Coastal Erosion
Management
Strategy

Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound, Washington

Coastal Erosion Management Studies, Volume 5

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Shorelands and Water Resources 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 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:

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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 Effects, Vegetative Erosion Control, and Beach Nourishment	Published June 1994
Volume 3	Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993	In press
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	Scheduled, 1994-95
Volume 11	Coastal Erosion Management in Puget Sound: Technical and Policy Guidance for Local Government	Scheduled, 1994-95

Preface

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 steep slope failure, 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 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.

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. The scientific literature seems to indicate that shoreline armoring (and the associated vegetation clearing) 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 three 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 provides quantitative estimates of the rate and character of 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 are 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, 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.

This report on the impacts of shoreline armoring on physical coastal processes is complemented by a report on the impacts of shoreline armoring on living resources and ecological processes (task 5; volume 7). The reader is cautioned against assuming that these two reports are the last word on the subject. We are confident that these reports do represent an accurate understanding of the issue within the limits of [1] the funding available for the CEMS project and [2] the state-of-the-knowledge with respect to published research and monitoring data. Subsequent to the completion of this task, a small body of additional professional literature was published. That information will be incorporated into the environmental impact statement to be published as a part of this project and report series.

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."

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The principal authors of this report are Keith Macdonald, Ph.D., Oceanography (Scripps Institution of Oceanography), David Simpson, M.S., P.E., Civil Engineering (University of Washington), and Bradley Paulson, M.S., Geological Oceanography (University of Washington). Additional contributions were made by Jack Cox, M.S., P.E., Engineering (Purdue University), and Jane Gendron, B.A., Biology (San Francisco State University). The entire report was edited by both Tom Rigert, M.S., Physics (Renssalaer Polytechnic Institute) and Dr. Macdonald, who is also the Project Manager for the Coastal Erosion Management Strategy contract.

We owe special thanks to the following individuals, each of whom reviewed our draft report and offered constructive suggestions for improvements: Douglas Canning and Hugh Shipman, both with the Washington Department of Ecology's Shorelands and Coastal Zone Management Program; Ken Bates, P.E., and Neil Rickard, both with the Washington Department of Fish and Wildlife; and Professor Richard Sternberg, a specialist in nearshore processes and sediment dynamics at the University of Washington School of Oceanography; Peter Skowlund also with Ecology; and Eric Nelson, Seattle District, U.S. Army Corps of Engineers.

Additional valuable insights were provided by marine ecologist, Ronald Thom, Ph.D., and environmental policy specialist, Gretchen McCabe, M.S., both with Battelle.

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Contents

Contents (continued)

Appendices

Tables

Fact Sheets

Figures

Figures (continued)

Figures (continued)

Figures (continued)

Section 1
Introduction

Objectives

This report summarizes present understanding of shoreline physical processes within Puget Sound and how they are impacted by the installation of shore protection structures. This interaction has been debated among technical specialists for many years, and diverse opinions about the effects of different shore protection methods still exist. Misunderstanding in the lay community can be expected to be at least as great as the intensity with which opinions are defended among the specialists. Ultimately, however, workable solutions to frequently competing concerns for upland property protection and nearshore natural habitat preservation must be implemented. Information in this report can assist resources and regulatory agency planning and permitting staff to more accurately assess the potential impacts of proposed coastal construction both locally and at adjacent sites, as well as cumulatively within the regional zone of influence. This information can also help property owners make informed decisions regarding improving and protecting property affected by local wave and current forces and the unique geological settings of Puget Sound.

This report provides technical information on the interaction of shoreline processes and structures pertinent to Puget Sound. The aim is to describe the fundamentals of processes acting in Puget Sound's varied nearshore and beach environments that will enable prediction of consequences of constructing shore protection measures. General guidance and recommendations can then be developed within the Department of Ecology (Ecology) for use by the planning staffs of counties or other entities who must make permitting decisions regarding property owners' applications for shoreline modifications.

Approach

Planning Considerations

Although this report focuses on the impacts of shoreline modifications to the physical environment, attention is given to presenting information on the type of processes and responses particularly relevant to biological studies. (A subsequent report, for Task 5, *Shoreline Armoring Effects on Biological Resources and Coastal Ecology in Puget Sound*, will specifically address the biological impacts of shoreline modifications in greater detail.) Our approach has been to develop and address a series of basic questions regarding interactions of shore protection, such as bulkheads and beach nourishment, with the hydraulic and sedimentary regimes that characterize Puget Sound shorelines. Technical information on physical coastal processes has been reviewed for applicability to those questions at site-specific as well as more distant shore locations.

