEPTH)									
ROCK, OPEN	*Nereocystis* *Agarum*	*Metridium*	Restoration Point	X	X	X	X		X
COBBLE, OPEN	*Laminaria*	*Saxidomus giganteus*	Fox Island	X	X	X	X	X	X
SAND, OPEN	*Zostera marina*	*Dendraster excentricus*	Windy Point	X	X	X	X		X
MIXED FINES OPEN	*Zostera marina* *Laminaria*	*Clinocardium* *Psephida lordi*	Lummi Island	X	X	X	X		X
MUD, OPEN	*Zostera marina*	*Psephida lordi* *Macoma nasuta*	Samish Bay	X	X	X	X		
MUD, PARTLY ENCLOSED	none listed	*Macoma nasuta* *Mysella tumida* *Armania brevia*	Commencement Bay		X	X	X		X
SAND AND MUD CHANNELS	none listed	*Magelona* *Corophium salmonia* *Macoma balthica*	none listed			X	X	X	

Source: Dethier, 1990.

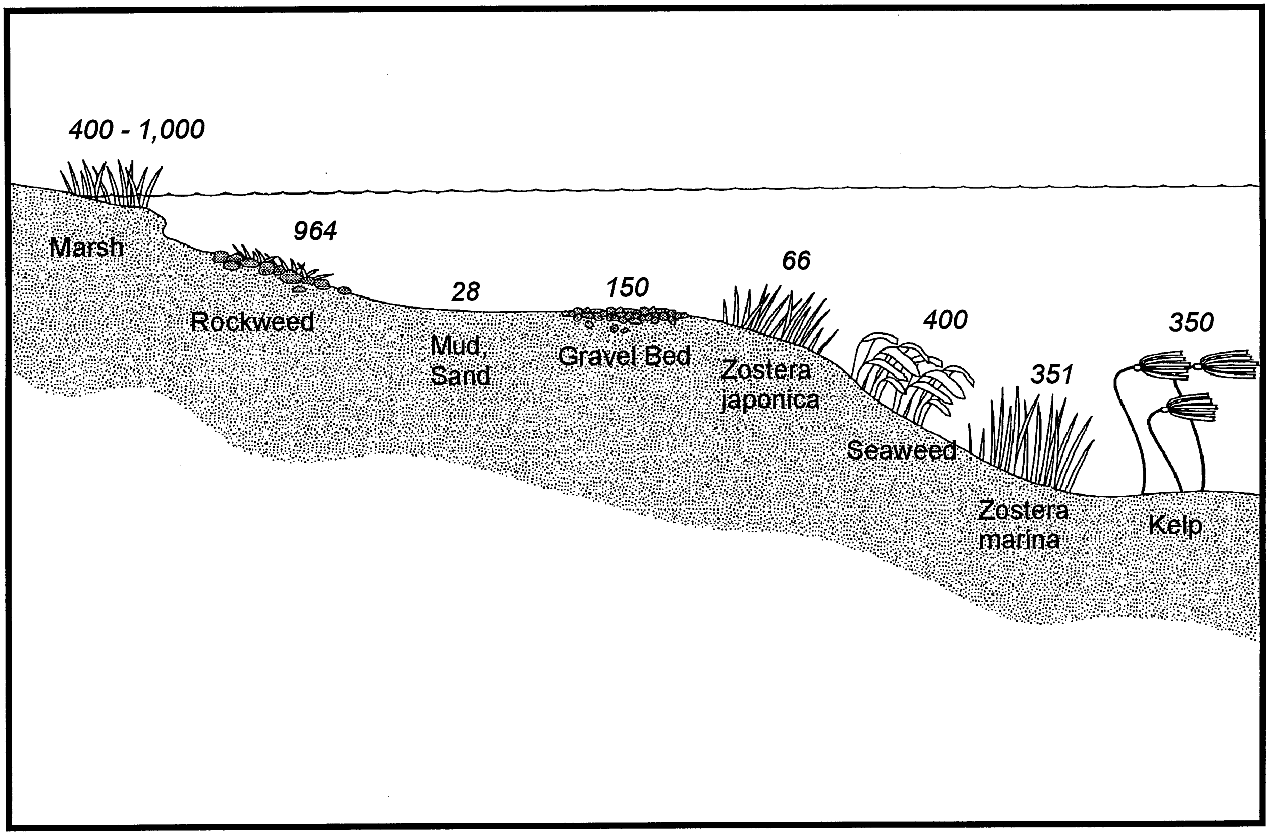


Figure 5.2 Net Annual Primary Productivity by Habitat in Puget Sound, Washington.

All measurements as grams of carbon/m²/year. Sources: Thom, 1983, 1987, 1989, 1990; Thom and Albright 1990.

"Primary productivity" is the measure of productivity, or growth, of plants (the primary producers). It is measured as the amount (usually grams) of carbon produced per some unit of area (here in square meters) per year. Primary productivity is the 'yardstick' by which the annual growth of different habitats is compared.

In 1991, the agencies that manage aquatic and terrestrial resources met to summarize ecological data on the species they manage (Armstrong and Copping, 1990). The purpose of the meeting was to examine temporal trends in population sizes, catch statistics, and other factors. An important finding was that virtually all of the resources that are managed or of concern spend part or all of their life history on, in, or otherwise associated with beaches. These animals use beaches as a place to feed, rear, reproduce, and rest.

The shoreline habitats of Puget Sound have suffered significant losses over the past 125 years. Bortelson et al. (1980) estimated that approximately 32 percent of intertidal wetland and 73 percent of subaerial wetland bordering Puget Sound has been lost. Much of this loss is due to diking and filling of these areas. By the late 1800s, many of the tidal marshes in the Skagit River delta had been enclosed by dikes. Most losses in Puget Sound took place between 1910 and 1950, during a period of rapid port development (Thom and Hallum, 1990). Kelp beds appear to have increased between surveys early in this century and surveys done in the mid-1970s (Thom and Hallum, 1990). A partial explanation for this increase may be the increase in hard substrata in the shallow subtidal zone which is required by kelp for attachment.

5.3.2 Armoring Effects on Habitat Structure

Using Dethier's (1990) scheme (Table 5.2), marsh erosion in partly enclosed conditions would predictably proceed from an assemblage dominated by marsh plants, to sand dominated by infauna bivalves, worms, and amphipods, to one dominated by assemblages preferring gravel substrates. If the gravel is located at moderate to low elevations, significant numbers of bivalves could predominate in this habitat. The rate of change is unknown but is probably slower in protected situations than under more open conditions.

Open sand would erode to mixed-coarse sand, gravel, hardpan, and finally, bedrock. This would mean a shift from an assemblage dominated by small crustacea (harpacticoid copepods, amphipods) at higher elevations and eelgrass (*Zostera marina*) in the lower intertidal zone; through an *Ulva*-hardshell bivalve habitat; to one containing primarily crustaceans such as isopods and larger amphipods; to barnacles and rock-boring bivalves; and finally to barnacles and seaweed. Existing, open gravel habitats would essentially erode to hardpan and then bedrock. The rate of change from beach sand to hardpan, based upon studies at Lincoln Park, Seattle, would be on the order of 20 years. Periodic storm events would speed the rate of habitat alteration along some portions of the beach.

Hard substrata such as a vertical concrete seawalls, riprap breakwaters, and gabion walls, can be colonized by a hard bottom assemblage. This assemblage, in the higher intertidal zone, consists of barnacles, mussels, and macroalgae such as rockweed (*Fucus* spp.) and sea lettuce (*Ulva* spp.). Under stable conditions, rockweed can become quite dense on riprap breakwaters and shoreline protection structures, as has been shown for West Point (Thom, 1983) and the Fraser River estuary (Pomeroy and Levings, 1980).

5.3.3 Armoring Effects on Ecological Processes

Studies cited in Volume 7 (Thom, Shreffler & Macdonald, 1994) show that altered beach substrata—as might be expected to occur with shoreline armoring—will change the types of plants in the area, but may not alter the productivity rates per unit area. Respiration rates, which are indicative of animal density, may increase under some conditions.

Shoreline armoring has been shown to increase erosion rates on beaches. This can convert the beach from a system that shows *net accumulation* of organic matter to one that shows *net loss* of organic matter on an annual or seasonal basis. Organic matter accumulates from adjacent, updrift beaches and from uplands bordering the beach. Organic matter produced on a beach can either be deposited and cycled there or be exported to adjacent areas. Alterations in the dynamics of organic matter production and deposition can dramatically change the beach communities.

In general, it is difficult to document clear linkages between shoreline armoring and ecological processes.

5.3.4 Armoring Effects on Biological Resources

Washington State Department of Fish and Wildlife (WDFW) commentary on the CEMS program design (Neil Rickard, pers. comm., December 1993) identified concerns regarding shoreline armoring effects on fisheries resources. Fish and Wildlife's concerns centered around use of habitats by juvenile finfish, hardshell clams, and other invertebrates of commercial or recreational importance. The habitats that these resources use could be directly affected (i.e., destroyed) or indirectly affected (e.g., alterations of substrata adjacent to a seawall). Concerns centered around the critical importance of beaches for finfish spawning, foraging and rearing, and as habitat for adult and juvenile invertebrates (WDF, 1992; Pryne, 1994). WDFW also noted that miles of historic habitat have been permanently lost due to the placement of structures and fill, with commensurate permanent loss of riparian vegetation and large organic debris, as well as extensive intertidal habitat degradation from increased wave and current turbulence waterward of such structures (Neil Rickard, WDFW, pers. comm.).

The species included in Fish and Wildlife's list are provided in Table 5.3. In order to simplify the analysis of impacts to biological resources, the study focused on these species as *indicators* of effects from shoreline armoring. There is a body of information on most of these species that allows predictions of potential effects to be made with some certainty. However, there are only a few studies that have verified and *quantified* the effects of shoreline armoring on these resources. Hence, predictions of effects remain both qualitative and subjective. In general, the direct effects of shoreline armoring on fish communities in Puget Sound have not been well documented. The linkages between armoring effects and biological process are summarized in Table 5.4.

Table 5.3 Fisheries Resource Species Potentially Affected by Shoreline Armoring

Fin Fish	
Chinook Salmon	*Oncorhynchus tshawytscha*
Chum Salmon	*Oncorhynchus keta*
Coho Salmon	*Oncorhynchus kisutch*
Pink Salmon	*Oncorhynchus gorbuscha*
Pacific Herring	*Clupea harengus*
Rock Sole	*Lepidopsetta bilineata*
Surf Smelt	*Hypomesus pretiosus pretiosus*
Pacific Sandlance	*Ammodytes hexapterus*
English Sole	*Parophrys vetulus*
Sand Sole	*Psettichthys melanostictus*
Shellfish	
Manila Clam	*Tapes philippinarum*
Littleneck Clam	*Protothaca staminea*
Butter Clam	*Saxidomus giganteus*
Gaper Clam	*Tresus capax*
Geoduck	*Panopea generosa*
Soft-Shell Clam	*Mya arenaria*
Pacific Oyster	*Crassostrea gigas*
Dungeness Crab	*Cancer magister*
Other	
Giant Red Sea Cucumber	*Parastichopus californicus*
Sea Urchin	*Strongylocentrotus* spp.