Impact Categories

Shore protection impacts analyzed in this report include changes to the overall beach profile and changes to the composition of material on the surface of the beach. Impacts in the vicinity of the shore protection, as well as at more distant beach locations, are discussed. The types of shore protection considered range from "hard" structures, such as bulkheads and revetments, to more compliant "soft" approaches, such as beach nourishment and vegetation management.

Cumulative Impacts

The majority of this report addresses the potential impacts of shore protection on physical coastal processes either at or immediately adjacent to the actual site of shoreline armoring. The broader goal of this entire study program, however, is to assess the potential cumulative effects of shoreline armoring upon both physical coastal processes and ecological systems throughout Puget Sound.

Such cumulative impacts might be simple and linear, steadily increasing as the total length of armored shoreline rises. Alternatively, they may be nonlinear and include critical threshold levels above which additional shoreline armoring has highly significant impacts—or conversely, ceases to greatly alter the beach. Studies addressing cumulative impacts of altering an environment as dynamic as the shore are very limited. This section outlines some examples of cumulative impacts and establishes a general framework within which potential cumulative effects can be further explored.

Puget Sound Case Studies

While extensive studies of shore protection impacts have been conducted in other parts of the country, very few studies are available for Puget Sound locations. The unique geologic and oceanographic setting of the Sound, together with the role of recent glaciation, all result in landforms, shore materials, and process rates that are significantly different from those at other locations (Downing 1983, Terich 1987). The goal of the Case Studies, therefore, is to identify those few sites within Puget Sound for which some descriptive and quantitative data describing the impacts of shore protection are available. A brief summary of these very limited available data is presented.

An obvious outgrowth of the scarce case study data for Puget Sound is the clear and critical need for more comprehensive field monitoring and quantitative research regarding the potential impacts of shoreline modifications. These needs are also addressed.

Section 2

Shore Processes

Physical processes that are important to understand for assessing effects of shore structures are wave generation and dissipation, and sediment transport in currents and waves. Wind blowing across a body of water transfers energy to it that forms water waves. For storms of usual duration and where the fetch is limited and restricted by the land boundary, the height and length to which waves grow will be less than for the unlimited fetch case with similar wind speeds. For this reason Puget Sound is only a moderate wave energy environment even in the most exposed locations. Waves dissipate energy through shoaling and breaking, and transfer energy by generating nearshore currents and transporting sediment. Energy is finally dissipated to zero in swash action on the beach face.

When wave energy is dissipated in the shore zone, sedimentary particles are transported by stresses generated at the boundary and by turbulence in the flow. As sediment is carried away from a site, it must be replaced by sediment flowing into the site or a deficit is created and the shoreline retreats to compensate. To a great extent, these processes are dependent on water depth. Tides vary the water depth at a site and thus also the location at which particular processes are most intense. As wave-generating events and tidal currents and elevations vary, the intensity and location of processes that modify or maintain shore features also change.

Definition of Terms

Terms used in the following discussion are defined below.

- Shore protection includes shore hardening, or armoring, and "soft" solutions to shore erosion.

- Shore armoring, or "hard" solutions, typically involve the addition of material to the shore that is not natural to the site, ranging from vertical walls to sloped rock rubble, to prevent the loss of property landward of the armoring.

- A "soft" solution is a nonstructural approach to preventing loss of upland property. It usually refers to the placement of beach material (i.e., beach nourishment or replenishment) or vegetation management at the shore. In implementing a soft solution, sediment might be added to replace eroded beach material or to feed a littoral current that would otherwise cause shoreline retreat. Beach grass might be planted to stabilize shore material against the actions of wind and flowing water. The shore might be covered with sedimenting material that is coarser than native sizes. The beach fill is dynamic and compliant to wave forces, but remains in the profile to a thickness adequate for protecting the underlying natural beach.

- Beach nourishment is a deposit of beach material, artificially placed along a shoreline to provide a buffer zone between the waves and the backshore. It is a "flexible" structure since its shape can be modified by natural littoral processes. It can restore an eroded beach where it is placed, or it can act as a "sacrificial fill" to be redistributed by longshore processes and supply downdrift locations.

- Drift sector (also known as drift cell or littoral cell) is a segment of shoreline that allows uninterrupted movement of beach materials. Each drift cell includes a feed source that supplies the sediment, a driftway along which the sediment moves, and an accretion terminal or sink where the sediment is deposited. Importantly, activities in one drift sector do not propagate effects to other drift sectors.

- Ordinary High Water Mark (OHWM) is a term with special regulatory significance in Washington State, where it is used in both the Shoreline Management Act (SMA) and Hydraulics Code to determine jurisdiction and setback requirements. In a very general sense—as used in this report—it can be approximately equated with the mean higher high water line, often a little higher. This is <u>not</u> true from a precise legal and regulatory perspective, however. As noted in the glossary, the legal definition describes OHWM as a geographical location along the shoreline determined by a change in vegetation type—from predominately aquatic to predominately terrestrial vegetation. As such it is a dynamic biological location that cannot be precisely or consistently equated to any specific elevation or tidal datum.

- The beach is the whole profile of the shore in which sediment is moved by natural forces, from deepest depth on the profile where the most extreme waves cause motion, up to the limit of wave uprush. This can be seen in Figure 2-1, which documents beach profile changes in response to storm waves.

- Sediment starvation is a long-term regional sediment deficit in the littoral system. The sediment supply to a starved beach is less than the quantity being removed by natural or other means.

- Erosion is the result of a localized concentration of sediment transporting forces—perhaps due to a structure's concentrating wave energy or altering the local shoreline angle—that carries away local shore material.

General Orientation

When a shore in a dynamic environment consists of mobile sedimentary particles, maintaining stability of the shore features requires continuity of sediment flow. Individual particles comprising a part of the shore might move through the system, but in the long

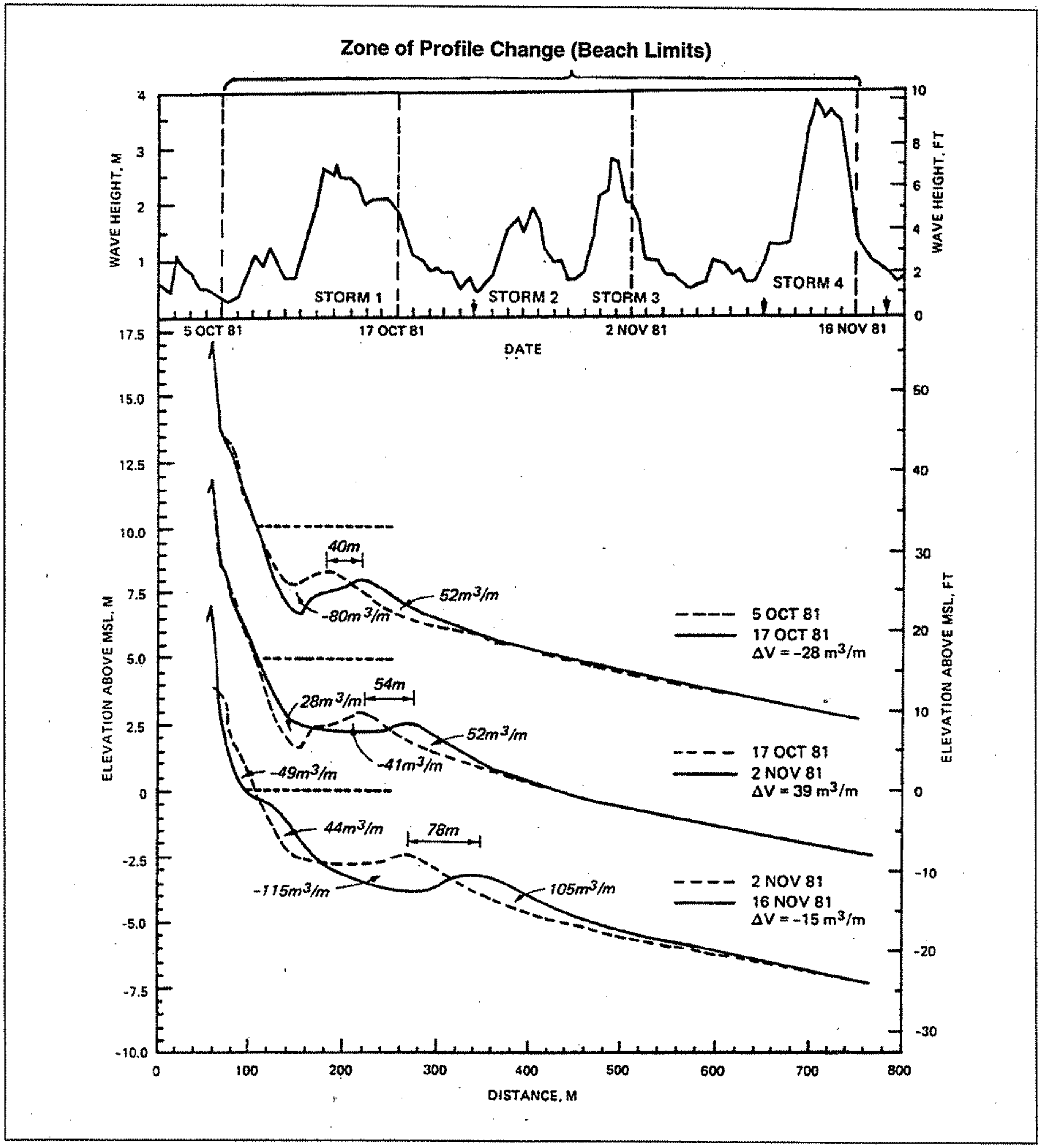


Figure 2-1
Beach Limits

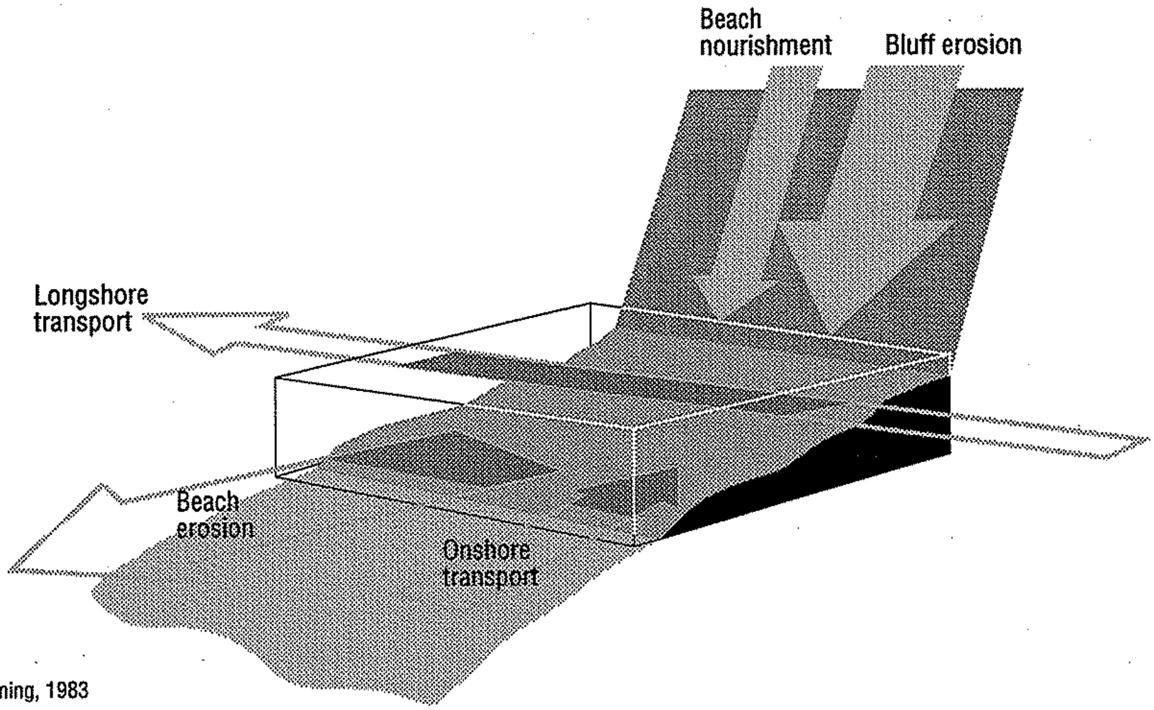
term they must be replaced by an equal volume of beach material or lowering of the beach results. Shore features undergo changes on all time scales, but year-to-year comparisons form the basis of claiming that a shore is eroding, stable, or accreting.