Table 5.4 Shoreline Armoring Effects Linkages to Biological Processes

1. Direct Effects
   a. Temporary Construction Effects
   b. Permanent Effects
      - Habitat (Substrate) Burial or Removal
      - Change Vegetative Cover/Organic Inputs

2. Indirect Permanent Effects
   a. Modification of Groundwater Regime
   b. Changes to Shoreline Environment Due to Hydraulic Effects
      - Loss Spawning/Foraging/Rearing Habitat for Fish
      - Loss Migratory Corridor for Fish
      - Substrate Changes Reflected in Benthos
      - Effects on Shellfish

3. Cumulative Effects
   a. Incremental Increases in All Effects
   b. Potential Threshold Effects

Source: Macdonald et al. (1993).

Direct Effects to Finfish

Direct effects to finfish can be organized into the following categories: loss of spawning habitat; loss of shoreline vegetative cover; loss of wetland vegetation; loss of large organic debris; changes in food resources; and loss of migratory habitat.

Loss of Spawning Habitat Surf smelt (*Hypomesus pretiosus pretiosus*) are widespread in Puget Sound (Garrison and Miller, 1982). Major spawning areas are found in protected inland waters of southern Puget Sound, southern Hood Canal, northern Saratoga Passage, and the Liberty Bay area, as well as the semiprotected shores of the Strait of Juan de Fuca and on exposed beaches along the northwest shore of the Olympic Peninsula (Pentilla, 1978).Because surf smelt spawn high in the intertidal (from +7 feet MLLW up to EHHW), they are particularly susceptible to permanent habitat loss resulting from shoreline armoring.

In Puget Sound, Pacific sand lance (*Ammodytes hexapterus*) are common and widely distributed (Garrison and Miller, 1982). Sand lance populations form localized schools that are usually associated with clean sand bottoms. Sand lance spawn at elevations from +5 feet MLLW to MHHW on substrates varying from sand to sandy gravel. Like surf smelt, sand lance are susceptible to deleterious effects of shoreline armoring because of their preference for spawning high in the intertidal.

Rock sole (*Lepidopsetta bilineata*) are widely distributed in Puget Sound and adults are typically found at depths between 10 and 40 m on a rocky or firm bottom (Garrison and Miller, 1982). Spawning is thought to take place on sand or soft substrates. In some areas of Puget Sound, rock sole deposit their eggs on the same beaches as sand lance and surf smelt, but there is some indication that rock sole are not obligate intertidal spawners like surf smelt and sand lance (Pentilla, WDFW, pers. comm., December 1993).

According to Pentilla, Fish and Wildlife has observed four primary effects of shoreline armoring on surf smelt, sand lance, and rock sole: (1) reduced sediment input from feeder bluffs, (2) permanent loss of habitat +5 feet MLLW and above, (3) loss of riparian vegetation that provides shade to the upper beach, and (4) changes in beach substrate from finer to coarser grained material.

Loss of Shoreline Vegetative Cover While there is a vast literature on the structural and biological importance of streamside riparian vegetation (e.g., Warner and Hendrix, 1984; Mitsch and Gosselink, 1993), much less has been written about the ecological roles of "marine shoreline riparian vegetation" along estuaries and coastal beaches. In general, riparian vegetation contributes to maintenance of both fisheries habitat and water quality and may perform many important ecological functions in estuaries and coastal beaches (Johnson and Ryba, 1992).

Loss of riparian cover is of particular importance to juvenile salmon. Shoreline vegetation provides shade, protective cover, detrital input, and terrestrial prey (e.g., insects) to young salmonids moving close inshore (Levings et al., 1991). Yet despite its obvious potential importance, the direct loss of riparian vegetation resulting from shoreline armoring around Puget Sound has not been documented.

Shoreline riparian vegetation may have particularly high value in Puget Sound because of its contributions to marine fish species that utilize the upper intertidal zone for spawning habitat (Daniel Pentilla, WDFW, pers. comm.) and to juvenile salmonids (e.g., cover, detrital input, insect prey).

Loss of Wetland Vegetation It is well documented that estuarine emergent wetlands function in support of juvenile salmonids. In addition to providing habitat for temporary residence and foraging, wetlands are important for seawater acclimation and refuge from predation (Dorcey et al., 1988; Simenstad and Salo, 1980; Simenstad et al., 1982; Macdonald et al., 1988; Shreffler et al., 1990; Shreffler et al., 1992). The direct loss of wetland vegetation as a result of shoreline armoring has the potential to have dramatic negative impacts on juvenile salmon. In particular, the loss or reduction of wetland vegetation could result in diminished populations of the preferred prey organisms of juvenile salmon, which are dependent on wetland vegetation detritus.

No rigorous tests have been conducted of the effects of shoreline armoring on wetland vegetation, nor of corresponding effects of wetland vegetation loss on juvenile salmonids. Because of the documented importance of wetland vegetation to juvenile salmon for feeding and refuge, loss or reduction of this habitat resulting from shoreline armoring is inferred to negatively affect juvenile salmon.[6]

Loss of Large Organic Debris The majority of the literature on large organic debris (typically referred to as LOD or woody debris, depending on the size of the material) pertains to stream ecosystems, and particularly to juvenile salmon in streams, whereas few studies have focused specifically on the ecological roles of LOD in estuarine or coastal habitats. Habitat complexity is a primary factor influencing the diversity of stream fish communities (e.g. Angermeier and Karr, 1984) and LOD is a primary element influencing habitat diversity and complexity in streams (e.g., Bisson et al., 1987; Reeves et al., 1993).

During the past 150 years, a continuum of landscape-modifying human activities (including shoreline armoring) has altered the sources of wood inputs to estuaries and beaches. Historical records of northwest U.S. coastal rivers in the mid-1800s documented extensive heavy drift logs (many 150 feet long and 18 feet in circumference), and large numbers of trees transported by freshets to the river mouths (Benner and Sedell, 1987). In addition, estuary banks probably contributed large fallen trees. Beach stabilization, dune formation, and cliff protection have been suggested as possible structural functions of wood in estuaries (Terich and Milne, 1977; Stembridge, 1979; and Komar, 1983; cited in Benner and Sedell, 1987), while ecological functions are poorly known.

Changes in Food Resources Natural beaches in estuaries act not only as migration corridors for juvenile salmonids, but also as transportation corridors for sediment (littoral drift), as well as inorganic and organic nutrients and detritus. Shoreline armoring disrupts this natural pattern of littoral drift and beaches can become "starved" for sediment and nutrients (Macdonald et al., 1994). One of the major biological effects that results from disrupting littoral drift is the loss or reduction of nutrients and food sources needed to sustain juvenile salmonids. Because juvenile salmonids are actively feeding during their outmigration, they need prey of appropriate species and sizes in appropriate quantities at the right time. Thus, growth rates of juvenile salmonids may be negatively impacted if their natural food supply is reduced or cutoff because of shoreline armoring, adversely affecting their survival. While researchers have begun to investigate the physical effects of shoreline armoring in terms of disruption of the littoral drift, no studies assessing the loss of salmonid food resources due to shoreline armoring were found. Simenstad et al. (1991) did show that placement of gravel on mudflats did enhance selected salmonid prey resources.

Loss of Migratory Corridors One potential physical effect of shoreline armoring is increased slope and water depth along the shoreline (Macdonald et al., 1994). The biological ramification of this physical effect is that increased water depth is hypothesized to increase the likelihood of predation on juvenile salmonids. Chum and pink salmon, because they migrate to sea immediately upon emergence and are typically small upon entry into saltwater

---

[6] While past shoreline armoring practices undoubtedly had adverse effects on wetlands habitats and vegetation, current Washington Department of Ecology policy is to not permit shoreline armoring across the face of wetlands.

(<35 mm fork length), are thought to be particularly vulnerable to predation (Cardwell and Koons, 1981). Fish and Wildlife biologists have expressed concern that avoidance of bulkheads and breakwaters forces migrating salmon into deeper water where they are more susceptible to predation by coho salmon smolts and cutthroat trout (Toal, 1993). In an experiment to test the importance of estuarine residency to chinook survival, Macdonald et al. (1988) documented that marine-released fish were exposed to more bird and fish predators than river- or estuarine-released fish.

Heiser and Finn (1970) observed that migrating juvenile pink and chum salmon (35 to 45 mm) in Hood Canal were reluctant to leave the shoreline. Fish of this size also appeared to be reluctant to venture along bulkheads and breakwaters. Observations in northern Hood Canal revealed that juveniles in the 50 to 70 mm size range would move into deeper water when confronted with large piers or bulkheads. Such behavior resulted in increased predation by various cottids, coho salmon smolts, and cutthroat trout (Heiser and Finn, 1970).

Heiser and Finn (1970) also evaluated different bulkhead and breakwater designs in terms of how they may influence juvenile salmon behavior. These designs included vertical concrete walls, sediment piles, riprap breakwaters, a concrete retaining wall with a stairstep design, wooden sheet pile, and concrete sack walls. Based on behavioral observations of chum and pink salmon fry migrating past the various breakwaters, the authors determined that vertical designs-which are the most common in Puget Sound and Hood Canal-are the least desirable. They concluded that desirable designs include rip rap or similar natural material placed on a 45 or less degree angle, and also exhibit considerable irregularity in surface configuration to provide protective habitat for young salmon. In addition, evaluation of tidal data demonstrated that bulkheads should be placed no lower than the equivalent of +9.0 feet MLLW (Seattle) level in Puget Sound or Hood Canal to minimize the risk of predation to migrating salmon fry. However, *sloped* revetments can have the disadvantage of covering a greater area of intertidal habitat.[7]

Indirect Effects to Finfish

Because of their commercial importance, Pacific herring has been extensively studied (Garrison and Miller, 1982). In Puget Sound, herring spawn from the low intertidal to subtidal zones, between +1.2 m (+4 feet) to -6.1 m (-20 feet) in tidal elevation (Garrison and Miller, 1982) and the eggs are tolerant to temperatures in the range of 5°C to 14°C and salinities in the range of 3 to 33 ppt. There are about 24 distinct herring spawning areas in Puget Sound that appear to be used annually (Pentilla, 1986).

---

[7] Armoring such as described by Heiser and Finn in Hood Canal represents some of the most egregious shoreline alteration in Puget Sound from an era when shoreline armoring for the purposes of land filling was still permitted. Shoreline armoring for the purposes of land filling is inconsistent with current policy of both the Washington Department of Ecology and the Washington Department of Fish and Wildlife.

Although the effects of shoreline armoring on herring would be expected to vary with location, the major effect would probably be alteration or loss of preferred spawning substrates. This effect of shoreline armoring has not been directly documented in Puget Sound, nor elsewhere along the Pacific Coast. However, because mortality of herring eggs and larvae is so high (up to 90 percent), any shoreline armoring that has the potential to directly or indirectly decrease survivorship-by altering the spawning substrate-will likely have a deleterious effect on herring. On the other hand, shoreline armoring may enhance seaweed recruitment by robbing the beach of fine substrates. Thus, substrate changes resulting from shoreline armoring could have either a positive or a negative effect on herring spawning.