Hydraulic forces acting on a volume of sediment at the shore are the primary determinate of the character of the beach. Whether water flows horizontally or is accelerated by waves in the surf zone, it exerts a force at the (shore) boundary. If that boundary is composed of transportable particles, the flow has a capacity for sediment transport, determined by the magnitude of the forces and depth of flow. A volumetric quantity is implied. If there is excess sediment available for transport, then the actual sediment transport rate equals the potential transport rate. The magnitude of the force applied at the sediment surface determines the competence of the flow, which implies the upper limit of the particle size able to be transported. A standard formula for relating the longshore transport rate to wave parameters does not contain particle size explicitly (USACOE/SPM 1984, pp. 4-96). Most beaches for which there is a concern of shore retreat are outer (ocean) coast sandy beaches and the size range of beach material is so narrow that size is unnecessary for empirical formulas. Puget Sound beaches, however—typically derived from poorly sorted glacial till that contains cobbles, gravel, sand, and clay—include particles coarse enough that the competence of the transporting forces is often too low to transport the median particle size. For a given wave and flow condition, there is a theoretical capacity for each size class of sediment (i.e., cobbles, coarse sand, fine sand, sediment). At many Puget Sound locations, actual transport is less than the mathematical potential transport because of the limitation of availability. This leads to "starved" segments of the beach and removal of all the finer sediment sizes from the surface and near-surface of the substrate.