Direct and Indirect Effects to Shellfish

Reviewing the study plan for the CEMS ecological impacts task, Richard Bumgarner (WDFW, pers. comm.) noted that,

> if beach armoring results in the erosion of fine sediment on the armored beach, accretion will likely occur on the adjacent beach in the direction of littoral drift. This often results in seed clam and oyster mortality that is caused by smothering on the accretion beach and by increased exposure to predation on the eroded beach. Change in substrate composition can also impact clam recruitment when the altered sediment is no longer suitable to support calm seed survival. Dungeness crab require intertidal habitats containing suitable cover and forage to survive during their first year of life. Erosion and accretion can significantly alter this required habitat by removing key forage species and plant cover that is used to avoid predation. This habitat is considered critical to the survival of the Dungeness crab population.

Hardshell Clams There are well over a dozen species of hardshell clams that are used either commercially or recreationally in Puget Sound (WDF, 1992). Table 4.3 lists those species that are most often harvested. Most species prefer a gravel/sand substrate. Mixed-coarse beaches of varying degrees of exposure are suitable for these species, which occur primarily in the intertidal zone.

Ellifrit et al. (1973) investigated the effect of bulkheading and attendant fill in upper intertidal levels on densities of Manila clams in Hood Canal. They found significantly fewer clams at stations located seaward of bulkheads, with three of the four bulkheaded stations yielding densities less than half those from adjacent natural beaches. However, they found that clams inhabiting lower intertidal levels on the beach were not affected. Alterations in current patterns caused by the bulkheads, which resulted in less favorable conditions for settlement and survival of clam larvae, were proposed to explain lower clam densities near bulkheads.

Thompson and Cook (1991) and others have documented the effect of placement of gravel on sandy and muddy Puget Sound beaches. Gravel placement has resulted in significant recruitment of littleneck clams onto former mudflats. Seeding of gravel patches, coupled with measures to protect small clams from predators, has resulted in enhanced clam densities. These data strongly suggest that erosion, which results in removal of some fines and exposure of gravel, may improve conditions for hardshell clams. This enhancement would only persist if erosion ceased following exposure of the gravel. No examples have been found to date where such enhancement has been documented in Puget Sound.

Oysters Because oysters occur naturally in the mid- to low intertidal zone, shoreline armoring effects would either be through direct disturbance during armoring construction or through indirect effects from erosion and beach lowering. Oysters can grow in a variety of substrate types ranging from mud to cobble; alteration of substrate type may not have a direct effect on oyster survival and growth. Variation in survival and growth over a variety of substrata types needs to be investigated more fully to evaluate this latter point.

Direct and Indirect Effects to Upland Habitat

Residential development in coastal bank and bluff settings often results in land clearing, tree cutting (to enhance views), and drainage modifications (increased runoff, septic field drainage) that can seriously impact natural slope geophysical processes and habitats. Initially, no systematic studies or published accounts describing the natural habitats or plant and animal communities of Puget Sound's banks, bluffs, and cliffs were identified. However, numerous narrow focus studies on the use of bluffs by avifauna have been carried out (Hirsch, 1981; Brown, 1985; Speich and Wahl, 1989; Vermeer et al., 1987, 1993). This summary is, therefore, based principally on personal communications with regional experts.[8] During the review process Neil Rickard and Robert Zeigler (WDFW, pers. comm.) pointed out that the narrative volumes associated with the *Coastal Zone Atlas of Washington* (Ecology, 1977-80; Albright et al., 1980) contain summary information on vegetation and wildlife uses of Puget Sound shoreline bluffs and cliffs, as indeed do the Atlas maps themselves.

There is a clear consensus among those experts contacted that the bluffs and cliffs surrounding Puget Sound represent neglected habitats. They have a high potential to yield unique values for plant and animal communities yet presently remain virtually unstudied and unknown.

Forested bluffs and cliffs provide several unique habitat features:

- Have very steep slopes, often inaccessible-resulting in protection from human disturbance.

- Experience mass wasting and failure-results in open canopy/pioneer plant communities.

- Experience fewer, less intense fires than adjacent upland habitats.

---

[8]We particularly thank the following individuals for their contributions: Rex Crawford (Natural Heritage Program, Olympia), Sarah Gage (University of Washington Herbarium Curator), Arthur Kruckeberg (University of Washington, Professor Emeritus, Botany), Gregg Miller (Seattle Department of Parks and Recreation, Wildlife Biologist), Ken Moser (Puget Sound Keeper, Seattle), and Kate Stenberg (King County, Wildlife Planner).

- Have unique groundwater seep habitats.

- High slopes immediately adjacent to water offer isolated trees with excellent visibility for perching/nest sites.

- Cliffs provide isolated ledges and cavities for nesting.

Gage and Kruckeberg (pers. comm.) both note the potentially unique seep habitats of bluffs; regional occurrences of the chain fern (*Woodwardia fimbriata*) are restricted to these habitats. Gage also notes occurrences of distinctive—but unstudied—"mossy balds" on rock cliffs at Washington Park, Anacortes, and in the San Juan Islands. These same communities yield spectacular wildflower displays in spring.

Kruckeberg suggests that because of their relative inaccessibility and thus limited human disturbance, the bluff and cliff habitats of Puget Sound may provide "refugia" for species that have otherwise largely disappeared from more heavily urbanized lowland habitats.

Stenberg and Miller (pers. comm.) both note that high bluff and cliff habitat values for animals are mostly associated with secure nesting sites for birds. Depending on substrate, unvegetated cliffs may support cavity nesters such as Pigeon Guillemot, Belted Kingfisher, or even Barn Owls. Speich and Wahl (1989) prepared a *Catalog of Washington Seabird Colonies*. It lists breeding locations for pigeon guillemot, glaucous-winged gull, double-crested cormorant, Brandt's cormorant, pelagic cormorant, black oystercatcher, tufted puffin, rhinoceros auklet. It is comprehensive in its coverage of Puget Sound, islands, and coastal areas.

5.3.6 Cumulative Ecological Effects

Cumulative impacts can be defined as the sum of all individual impacts to a system. In the case of shorelines, small armoring projects may have little measurable ecological effect. Increasing the number of small projects within an embayment, however, would be expected to result in significant effects to the bay. The point at which these cumulative effects result in significant reduction in the ecological functions of the bay can be referred to as the threshold or catastrophe point (Forman and Godron, 1986). For example, one 50-foot-long bulkhead may only cause direct impacts to organisms within the armoring structure footprint. However, 50 similar projects modifying 2,500 feet of shoreline could substantially alter sediment erosion/deposition patterns and impact organic matter production and flux, resulting in measurable changes to the types and areas of habitat within the bay. In the worst case, fisheries species that would normally utilize these habitats may enter the bay, but not remain there, due to the modified distribution, structure, and area of bay habitats.

Available data indicate that increases in disturbances from contamination and physical modifications of the shoreline have resulted in measurable changes to habitats in Puget Sound (Thom and Hallum, 1990). However, we presently lack an understanding of the linkages between the degree of disturbance and changes in habitat distribution and function. Furthermore, data are lacking to quantitatively link changes in nearshore habitats (that might be affected by armoring) with resultant changes in the numbers and types of fishery resources.

A recent approach to cumulative ecological impact assessment relies heavily on the emerging principles of landscape ecology. A landscape is defined as "a heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in a similar form throughout" (Forman and Godron, 1986). Landscape ecology studies the interactions between ecosystems within a landscape. A typical "landscape" along the shores of Puget Sound would consist of a moderately sloping beach of gravel and cobble, which grades down into a subtidal zone containing abundant seaweeds, kelp, or eelgrass. The landward side of the beach would consist of a steep, possibly forested, bluff. The components of this landscape would interact through the flow of materials (organic and inorganic) and resources between the components. The degree of interaction between two portions of shoreline depends upon the degree of isolation (i.e., distance or physical barriers) between them. Hence, the relative effect of alterations on one portion of the shore to another portion would depend upon their proximity. Simply put, beaches within a single bay interact much more that beaches in separate bays.

Cumulative losses from human impacts can be inferred for Puget Sound habitats. Dike construction, filling, and dredging have resulted in progressive, significant losses of tidal wetland and mudflat habitats. The introduction of wastewater through numerous discharges into Puget Sound has resulted in widespread contamination of shellfish beds by fecal coliforms (Puget Sound Water Quality Authority, 1992). Loss of upstream spawning habitat, degradation of estuarine habitat, and over-fishing are all generally blamed for significant reductions in salmon and other fisheries resources in Puget Sound (Schmitt, 1990).

Following is an *example* of the development of evidence for cumulative impacts.

Of the rural and suburban county shorelines bordering Puget Sound, Thurston County shoreline is among the most extensively armored. As of 1993, approximately 30 percent of the 117 miles of shoreline in the county was armored (Morrison et al., 1994). Thurston County contains primarily gravelly sand beaches fronting steep bluffs, and lowering of the beach elevations—as well as coarsening of substrata—would be predicted due to the armoring.

As was discussed for Lincoln Park (Volume 7), coarsening of subtidal sediment may have resulted in a substantial increase in kelp. Lincoln Park shoreline, which includes a steep bluff along 40 percent of its length, is virtually 100 percent armored with a vertical seawall. The change at Lincoln Park from a gravel to a hardpan habitat, with subsequent increases in kelp distribution, could be viewed as alterations that exceed the "threshold point" for that bay.

Based on comparisons of surveys made in 1911-12 and 1977, Southern Puget Sound showed the second largest increase in kelp distribution (+332 percent) among all regions of Puget Sound. It was second only to the main basin (the area between Tacoma and the southern tip of Whidbey Island) which had an increase of 483 percent in shoreline bordered by kelp beds.

The linkage between armoring, sediment composition, and kelp distribution requires further study but may prove to be an indicator for cumulative effects of shoreline armoring in the region.[9] We would predict a decrease in animals dependent upon intertidal soft substrata and an increase in animals associated with gravel and cobble bottom.

5.3.6 Conclusions

There is ample evidence illustrating various effects of shoreline armoring on the physical structure of Puget Sound's beaches. Changes in physical structure include loss of shade, reduction in leaf fall, lowering of beach profiles, coarsening of beach sediment, narrowing of the beach, and alteration of groundwater flows. Ecological effects associated with these physical changes are presently poorly understood in Puget Sound and are not well documented anywhere in the United States. Based upon the critical links between physical conditions and habitats, and links between habitats and biological resources, conclusions can be drawn about potential effects of armoring on the ecology of beaches and resource species. These conclusions are verified by numerous general anecdotal observations and by field data collected from a small number of specific beaches.

The conclusions are as follows:

1. Habitat structure is modified under severe armoring conditions such that fine-sediment beaches are eroded down to gravel, cobble, or hardpan within a few decades.

2. Armoring may have its most pronounced ecological effect along Puget Sound's gravel-cobble beaches as opposed to highly depositional (mudflat) beaches or protected marshes.

3. Along gravel-cobble beaches, the classic physical changes alter the substrate from one that favors the growth of hardshell clams to one that is dominated by surface-dwelling seaweed, kelp, and barnacles.

4. Shallow subtidal areas adjacent to armored beaches can show significant alterations to substrate and biological communities under severe conditions.

5. Processes such as organic matter deposition and nutrient flux rates are altered as the physical conditions and substrata change.

6. Surf smelt, sand lance, herring, and rock sole spawning areas can be lost due to removal of fine sediments and woody debris from the intertidal zone.

---

[9] It must be emphasized that this is a *example* of what could be a cumulative effect of shoreline armoring. The evidence is not well enough developed to make an unequivocal statement. Other processes, natural and human-caused, may also be in play.

7. Hard armoring structures provide poorer habitats for prey resources for many benthic-feeding fish-including juvenile salmon.

8. Cumulative effects of physical changes caused by shoreline armoring can result in major alterations to habitats found in shore-zone systems.

9. It is not presently possible to *quantitatively* predict the effects of shoreline armoring on the ecology of beaches or the biological resources they support.

10. Most information on biological effects was gathered from Puget Sound beaches which can be characterized as already being "significantly changed" by armoring.

11. The physical and biological effects studies presently available confirm that similar shoreline armoring can result in different impacts at different locations (e.g., feeder bluff versus accretionary beach); that the elevation of armoring within the intertidal zone (e.g., higher versus lower on the beach) is critical; and that different types of armoring can result in different impacts.

6. Institutional Approaches

Section 6.1 of this chapter is an introduction prepared by Department of Ecology staff. Sections 6.2 and 6.3 are summaries of the reports prepared by Battelle Seattle Research Center for the Department of Ecology.

6.1 Introduction

The Coastal Erosion Management Strategy project was designed to include two evaluations of institutional, or policy approaches: Alternatives within the existing Shoreline Management Act institutional framework of permitting project proposals on an individual, case-by-case basis; and secondly, of taking a broader view of coastal erosion management on a regional basis. Early on, we thought to focus regional management on the drift cell—the natural embodiment of a complete erosion–transport–deposition system (see Chapter 2). As the CEMS project evolved, we decided not to limit our study in that manner, and to think simply in terms of a vague 'region' which might be a drift cell or a small embayment or an island in the Sound.

We chose to include an evaluation of regional approaches for two reasons. First, we were responding to a concern amongst shoreline managers that business-as-usual, or permitting projects on a case-by-case basis, made it difficult to address cumulative impacts. Second, we were responding to interest in beach nourishment and other 'soft' approaches to erosion management which are rarely viable for the individual shoreline property owner. Was there some institutional means of addressing coastal erosion management on a broader regional basis to enable cumulative impacts assessment and soft approaches?

The nature and history of residential development on the shores of Puget Sound is also an important factor in setting a framework for any discussion of institutional approaches. Local government shoreline administrators must deal with a number of different residential shoreline erosion situations:

- repair or replacement of existing erosion control structures which have deteriorated or become damaged;
- construction of new erosion control measures for existing residential structures;
- siting of new residential structures and new erosion control measures on existing parcels of land; and
- platting of new residential shoreline parcels.

Many older shoreline residential developments were platted with small, shallow lots which severely restrict the placement of structures and on-site sewage disposal facilities. (In fact, modern health regulations for on-site sewage disposal occasionally result in the shoreline property owner choosing to purchase a second, non-shoreline parcel simply for sewage disposal.) This situation severely limits or precludes any possibility of requiring building setbacks as a response to erosion or landsliding threat.

Finally, the provisions of ESB 6128 articulated a clear legislative policy for regulation of shoreline erosion under the state Shoreline Management Act. Local governments were to adopt standards for both structural and non-structural methods of erosion management which give a preference for permitting of erosion protection measures[10] for residences occupied prior to January 1, 1992. The erosion protection measure proposed by an applicant must be "designed to minimize harm to the shoreline natural environment." Furthermore, permit application processing must be carried out in a timely manner.

Because it is clear that the legislature intended that the erosion protection option remain a preference for residential property owners, the overall CEMS program was designed such that options for structural erosion management be addressed by the engineering and geotechnical study team (see Chapter 3), and that alternatives to structural solutions be addressed by the policy study team (this chapter).

6.2 Project Options

This project task, Policy Alternatives for Coastal Erosion Management (Volume 6), provides an overview of the current policy framework being used in Puget Sound to address coastal erosion plus a critical evaluation of alternative erosion management policies, strategies, and policy support tools that may enhance the framework. A major challenge to managing estuarine development is the need to balance the interests of private property owners who want to develop and stabilize their shoreline to protect their investment, and the mandate to public agency resource mangers to conserve, through rational management, public resources.

The research for this study task was conducted using four primary methods. First, a regular meeting of Puget Sound shoreline managers was used as a forum to solicit their views on the issues and problems they are confronting in coastal erosion and managing individuals' response to perceived and/or real coastal erosion. Second, a questionnaire was sent out to 223 individuals to further understand the range of issues and problems being confronted. Fifty responses were received. The third method used to better understand the current framework was a review of the state Shoreline Management Guidebook which includes the Administrators' Manual, the Handbook, and the Urban Waterfront Policy Analysis Addenda. In addition,

[10] This state policy and the national policy under the Coastal Zone Management Act are inconsistent. Current regulations for implementation of the CZMA encourage states to prohibit or at least discourage shoreline armoring and other forms of hard shoreline erosion control.

local government Shoreline Master Programs (SMPs) were reviewed to understand how local governments developed their programs, based on the Guidebook. Finally, phone interviews were conducted with local government shoreline administrators (city and county), private property owners, and bulkhead contractors to understand how the SMPs are being used.

While these analyses were conducted in the context of ESB 6128 and the Shoreline Management Act, other pertinent regulatory programs were reviewed including the Hydraulic Code, the Growth Management Act, the State Environmental Policy Act, and the federal Clean Water Act.

6.2.1 Issues in Puget Sound Coastal Erosion Management

From a review of questionnaire responses and telephone interviews with shoreline administrators, other local government officials, property owners, and shoreline protection contractors and from a review of various documents, a list of issues concerning Puget Sound coastal erosion management was identified. These issues include:

- Inadequate private property owner involvement in evaluating shoreline modification alternatives
- Inefficient and complicated shoreline modification application permit process
- Limited use of available soft shoreline modification solutions, where appropriate
- Reliance on hard shoreline modification solutions that results in negative impacts
- Frequent use of variances for residential development that creates a demand for future shoreline modification solutions
- Lack of familiarity with potential risks associated with shoreline property
- Inadequate environment designation provisions to control inappropriate development
- Lack of guidance or consensus on the appropriate balance between private and public property rights

Several of the shoreline administrators interviewed stated that property owners are not adequately involved in the shoreline modification permit application/review process. Typically the contractor, not the property owner, deals with the permit application process. As a result, there is no point in the permit process at which property owners can be made aware of alternative shoreline modification solutions and involved in the choice of the most optimal solution.

Some contractors, applicants, and property owners stated that the shoreline modification application permit process is cumbersome, costly, and extremely time consuming.

Soft shoreline stabilization methods are infrequently used in Puget Sound. Local SMPs generally encourage property owners to use soft solutions in controlling erosion; however, shoreline administrators have found that there are often serious impediments to using such solutions.

Most of the individuals interviewed reported that their jurisdictions' shorelines are becoming more and more hardened. Several shoreline administrators who responded to the questionnaire or were interviewed stated that hard solutions were generally approved even though their SMPs may discourage such solutions.

Because there are no standards or criteria for property owners to obtain a variance for residential development, frequently residences are constructed too close to the shoreline, resulting in the need or perception of the need for shoreline erosion control.

Property owners are often unaware of the risks associated with shoreline property. When buying a lot with the intent to build a home, or buying a lot with an existing home, the property owner may not be aware of the potential for erosion by either wave action or bluff instability.

All of the SMPs use the environment designation provisions defined in the Guidebook. However, many find that the provisions do little to restrict inappropriate shoreline development or that they are arbitrary and irrelevant to their coastal erosion management planning.

Overall, the jurisdictions find it difficult to balance private property and public rights. The Shoreline Management Act and its corresponding regulations emphasize both, yet are subsequently vague as to how to handle the conflict, leaving it up to the jurisdictions to interpret the regulatory language as they see fit.

6.2.2 Policy Alternatives

The policies, strategies, and policy support tools that have been identified as potentially useful in addressing coastal erosion are identified in Table 6.1.

Existing environment designation provisions could be modified and enhanced to make them more useful in evaluating residential development and shoreline modification applications. Enhancement of local SMP environment designation provisions could result in more effective evaluation of proposed residential and shoreline modification projects.

Table 6.1 Alternative Policies, Strategies and Policy Support Tools
Broad Environmental Policies
• Enhance environment designation provisions • Encourage coordinated environmental impact review
Shoreline Modification Policies
• Require evaluation of shoreline modification alternatives • Enhance use of soft solutions • Reduce reliance on hard solutions
Residential Policies

• Undeveloped Land
    • restrict inappropriate residential development
    • create market incentives to reduce inappropriate residential development
• Developed Land
    • create incentives for relocation or removal of threatened structures
    • require property listing disclosures

Strategies for Combining Policies
Policy Support Tools
• Develop research, monitoring and data collection programs • Develop education and outreach programs

A coordinated environmental impact review could be encouraged or required as a method for coordinating stakeholders (public agencies and private interested parties) involved or interested in a shoreline modification project. A coordinated environmental impact review could be used in the application review process to expedite the permit process and to ensure that all concerns are considered.

An evaluation of various shoreline modification alternatives such as bulkheading, riprapping, beach enhancement, and revegetation, for example, may be included in the application process. One approach to evaluating alternatives is to design a new application form that includes a hierarchy of alternatives for the applicants' consideration.

The use of the most non-intrusive or environmentally benign methods for shoreline protection, if appropriate could, be required. Soft solutions allow some drift cell processes to occur naturally without interruption from a hard structure. Soft solutions are, however, not appropriate everywhere. Incentives for using such methods, particularly if in on drift cell basis, could be instituted.

The reliance on hard, or structural solutions could be phased out, where feasible, for both public and private properties. An additional policy could be to impose structural design standards where hard solutions are needed.

Residential development policies address the management of increased shoreline residential development and human responses to perceived and/or real coastal erosion or bank failure. Separate policy options are necessary for undeveloped land for developed land (see Table 6.1). Restrictions on inappropriate residential development could include the use of setbacks; post-construction standards; public health ordinances (especially regarding waste disposal); and limitations to hard shoreline modification. Market incentives could include tax credits; transferable development rights; and land acquisition.

Data and technical studies are critical to the management of erosion control and reactions to erosion control. Shorelines with the greatest information needs should be targeted by their jurisdictions. Baseline maps and inventories for these shoreline areas could be updated and enhanced with the integration of development and land use patterns. Enhanced data bases can also be used to update/modify environment designation provisions. Research on full drift cells (e.g., determination of littoral drift), erosion rates, and the monitoring of modification solution impacts should be encouraged.

Programs could be developed to educate the general public, shoreline property owners, developers, architects, insurers, contractors, engineers and financial institutions concerning the natural dynamic properties of the shoreline and the possible impacts upon them from shoreline protection.

6.2.3 Evaluation of Policy Alternatives

Individual policies and programs within each of the three categories of policy alternatives, strategies for combining policies, and policy support tools were analyzed according to the factors outlined in Table 6.2 as well as lessons learned from other states. The analyses were not intended to result in policy prescription. Rather, it is intended to offer a broad outline of the advantages and limitations of the menu of policies, strategies for combining policies, and policy support tools provided.