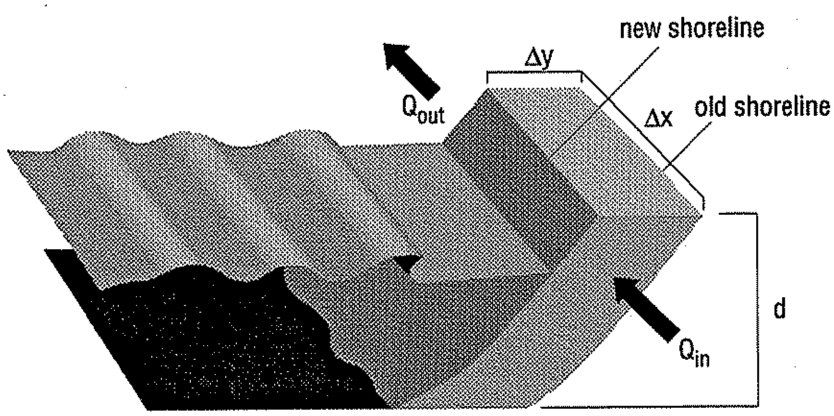
When a shoreline reach is in equilibrium, sediment is supplied to the reach at the same average rate it is transported out of the reach. The concept of "conservation of sediment" describes sediment erosion, transportation, and deposition. The concept is applied by way of establishing a control volume in which one accounts for the mass of sediment added and removed, as illustrated in Figure 2-2. The physics of sediment transport operate at the micro-scale. The aggregate of the micro-scale processes results in the macro-scale features: beach width, profile shape, and cross-shore and longshore distribution of particle sizes. The scale one uses is determined by how fine the resolution is needed for analyzing processes and morphology at a particular site. In simplified studies, the control volume in which sediment conservation is observed extends over large areas, for example from the greatest depth at which waves cause motion to dune or bluff crest and perhaps for a great distance in the alongshore direction. For examining more local effects of structures on the shore and on shore processes, it is necessary to consider much smaller areas in which sediment inflow and outflow are quantified.

Beach Profile and Shore Plan Form

Wave energy approaching shore drives currents that tend to move sediment both across the shore and along the shore. At times material is removed from the back shore and distributed in deep water, and irregularities in the shoreline are smoothed, or possibly



Source: Downing, 1983



Control Volume, $\Delta V = d \cdot \Delta x \cdot \Delta Y$

Change in sand volume ΔV produced by littoral drift into and out of shoreline cell results in shore line change, ΔY.

Source: Komar, 1973

Figure 2-2

Beach Control Volume for Analyzing Sediment Transport

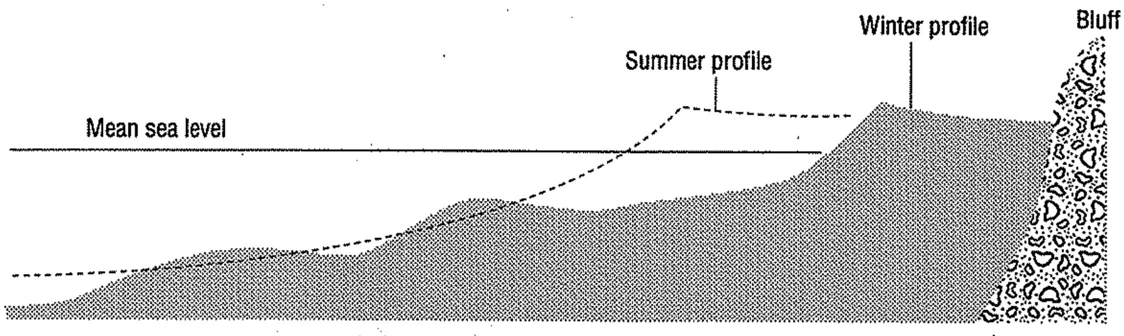
accentuated. In the shore environment a complicated balance in three dimensions is being approached at any instant involving the work that waves and currents do in modifying the sediment surface and the rate at which energy is expended as determined by the local bottom slope and orientation of the depth contours. In the following paragraphs, the processes acting to achieve this balance are described separately from the standpoint of general physics. Then processes having particular applicability to Puget Sound are discussed. This understanding will form the background for evaluating technical material relating to detailed impacts of shore protection on Puget Sound shores.

Cross-shore Processes. Waves propagating toward shore begin to transform when they encounter water depth that is about half the wave length. In this process wave length and speed decrease. One result is to turn the direction of wave propagation so that the wave crest tends to align more parallel with bottom contours (i.e., refraction).