Table 6.2 Factors for Analyzing Policy Alternatives
Technical Effectiveness
• Ability to meet objectives in short- and long-term • Certainty or uncertainty associated with the policy's ability to meet objectives • Flexibility to apply other policies at a future time • Reliability/durability/efficiency of technologies • Compatibility with geologic and hydraulic site characteristics • Compatibility with existing land use
Environmental Appropriateness
• Consideration of environmentally sensitive and critical areas (including fish and wildlife habitat) • Consideration of general environmental impact including water quality
Legal And Regulatory Acceptability
• Ability to comply with federal, state, and local laws and regulations • Consistency with ESB 6128 amendment of State SMA • Compatibility with state shoreline and growth management priorities and other state and local programs
Net Cost Of Implementation
• Public and private benefits • Capital costs • Administrative costs • Discount rate • Uncertainty • Irreversibility
Socio-Political Acceptability
• Balancing environmental conservation/protection and economic growth • Public perception of impacts on private property rights and/or the environment • Familiarity and simplicity of technical concepts and terms • Level of public participation in actual decision-making process
Ease Of Implementation (An Integration of Other Factors)
• Legal and regulatory constraints • Cost of implementation • Political acceptability • Level of understanding of policy implications • Level of coordination among stakeholders

6.3 Regional Options

This project task, Regional Approaches to Address Coastal Erosion Management (Volume 9), builds upon the results of the 'project options' study task (see section 5.2 of this chapter). Region is not prescriptively defined to allow state and local decision makers to tailor the word to meet their needs. It could, for example, mean a drift cell, reach of shoreline, or embayment. "Region" represents an area where the extent of possible effects, physically or biologically, are felt from some action.

The research for this report was conducted using two primary methods. First, a discussion paper on regional approaches was prepared based on the previous report, follow-up interviews, and new case study summaries. Second, a workshop was held on March 8, 1994 with decision makers who participate, at some level, in the review of applications for shoreline development and modification (e.g., armoring). The participants included local planners, state officials from Ecology and the Department of Fish and Wildlife, a representative of the U.S. Army Corps of Engineers, academicians, and the project manager. The discussion paper was used extensively during the workshop to illustrate the pros and cons of the proposed regional policy approaches and support tools in the context of Puget Sound. The workshop discussion was based on two primary needs that were raised by individuals interviewed during the first phase of this study:

- restrict inappropriate modification of shorelines
- restrict inappropriate residential development and foster appropriate development of undeveloped lands.

The report for this task is organized into four sections. The first describes possible command and control approaches that could be used regionally in the management of development and shoreline modification measures (e.g., bulkheads). These approaches are meant to capture the types of restrictions or requirements that could be used in a regulatory sense. The second section describes economic incentives and other market based solutions that could be used in coastal erosion management. Third, policy support tools such as research, monitoring, data collection, and education and outreach programs are described that might be necessary or desirable to ensure that the regional policy approaches succeed. (Sections one, two, and three are based upon case examples drawn from other states or regions.) Fourth and finally, a conclusion section is provided to summarize the major findings regarding which approaches appear to have the most merit in Puget Sound and to set the stage on what near-term actions need to be taken or at least considered as a next step.

This summary reproduces the conclusions section.

6.3.1 Command and Control Approaches

Ranking the regional approaches as to their effectiveness and appropriateness for Puget Sound is a difficult and, perhaps, inappropriate task. The choice of which approaches, if any, to implement will depend upon the circumstances of a particular local jurisdiction. These circumstances include language of the SMP, political will, stakeholder support, and status of the coastal property (undeveloped and unplatted, platted but undeveloped, and platted and developed). Each of the approaches described could be appropriate for some number of regions and their jurisdictions.

Erosion overlay district ordinances appear to be particularly interesting in that they could be implemented fairly easily under GMA and as an overlay to the Guidebook environmental designation provisions. Furthermore, they could be established for an entire physical region (e.g., drift cell) instead of by subdivision (as is the case for restrictive covenants and erosion control easements). One downside of erosion overlay district ordinances is that, unlike restrictive covenants and erosion control easements, a parcel's deed may not reflect the requirements or restrictions that apply to the property.

Coordinated regional review of environmental impacts should be changed to regional coordination to better describe what is possible and what is needed. Such coordination would not be limited to erosion issues as part of reviewing a permit. If implemented effectively, permit reviews could be greatly streamlined, particularly to identify BMPs. Regional coordination would be critical in collecting data that multiple jurisdictions need in conducting their roles and responsibilities.

Coordination of property owners, though beneficial, may be difficult to accomplish without some restrictive policy being the target of the coordination. The example of the Maryland Shore Erosion Control Program is a case in point. Property owners need to feel that the cost of not participating is greater than the loss of taking an independent approach that fails to consider the impact on neighbors' properties.

6.3.2 Economic Incentive and Other Market Based Approaches

Of the eight economic and other market based approaches identified in the previous report (Volume 6; section 5.2 in this chapter), the two that appear to be the most applicable in Puget Sound, given the existing regulatory and legal environment, are coastal preservation trusts and local improvement districts. These two approaches, if implemented properly, are both technically effective and environmentally appropriate. Both have the advantage of being voluntary and nonintrusive, and thus socially and politically acceptable. In addition, neither approach would require significant up-front investments or costs on the part of public agencies. Both of these approaches will involve the coordination of property owners which, while difficult, can be encouraged through education and outreach programs and state agency support. A thorough understanding of the successes and failures of preservation trusts such as the Maine Coast Heritage Trust and local improvement districts in other states may be an appropriate next step.

While similar to the preservation trusts in its public acceptability and environmental appropriateness, the technical effectiveness of land acquisition programs is entirely dependent on the public agency's ability to allocate significant funds. It may be possible to alleviate this problem to some extent by combining the acquisition program with some other fee or penalty based program whose revenues would be used exclusively for land acquisition.

The use of tax credits and financing policies may be effective but probably only in coordination with some other command and control policy. The effectiveness of tax credit and financing programs is directly linked to the reaction of property owners and developers to the tool. To predict the potential effectiveness of such a program, an economic analysis of property owner and developer behavior in the face of subsidies will be required.

Transferable development rights (TDRs) and mitigation banks, while not out of the question, appear to not be feasible options for coastal erosion management in Puget Sound at this time. The transferable development rights approach is very complex, involving rezoning, a market for transfer, and a rational property value assessment methodology — all of which may be costly. In addition, the technical effectiveness of TDRs is questionable due to great uncertainty about external market conditions.

Like TDRs, the effectiveness of mitigation banks in coastal erosion management is highly uncertain. The jury is still out on our ability to actually "create" or restore injured natural resource functions and services. The use of mitigation banks may be effective under some very critical conditions. First and foremost, coastal beaches will have to be raised to the same level of public consciousness as are wetlands. The above is not to say that conventional compensatory mitigation projects will not add greatly to coastal erosion management in Puget Sound. A first step may be to consider the combination of compensatory mitigation and local improvement districts. In this case, property owners within a region could coordinate and finance beach nourishment programs, for example, from which all residents would benefit.

To operationalize any of the approaches described above, property owners' and developers' behavior to incentives must be analyzed. If these stakeholders are not willing to participate than the program is doomed to fail. Such an analysis can be conducted through a public involvement exercise and/or simple economic behavioral analyses.

6.3.3 Policy Support Tools

Two major needs identified with implementing most of the approaches described in this report are identification and characterization of erosion-critical regions and public education and outreach programs to heighten stakeholder awareness of the problems that can stem in these regions from inappropriate property development and shoreline modification structures. Federal, state, and local funding is critical to address these two needs. Finally, involving the full range of stakeholders described in this report is a necessary next step to evaluate these regional approaches and to decide which ones have the most merit in Puget Sound.

7. Conclusions

No comprehensive conclusions regarding coastal erosion management were required of the CEMS consulting team. The views expressed in this chapter are those of the Department of Ecology CEMS staff (except as noted).

The purpose of this chapter is to place the results of the specific CEMS tasks in a unified context based upon what we have learned after the two years of consultant studies plus other consultations and discussions with local government staff, shoreline armoring contractors, and others.

7.1 Shoreline Armoring in the Puget Sound Region

The results of the Thurston County inventory, characterization, and trends study (Chapter 2) are probably representative of residential armoring activity in the south- and central-Puget Sound suburban counties—Thurston, Pierce, Mason, and Kitsap. No similar inventory has been conducted elsewhere in Puget Sound, nor are any contemplated.

King County shorelines (including the incorporated cities) have long been densely urbanized and heavily armored.

The north Sound—Snohomish, Skagit, Island, and Whatcom counties—probably experience relatively less shoreline armoring, if only because of lower population densities and shoreline development.

San Juan Islands are composed of proportionally greater amounts of stable, rocky shoreline. Erosion-prone shorelines, however, are subject to the same desire for armoring as other regions of Puget Sound.

Armoring of rail road embankments on the east shore of Puget Sound is continuous (except for stream mouths) in Pierce County from the Nisqually Delta to Commencement Bay, and in King and Snohomish counties from Shilshole Bay to the Snohomish Delta. Placement of this armoring began with construction of the rail road beds in the late 19th century and for the most part was completed prior to the World War I era. Most of the armoring is rock revetments. In places one can still see the now rapidly deteriorating wood bulkheads placed to protect the revetment work. Between Shilshole Bay and Everett there is a well constructed, near-vertical, rock seawall punctuated by short revetments.

7.2 Coastal Erosion Management Techniques

Our knowledge of the types of shoreline armoring used throughout the Puget Sound region is largely anecdotal as little information is collected. Between June 1993 and February 1994 we tabulated information on marine shoreline armoring permit applications from the State Environmental Policy Act (SEPA) Register. The SEPA Register is a weekly listing of SEPA activities—determinations of environmental significance or nonsignificance, and the release of draft and final environmental impact statements. Not all Puget Sound counties subject shoreline armoring permit applications to SEPA review, therefore the data are incomplete. Also, not all SEPA reviews indicate the armoring material. The available data are summarized in Table 6.1.

Table 7.1 Marine Shoreline Armoring by County, June 1993 through February 1994

County	Concrete	Rock	Wood	Unknown	Total
Island	7 (64%)	2 (18%)	0 (0%)	2 (18%)	11 (100%)
King	0 (0%)	3 (60%)	0 (0%)	2 (40%)	5 (100%)
Kitsap	3 (13%)	18 (79%)	1 (4%)	1 (4%)	23 (100%)
Mason	16 (49%)	9 (27%)	0 (0%)	8 (24%)	33 (100%)
Pierce	8 (24%)	18 (52%)	5 (15%)	3 (9%)	34 (100%)
Thurston	16 (47%)	14 (41%)	0 (0%)	4 (12%)	34 (100%)
Total	50 (36%)	64 (46%)	6 (4%)	20 (14%)	140 (100%)

Throughout Puget Sound, two structural solutions to shoreline armoring predominate—the concrete bulkhead and the vertical rock wall (see illustrations, Figure 2.1). Which technique is locally popular seems to depend upon which technique is promoted by local bulkheading contractors.

Our impressions are that throughout the Puget Sound region, the vertical rock wall is the most commonly constructed form of marine shoreline armoring. The data in Table 6.1 appear to confirm this, but information from Whatcom, Skagit, Snohomish, and San Juan counties is limited to personal observations.