Another result is to locally change the wave steepness (ratio of height to length). Wave steepness and length, in combination with bottom slope, determine the location in the profile where the wave breaks and the type of wave-breaking that occurs. Under conditions of long waves and low steepness, breaking waves move beach material up the profile and build the beach. Those waves are called constructive waves. Destructive waves, often associated with winter storms, alter the profile by moving material from the upper profile to deeper water. This results in a seasonal exchange of material across the beach profile. A balanced system provides material for the lower part of the profile by temporarily removing it from storage in the upper part. If the beach material cannot move laterally, the beach would be in dynamic equilibrium.

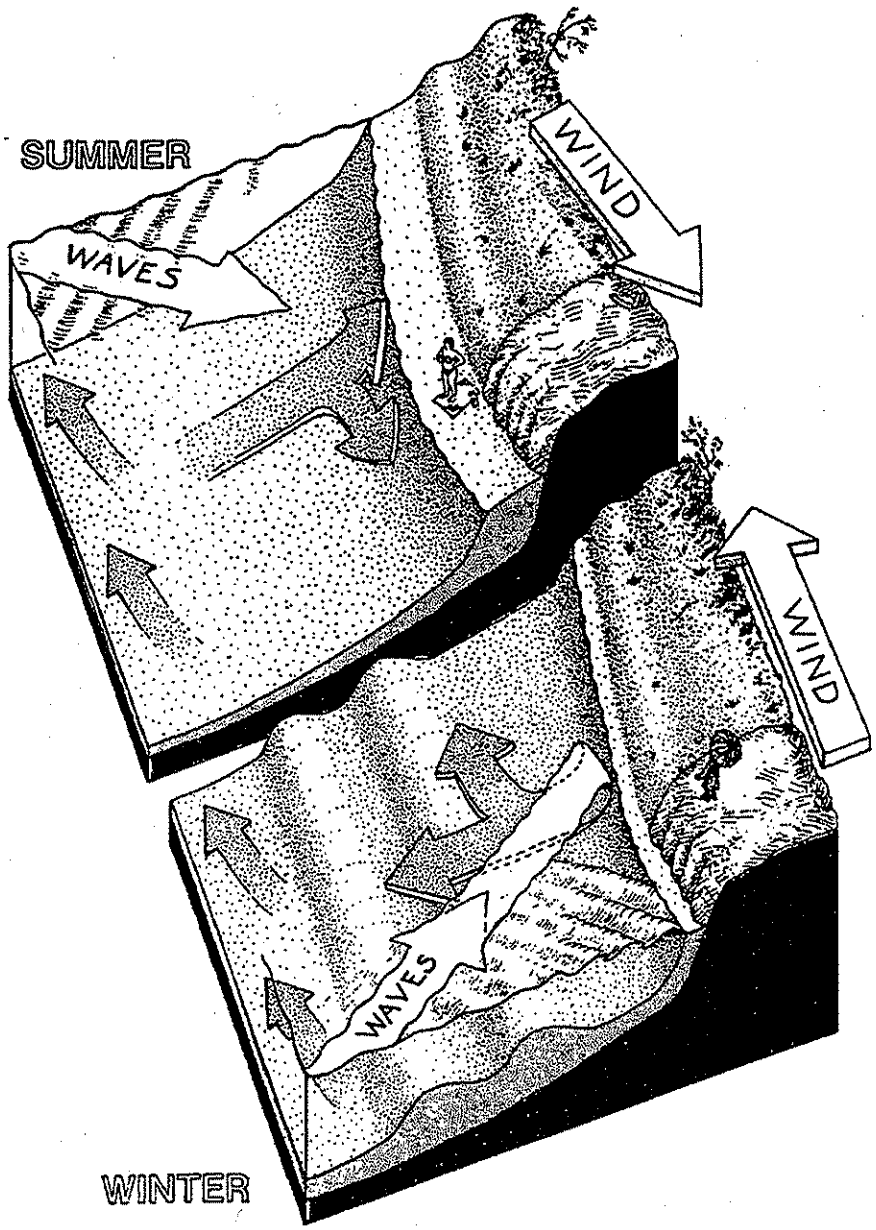
Larson (1988) describes how under steep waves—conditions usually associated with locally generated storms—beach material is removed from the upper profile and transported to deeper depths to create a breakpoint bar and steeper profile. This type of profile is referred to as the "winter profile" or "storm profile." During periods of lower wave steepness, the bar material migrates toward the shoreline and rebuilds the beach, producing the "summer profile" or "berm profile" (Figures 2-3 and 2-4). Most studies of beach profile dynamics were conducted on sandy beaches. Beaches containing a significant gravel fraction also exchange material across the profile, but the responses of the different sizes of shore material cause the shore morphology to be different from that of a purely sandy beach. Coarse material is found at the upper part of the winter profile. Gravel exposed there with sands found lower in the profile might result from the winnowing action of the surf and effects on swash asymmetry by percolation in coarse material. Removal of material from the dry part of the beach for temporary storage in the wet part of the profile does not constitute a net loss of beach material.

Percolation of swash into the beach material is important in determining the beach face slope and the inequality of transporting forces of the wave runup and runback. Beaches of coarse material (i.e., gravel) allow for more infiltration of water in the swash zone, and for a fuller part of the swash cycle, than do fine sandy beaches. This results in greater transporting forces directed landward than seaward in the case of gravel beaches. The slope



Source: Downing, 1983.

Figure 2-3
Seasonal Beach Profiles



Source: Suislaw Monitoring Report, Oregon Coast.

Figure 2-4

Seasonal Exchange of Beach Material Across Profile

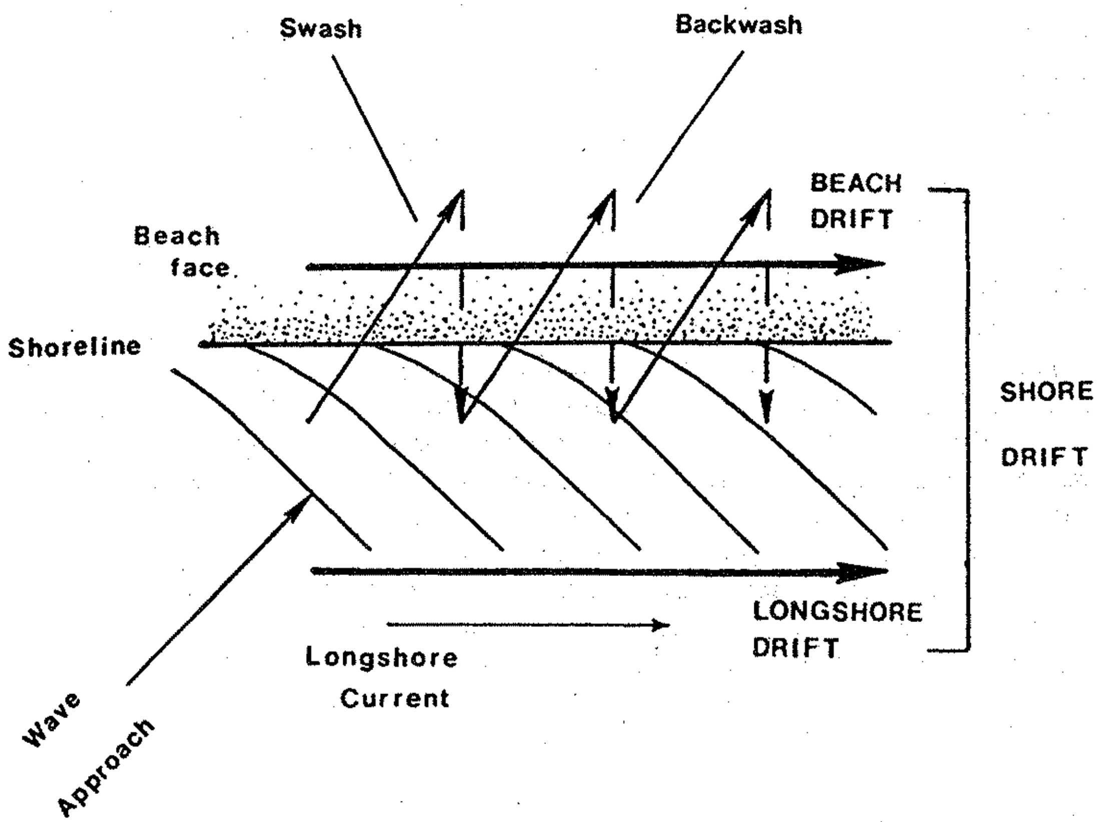
thus steepens until the forces balance with the downslope component of gravity. Fine sand beach material is easier to saturate than is coarse material. High water content of the beach material causes the transporting forces of wave uprush and downrush to be more equal, resulting in a flatter beach. Similarly, a high water table in the backbeach adds to the seaward flow through the beach and has the effect of increasing the transport of beach material during the downrush. This accelerates the formation of the winter profile in the presence of the type of waves that would produce that profile. Experimental evidence shows that the escape of groundwater seeping through the surface of the beach can be erosive and that accretive waves are required to maintain a tidal beach at an equilibrium slope (Sato, 1990). Obviously, any action that alters the water table of the beach, or the pore pressure in the beach material, affects the beach profile.