The concrete bulkhead is still the predominate armoring method in Thurston and Mason counties, but in recent years the use of vertical rock walls has been increasing. The availability of appropriate sizes and qualities of rock was a limitation. In the past, rock was little used in Thurston County because the commonly available quarry rock, a basalt, was highly fractured and thus susceptible to water penetration and shattering during winter freeze-thaw cycles. A basalt rock wall was soon reduced to a scattering of rubble on the beach. In recent years one Thurston County armoring contractor has begun using a sandstone which to date appears to not be susceptible to freeze-thaw shattering.

Rock revetments, by themselves, are rarely used for residential marine shoreline armoring, but repairs to failing bulkheads are often accomplished by placement of revetments in front of the failing concrete wall. Revetments were commonly used for armoring rail road embankments as noted above. Revetments are also commonly seen in on industrial and municipal water-fronts. (Revetments have also commonly been used to armor river dikes and river banks, but this practice now discouraged by the Department of Ecology which recommends bioengineering techniques on fresh water shorelines.)

Stacked log bulkheads, once a common shoreline armoring technique throughout Puget Sound, are now rarely constructed. The lack of large, inexpensive logs now all but precludes this construction technique.

Wood piling-and-plank bulkheads and wood piling bulkheads are still constructed, but not so commonly as in past decades. Most local governments and the Department of Ecology discourage the use of pressure treated wood, especially creosote treated wood, in the marine environment.

Adoption of innovative techniques, both structural and nonstructural, would be dependent on regulatory acceptance by the Department of Ecology and the Department of Fish and Wildlife, as well as by the construction industry.

7.3 Impacts of Erosion Management

Growing population in the Puget Sound region has led to increased rates of shoreline development. At the same time, the scale of shoreline development has increased. Small vacation cabins are being replaced with larger primary residences. The intensity of shoreline development, and higher value shoreline development, has brought with it large increases in the demand for erosion protection.

The rate of armoring, coupled with an increased understanding of the ecological complexity and importance of Puget Sound, has led resource managers, planners, and the general public to voice concerns about potential adverse impacts associated with shoreline hardening. Specific concerns include habitat loss, aesthetic degradation, reduced public access, and the possibility that shoreline protection in one location may actually increase erosion in downdrift locations. Many of these issues relate to changes in the physical shoreline environment through changes in wave regimes, longshore sediment transport, and sediment supply. Other impacts are more direct.

Among the direct impacts of shoreline armoring are construction-related disturbances, physical impediments to public access along the shore at high tide, and the significant modification of the natural character of the shoreline. A less direct, but particularly difficult aspect of shoreline armoring is the degree to which it allows upland development to occur much closer to the shoreline than might be reasonable without shore defense. This leads to loss of natural buffers along the shoreline, greater human impacts on bluff hydrology, and increased likelihood of water quality problems due to the proximity of septic drainfields and decreased filtration of surface runoff.

7.3.1 Impacts on Physical Processes

Shore protection structures, by their nature, alter physical processes along the shoreline. They are designed to retain upland soils and to absorb or redirect wave energy. In so doing, they can lead to numerous secondary consequences. Bulkheads, seawalls, and to a lesser degree, revetments, can redirect wave energy onto adjacent shorelines or onto the beach. We commonly observe accelerated erosion on unprotected shorelines adjacent to structures. We also observe scour troughs in front of bulkheads following storms, but these features are rarely persistent and we do not know if they lead to long term beach changes.

We frequently observe evidence of measurable lowering of beach levels along extensively armored shorelines. Older bulkheads along these reaches of shore may be undermined. Unfortunately, we rarely have photos or information regarding rates of change or of conditions at the time of construction. The impact of seawalls and bulkheads on the beachface is a subject of ongoing scientific debate, but the discussion has largely focused on seawalls on open coasts and on their possible influence on cross-shore sediment movement. Although such factors may effect beach elevations and profiles on armored beaches in Puget Sound, we suspect that much of the observed effect is the result of reduced sediment supplies from updrift sources.

Even when bulkheads are built with minimum of waterward encroachment, they inevitably cover a portion of the upper beach and the backshore. This area represents sediment storage during summer months and other periods of low wave energy. The loss of this material and this beach area reduces the beach's capacity to absorb and react to storm waves and may lead to greater erosion elsewhere. We speculate that this loss of storage capacity within the littoral zone, combined with increased wave reflection, may lead to an acceleration of longshore transport rates.

We often observe that bulkheads act as groins to longshore drift. Even when bulkheads have been constructed close to the base of a bluff, we observe trapping of material on the updrift side and accelerated erosion on the downdrift side.

7.3.2 Impacts on Sediment Supply

Shore protection structures are designed and built to limit erosion, yet Puget Sound beaches are derived directly from the erosion of adjacent bluffs. Not surprisingly, the greatest concerns regarding shoreline armoring have to do with the consequences of eliminating traditional sediment sources. The result of sediment starvation may be difficult to document. The impact will be gradual and may lag the causal activity by decades. The impact will be confounded by many other variables in sediment supply and in downdrift beaches.

Two expected consequences of decreased sediment supply are a gradual coarsening of the beaches, as finer sands are preferentially moved downdrift and not replaced, and a narrowing of the beach due to its decreased volume and elevation. Lowering of the beach surface also results in exposure of the underlying shore platform.

Ediz Hook at Port Angeles provides an extreme example of the effect of shoreline armoring on downdrift sediment supply (Galster and Schwartz, 1989). Ediz Hook is a spit extending across the entrance to Port Angeles harbor on the Strait of Juan de Fuca. The construction of a water supply line along the base of the bluffs in 1930, and its subsequent armoring, led to a loss of 80% of the traditional source of sediment to the spit (the other 20%, from the Elwha River, had been reduced by the damming of that river earlier in the century). Serious erosion on the spit itself has resulted in extensive efforts by the Corps of Engineers to stabilize the shoreline. Initially this was done through large-scale armoring with rock, but more recently has involved the periodic nourishment of the spit with gravel and cobble.

Ediz Hook is only one of hundreds of depositional landforms and barrier beaches in Puget Sound. Each depends for its maintenance on continued updrift erosion. Because these features occur at the termini of littoral transport cells, their response to sediment restrictions may be delayed. They also are highly dynamic features and separating chronic influences of sediment deprivation from seasonal and interannual variations in sediment supply and storminess may be difficult. The narrow necks of spits and bars appear to be particularly sensitive to changes in sediment supply.

7.3.3 Confirming Observations

In recent years we have conducted a number of marine shoreline reconnaissance studies on the request of local government staff, elected officials, private property owners, and home owners associations. While lacking in the rigor of a formal investigation, our observations tend to support the conclusions of the CEMS consultant team.

Samish Island, Skagit County

On 2 July 1993, at the request of a local shoreline property owner, we conducted a reconnaissance inspection of the north shore of Samish Island in the vicinity of Section 26, T36N, R2E. Their stated concerns were recent beach erosion and lowering. The subject property is located along the transport portion of a two-mile-long drift cell, approximately mid-way between the feeder bluffs to the west and the deposition zone to the east. Most of the drift cell up-drift (west) of the subject property had been armored, some of it as early as the 1930s. At least two groins were in place west of the subject property.

Based on historical photographs, property owner testimony, and on-site measurements, we concluded the following. A concrete bulkhead was constructed at the subject property in 1982; bulkheads on nearby up-drift properties were constructed in the 1970s and earlier. Since the construction of the bulkhead at the subject property, the beach had lowered at least 1.0 to 1.5 feet, and possibly as much as 2.5 feet. The groins updrift of the subject property appeared to be trapping little sand, indicating that sediment transport through the drift cell is now scant. A few hundred feet east of the subject property the elevation of the upper beach was a few feet higher than at the subject property; here the beach dune included growths of Beachgrass and stranded drift logs which are absent along armored portions of the shore. This process is pictorially diagramed in Figure 7.1.

In essence, the sediment supply for the beach had been cut off beginning 60 years ago, and the beach is now exhibiting symptoms of starvation and lowering, consistent with the findings summarized in Chapter 5.

Rich Passage, Kitsap County

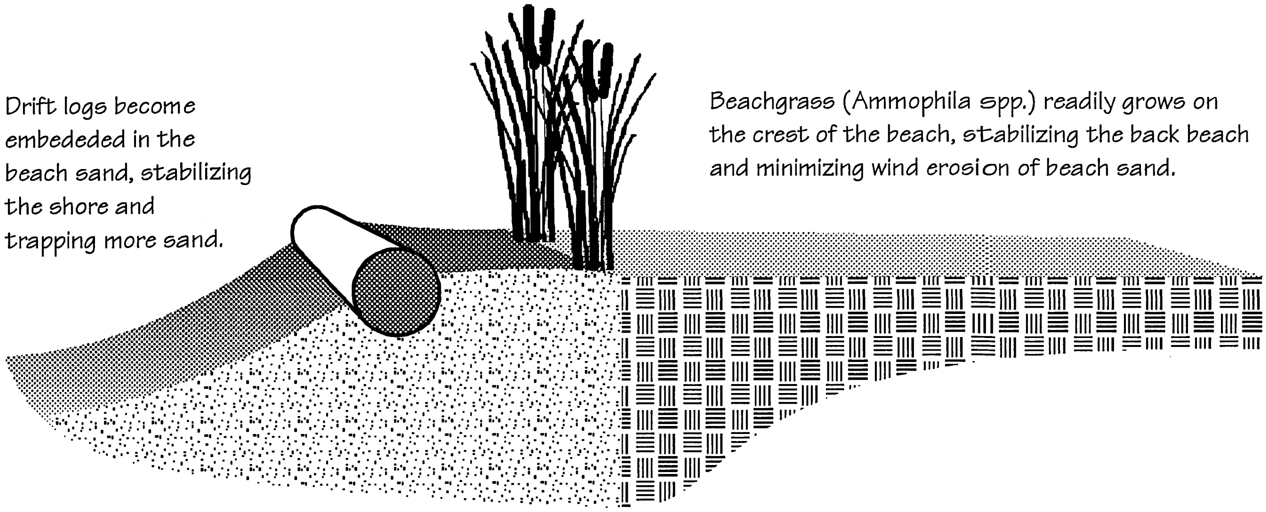
On 21 July 1990, at the request of then-Senator Bill Smitherman, we accompanied a group of legislators, local government staff, and shoreline property owners on an inspection of beach erosion allegedly caused by Washington State Ferry boat wakes on the south shore beaches of Rich Passage. We walked approximately 1.5 miles of shoreline from Waterman Point to Manchester State Park.

We noted that this portion of the shoreline was heavily armored, and that the armoring (mostly concrete bulkheads, with some rock revetments) was old, of poor design and construction, and deteriorating. Erosion, bank undercutting, and armoring damage was evident. Some bulkhead footings were exposed, indicating that substantial beach lowering had occurred. Except for shoreline indentations, the beaches appeared to have less sand and gravel and more cobbles and boulders than might be expected .

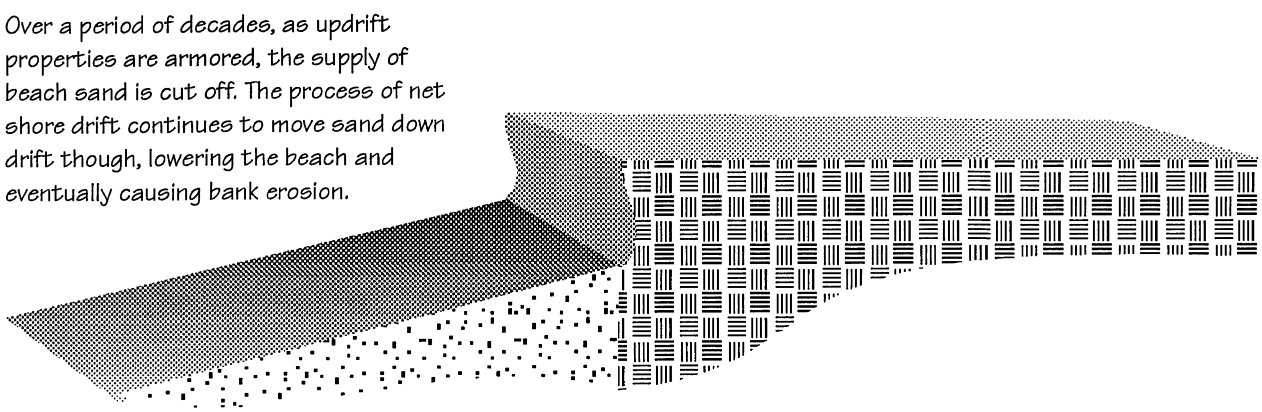
The beaches here showed evidence of lowering and coarsening, consistent with the findings summarized in Chapter 5. Factors other than extensive shoreline armoring could include geologic conditions[11] along the relatively narrow Rich Passage, as well as boat wakes.

---

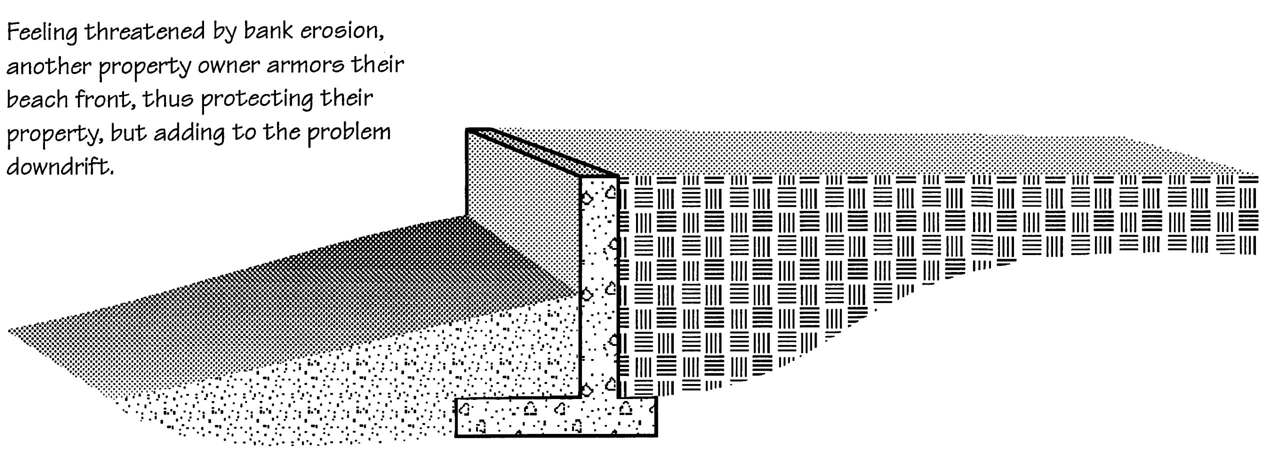
[11] Rich Passage lies over a fault where large scale, sudden vertical land movements have occurred in the past few thousand years in association with seismic events. It may be that a higher than regionally normal rate of current, chronic vertical land movement along Rich Passage contributes to both shoreline erosion and a coarse beach.



a. 'Natural' Beach with no Erosion and Abundant Drift Logs and Beachgrass



b. Early Stage of Beach Lowering and Erosion Due to Updrift Armoring



c. Bulkhead Constructed in Reaction to Erosion

Figure 7.1 Evolution of Samish Island Shoreline Erosion Due to Shoreline Armoring

7.3.4 Impacts on Living Resources

We have little to add to the discussion of biological and ecologic impacts in Chapter 5. Impacts to living resources and ecological processes are not always easily measurable or necessarily readily apparent. Moreover, these effects are insidious, often taking many years-to-decades to manifest themselves. (Though clearly, burial of habitat by beach fill for armoring occurs quickly and the habitat elimination is total.)

Shoreline armoring may result in significant habitat changes on the beach and in the nearshore environment over the long term. The immediate effect of bulkhead construction is to remove all vegetation from the lower bluff face and the backshore. This seriously reduces the complexity of the shoreline habitat and may eliminate certain habitats completely. The removal of large organic debris from the backshore may affect the supply of organic detritus and nutrients, reduce shading, and eliminate protective cover.

The structures cover the backshore and sometimes a portion of the upper intertidal. Surf smelt and other fish species depend on sand and small gravel in this zone for spawning. Increased water depths in front of bulkheads may increase predation on migrating juvenile salmon.

Physical changes to the shoreline lead to numerous secondary impacts on habitat by changing the energy regime and the substrate. Marine vegetation and beach fauna, including shellfish, find optimum habitat on a specific range of substrate types. When the beach substrates becomes coarser, shifting from sand to coarse sand to gravel to cobbles, the flora and fauna inhabiting the beach will also change. The rate of change will, at the most rapid, be on the order of a few decades.

Shoreline armoring also changes ecological processes on Puget Sound beaches, principally alteration of plant community composition and net primary productivity (see Figure 5.2), net loss of organic matter, and changes to the nutrient cycling processes.

7.4 Cumulative Impacts

The cumulative effects of shoreline armoring are of great concern to shoreline administrators and resource managers. In fact, concern over cumulative effects by local elected officials was one of the factors that prompted initiation the Coastal Erosion Management Strategy in 1992. But cumulative effects in general are not well understood, and there is little research specifically on the cumulative effects of shoreline armoring.

The inventory and characterization of Thurston County shorelines (Chapter 3) clearly illustrates how many small residential bulkheading projects over a period of decades leads to the armoring of substantial portions of the shoreline.

A typical concrete bulkhead may only occupy 50 m (150 ft) of shoreline and its immediate, individual environmental impacts may be relatively minor, but a large proportion of Puget Sound's shoreline is potentially subject to bulkheading. The environmental consequences of armoring several continuous miles of shoreline or the entire shoreline of an inlet or bay may be much greater. For this reason, we view the cumulative aspect of shoreline armoring as the most worrisome in terms of the long-term health of Puget Sound.

Cumulative impacts may be linear, or additive: the cumulative impact of 100 bulkheads may be equal to simply the impact of the 100 bulkheads. This may apply to direct impacts such as backshore burial or vegetation removal, but is more difficult to apply to offsite impacts or impacts related to changes in updrift sediment transport.

Cumulative impacts may also be nonlinear. There may be threshold levels of bulkheading below which the impacts are minor, but above which the implications are more serious. In some circumstances, the impacts of additional armoring on sediment supply may be minor. For example, in some littoral cells, a bulk of the sediment is provided by the erosion of a short stretch of bluffed shoreline. Once these bluffs are armored, additional bulkheading may not greatly alter beach characteristics.

The converse might be found within a littoral cell where the entire shoreline has significant potential for contributing sediment. The elimination of sediment sources by initial bulkheading might be readily compensated by small increases in downdrift erosion. As the shoreline becomes more continuously armored, the incremental impact on sediment supply of additional bulkheads will become much greater.

Finally, the effects may be synergistic, especially with respect to ecological effects. A combination of many direct impacts to biological resources or ecologic processes may combine to produce a cumulative effect where the whole is greater than the sum of its parts.

8 Bibliography

Albright, R., R. Hirschi, R. Vanbianchi, and C. Vita. 1980. *Coastal Zone Atlas of Washington: Land Cover/Land Use Narratives. Vol. I: Urban, Agricultural, Nonforested Uplands, Forest, Water* (Pp. 1-447); *Vol. II: Wetlands, Exposed and Other Lands, Appendices* (Pp. 448-887). State of Washington Department of Ecology, Olympia, Washington.

Angermeier, P.L., and J.R. Karr. 1984. Relationship Between Woody Debris and Fish Habitat in a Small Warmwater Stream. *Trans. Am. Fish. Soc.* 113: 716-726.

Armstrong, J.W., and A.E. Copping (eds). 1990. *Status and Management of Puget Sound's Biological Resources.* U.S. Environmental Protection Agency, Seattle, Washington. EPA 910/9-90-001.

Armstrong, J.W., C.P. Staude, R.M. Thom, and K.K. Chew. 1976. Habitats and Relative Abundances of the Intertidal Macrofauna at Five Puget Sound Beaches in the Seattle Area. *Syesis* 9:277-290.

Benner, P.A., and J.R. Sedell. 1987. Chronic Reduction of Large Woody Debris on Beaches at Oregon River Mouths. pp. 335-341 in *Wetland and Riparian Ecosystems of the American West.* Proceedings of the Society of Wetland Scientists Eighth Annual Meeting, Seattle, Washington.

Bisson, P.A., and eight authors. 1987. Large Woody Debris in Forested Streams in the Pacific Northwest: past, present, and future. pp. 143-190 in E.O. Salo and T.W. Cundy (eds). *Streamside Management: Forestry and Fishery Interactions.* University of Washington, Institute of Forest Resources Contribution 57, Seattle, Washington.

Bortelson, G.C., M.J. Chrzastowski, and A.K. Helgerson. 1980. *Historical Changes of Shoreline and Wetland at Eleven Major Deltas in the Puget Sound Region, Washington.* Atlas HA-617, Department of Interior, U.S. Geological Survey.

Brown, R.E. (ed.). 1985. *Management of Wildlife and Fish Habitats in Forests of Western Oregon and Washington, Part 1 and 2.* U.S. Department of Agriculture, Forest Service, Pacific Northwest Region.

Canning, Douglas J. 1991. *Cumulative impacts analysis.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Cardwell, R.D., and R.R. Koons. 1981. *Biological Considerations for the Siting and Design of Marinas and Affiliated Structures in Puget Sound.* Technical Report No. 60. State of Washington, Department of Fisheries, Olympia, Washington.

Cox, Jack, Keith Macdonald, and Tom Rigert. 1994. *Engineering and geotechnical techniques for shoreline erosion management in Puget Sound. Coastal Erosion Management Studies Volume 4.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Davies, Kate. 1993. Defining cumulative impact assessment. *Canadian Water Watch* 6 (7-8): 7-10.

Dethier, M.D. 1990. *A marine and estuarine habitat classification system for Washington state.* Washington Natural Heritage Program, Washington Department of Natural Resources, Olympia.

Dorcey, A.H.J., T.G. Northcote, and D.V. Ward. 1978. *Are the Fraser Marshes Essential to Salmon?* Univ. B.C. Westwater Res. Cent. Tech. Rep. 1: 29p.

Dotson, A. Bruce and Timothy Beatley. 1991. *Management of cumulative impacts in Virginia: Identifying the issues and assessing the opportunities.* Coastal Resource Management Program, Virginia Council on the Environment, Richmond.

Downing, J. 1983. *The Coast of Puget Sound.* Washington Sea Grant, Seattle, Washington.

Ellifrit, N.J., M.S. Yoshinaka, and D.W. Coon. 1973. Some Observations of Clam Distribution at Four Sites on Hood Canal, Washington. *Proc. Nat. Shellfish Assoc.* 63:7 (Abstr.).

Forman, R.T.T., and M. Godron. 1986. *Landscape Ecology.* John Wiley & Sons, New York, NY.

Garrison, K.J., and B.S. Miller. 1982. *Review of the Early Life History of Puget Sound Fishes.* FRI-UW-8216. Fisheries Research Institute, University of Washington, Seattle, Washington.

Heiser, D.W., and E.L. Finn, Jr. 1970. *Observations of Juvenile Chum and Pink Salmon in Marina and Bulkhead Areas.* Fish. Mgt. and Res. Div., Suppl. Prog. Rept. Puget Sound Stream Studies. Washington State Department of Fisheries, Olympia, Washington.

Hirsch, K. 1981. *A report on human activity on Protection Island and recommendations for a management plan for the Zella M. Schultz Seabird Sanctuary.* Nongame Wildlife Program, Washington Department of Game, Olympia, Washington.

Johnson, A.W., and D.M. Ryba. 1992. *A Literature Review of Recommended Buffer Widths to Maintain Various Functions of Stream Riparian Area.* Prepared for King County Surface Water Management Division. 28 pp.

Levings, C.D., K. Conlin, and B. Raymond. 1991. Intertidal Habitats Used by Juvenile Chinook Salmon Rearing in the North Arm of the Fraser River Estuary. *Marine Pollution Bulletin* 22(1):20-26.

Macdonald, J.S., C.D. Levings, C.D. McAllister, U.H.M. Fagerlund, and J.R. McBride. 1988. A Field Experiment To Test the Importance of Estuaries for Chinook Salmon (*Oncorhynchus tshawytscha*) Survival: Short-Term Results. *Can. J. Fish. Aquat Sci.* 44: 1233-1246.

Macdonald, Keith, David Simpson, Bradley Paulsen, Jack Cox, and Jane Gendron. 1994. *Shoreline armoring effects on physical coastal processes in Puget Sound, Washington. Coastal Erosion Management Studies Volume 5.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

McCabe, Gretchen H. and Katherine F. Wellman. 1994a. *Policy alternatives for coastal erosion management. Coastal Erosion Management Studies Volume 6.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

McCabe, Gretchen H. and Katherine F. Wellman. 1994b. *Regional approaches to address coastal erosion management. Coastal Erosion Management Studies Volume 9.* Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Menashe, Elliot. 1993. *Vegetation management: A guide for Puget Sound bluff property owners* (publication 93-31). Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Mitsch, W.J., and J.G. Gosselink. 1993. *Wetlands* (Second Edition). Van Nostrand Reinhold, New York. 722 pp.

Morrison, Steven W., Jacqueline Kettman, and Dan Haug. 1994. *Inventory and characterization of shoreline armoring, Thurston County, Washington, 1977 - 1993.* Coastal Erosion Management Studies Volume 3. Shorelands and Coastal Zone Management Program, Washington Department of Ecology, Olympia.

Mumford, T.F. 1990. Commercial and Recreational Management of Aquatic Vegetation in Puget Sound. pp. 5-19 in, Armstrong, J.W. and A.E. Copping (eds). *Status and Management of Puget Sound's Biological Resources.* U.S. Environmental Protection Agency, Seattle, Washington. EPA 910/9-90-001.

Pentilla, D.E. 1986. Current Status of Puget Sound Herring Stocks" pp. 59-63 in C.W. Haegele (ed). Proceedings of the Fifth Pacific Coast Herring Workshop, October 29-30, 1985. *Canadian Manuscript Report of Fisheries and Aquatic Sciences* No. 1871.

Pentilla, D.E. 1978. *Studies of the Surf Smelt (*Hypomesus pretiosus*) in Puget Sound.* Washington Department of Fisheries Technical Report 42, Olympia, Washington.

Phillips, R.C. 1984. *The Ecology of Eelgrass Meadows in the Pacific Northwest: A Community Profile.* U.S. Fish and Wildlife Service, Div. of Biological Services, FWS/OBS-84/24. Washington, D.C. 85 pp.

Pomeroy, W.M., and C.D. Levings. 1980. Association and Feeding Relationships Between *Eogammarus confervicolus* (Amphipoda, Gammaridae) and Benthic Algae on Sturgeon and Roberts Banks, Fraser River Estuary. *Can. J. Fish. Aquat. Sci.* 37:1-10.

Pryne, E. 1994. Many Fish Species on Decline in Northwest. *Seattle Times*, March 18, 1994.

Puget Sound Water Quality Authority. 1992. *1992 Puget Sound Update.* Puget Sound Water Quality Authority, Olympia, Washington.

Reeves, G.H., F. H. Everest, and J. R. Sedell. 1993. Diversity of Juvenile Salmonid Assemblages in Coastal Oregon Basins with Different Levels of Timber Harvest. *Trans. Am. Fish. Soc.* 122: 309-317.

Selisker, D.M., and J.L. Gallagher. 1983. *The Ecology of Tidal Marshes of the Pacific Northwest: A Community Profile.* U.S. Fish and Wildlife Service, Div. of Biological Services, FWS/OBS-82/32. Washington, D.C. 65 pp.

Shipman, Hugh and Douglas J. Canning. 1993. Cumulative Environmental Impacts of Shoreline Stabilization on Puget Sound. pp 2233-2242 in: *Proceedings, Coastal Zone 93, Eighth Symposium on Coastal and Ocean Management, July 19-23, 1993*, New Orleans, Louisiana, American Society of Civil Engineers, New York.

Shreffler, D.K., C.A. Simenstad, and R.M. Thom. 1992. Foraging by Juvenile Salmon in a Restored Estuarine Wetland. *Estuaries* 15(2): 204-213.

Shreffler, D.K., and R.M. Thom. 1993. *Restoration of Urban Estuaries: New Approaches for Site Location and Design.* Report Prepared for Washington State Department of Natural Resources, Olympia, Washington. Battelle Pacific Northwest Laboratories, Richland Washington.

Simenstad, C.A. 1983. *The Ecology of Estuarine Channels of the Pacific Northwest: A Community Profile.* U.S. Fish and Wildlife Service, Div. of Biological Services, FWS/OBS-83/05. Washington, D.C.

Simenstad, C.A., K.L. Fresh, and E.O. Salo. 1982. The Role of Puget Sound and Washington Coastal Estuaries in the Life History of Pacific Salmon: An unappreciated function. pp. 343-364. in V.S. Kennedy (ed). *Estuarine Comparisons.* Academic Press, New York, New York.

Simenstad, C.A., and E.O. Salo. 1980. Foraging Success as a Determinant of Estuarine and Nearshore Carrying Capacity of Juvenile Chum Salmon (*Oncorhynchus keta*) in Hood Canal, Washington. pp. 21-37 in B.R. Metleff and R.A. Neve (eds). *Proceedings of the North Pacific Aquaculture Symposium, Alaska Sea Grant Report 82-2.* University of Alaska, Fairbanks, Alaska. 379p.

Simenstad, C.A., C.D. Tanner, R.M. Thom, and L. Conquest. 1991b. *Estuarine Habitat Assessment Protocol.* EPA 910/9-91-037. Report to U.S. Environmental Protection Agency, Region 10, Fish. Res. Inst., University of Washington, Seattle, Washington. 201 pp.

Speich, S.M. and T.R. Wahl. 1989. A Catalog of Washington Seabird Colonies. U.S. Fish and Wildlife Service, *Biological Report* 88(6).

Stembridge, Jr., J.E. 1979. Beach protection properties of accumulated driftwood. American Society of Civil Engineers, New York. *Coastal Structures '79.* Vol II. pp. 1052-1068.

Terich, T., and S. Milne. 1977. *The Effects of Wood Debris and Drift Logs on Estuarine Beaches of Northern Puget Sound.* Department of Geography and Regional Planning, Western Washington University, Bellingham, Washington.

Terich, T.A. and M.L. Schwartz. 1993. The effects of seawalls upon beaches. *Proceedings of the Canadian Coastal Conference.* Coastal Zone Engineering Program, National Research Council. Ottawa.

Thom, R.M. 1983. Spatial and Temporal Patterns of *Fucus distichus* ssp. *edentatus* (de la Pyl.) Pow. (Phaeophyceae: Fucales) in Central Puget Sound. *Botanica Marina* 26:471-486.

Thom, R.M., J.W. Armstrong, C.P. Staude, K.K. Chew, and R.E. Norris. 1976. A Survey of the Attached Marine Flora at Five Beaches in the Seattle, Washington, Area. *Syesis* 9:267-275.

Thom, R.M., and L. Hallum. 1990. *Long-Term Changes in the Areal Extent of Tidal Marshes, Eelgrass Meadows and Kelp Forests of Puget Sound.* Final Report to U.S. Environmental Protection Agency, Univ. Washington, Fisheries Research Institute, FRI-UW-9008, Seattle, Washington.

Thompson, D., and W. Cook. 1991. Enhancement of Hardshell Clam Habitat by beach Graveling. pp. 521-527 in, *Proceedings Puget Sound Research '91.* Puget Sound Water Quality Authority, Olympia, Washington.

Toal, C.W. 1993. *The Effects of Bulkheads on Juvenile Salmonoids in Hood Canal.* Washington Department of Ecology, Southwest Regional Office, Olympia, Washington. (Unpublished manuscript). 9 pp.

Vermeer K. and R.W. Butler (eds.). *The Ecology and Status of Marine and Shoreline Birds in the Strait of Georgia, British Columbia.* 1987. Proceedings of a Symposium sponsored by the Pacific Northwest Bird and Mammal Society and the Canadian Wildlife Service.

Vermeer, K., and C.D. Levings. 1977. Populations, Biomass, and Food Habits of Ducks on the Fraser Delta Intertidal Area, British Columbia. *Wildfowl* 28:49-60.

Warner, R.E., and K.M. Hendrix (eds). 1984. *California Riparian Systems: Ecology, Conservation, and Productive Management.* University of California Press, Los Angeles. 1035 pp.

Washington Department of Ecology. 1978. *Coastal Zone Atlas of Washington* (12 volumes). Washington Department of Ecology, Olympia.

Washington Department of Fisheries. 1992. *Salmon, Marine Fish and Shellfish Resources and Associated Fisheries in Washington's Coastal and Inland Marine Waters.* Habitat Management Division Technical Report No. 79 (Revised).

Wiedemann, A.M. 1984. *The Ecology of Pacific Northwest Coastal Sand Dunes: A Community Profile.* U.S. Fish and Wildlife Service. FWS/OBS-84/04. 130 pp.

Yarranton, G.A. and G.L. Hegmann. n.d. *A decision-maker's view of cumulative effects assessment.* Environmental Research Center, The University of Calgary, Calgary, Alberta.