Longshore Processes. Waves rarely approach shore exactly perpendicularly. As a result, a longshore component of wave energy is applied in the surf zone. Two predominant variables for computing the potential longshore sand transport rate (Hanson and Kraus, 1989) are the breaking wave height and the angle formed between the breaking wave and the depth contour or local shoreline. Longshore transport rates vary across the surf zone (Bodge and Dean, 1987), the greatest amount of transport occurring just inshore of the (wave) break point. The longshore flow of water and sediment that occurs in this zone is called the littoral stream or shore-drift (Figure 2-5). The potential rate is variable in time and space, and the actual rate might not be as great as the potential. The sediment supply might limit the rate of introduction of sediment to the littoral stream. The littoral stream experiences a sediment deficit in that reach where its transport capacity is greater than the quantity being transported. In a sediment transporting flow, there is a continual exchange of particles between the flow and the sediment bed, even if it is not carrying material at capacity. If there is insufficient sediment already in the stream, littoral currents will attempt to erode available material, resulting in starvation of the reach and retreat of the shoreline.

Wave Diffraction and Refraction

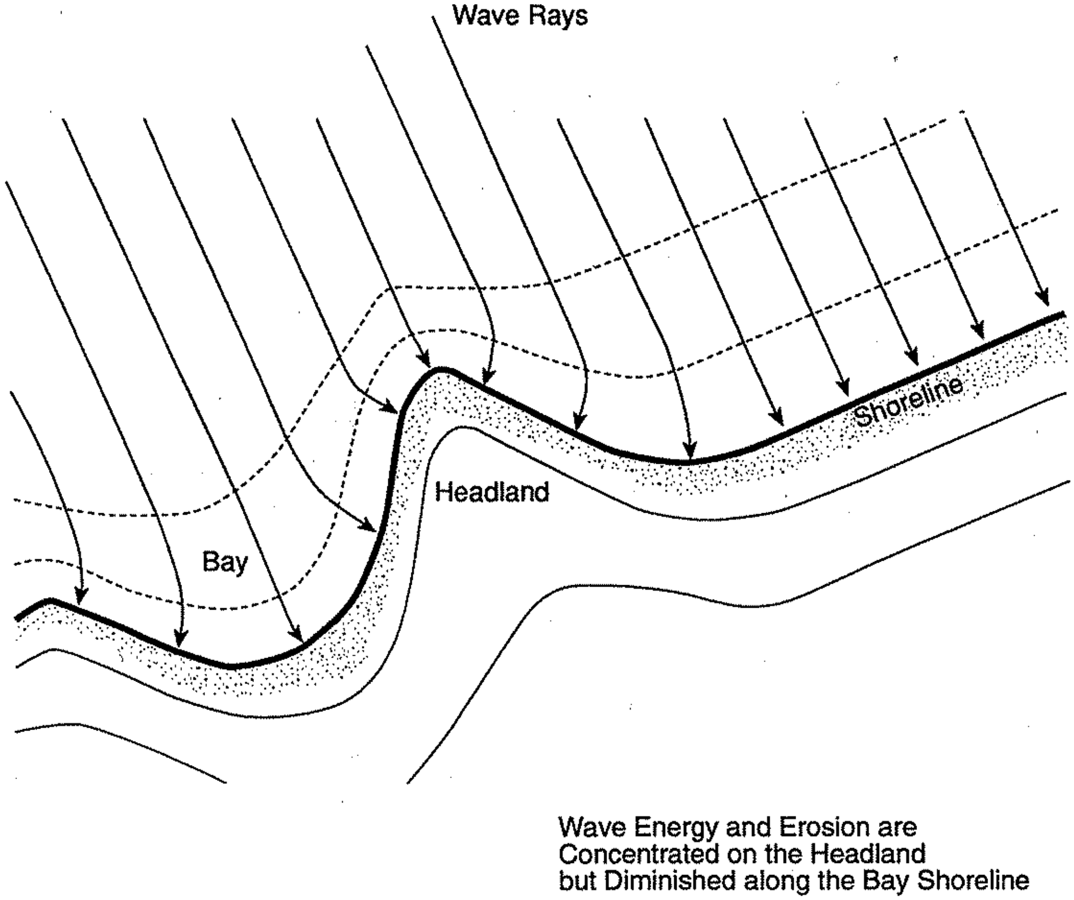
Bathymetry affects waves by changing the direction at which they arrive at the shore (i.e., wave refraction). Because headlands protrude beyond embayments into the surf zone, the bottom contours refract waves in a way to concentrate wave energy, and thus erosive forces, on the shore at the headland. Moving downcoast from a headland, the wave height and wave angle yield lower potential transport rates than at the headland. Figure 2-6 illustrates this variation in wave energy applied along an irregular shoreline. It is this attempt to "even out" the energy dissipation alongshore that makes headland bluffs—or areas made into headlands by structural modifications—areas of accelerated erosion.

Diffraction of waves occurs when unbroken waves pass the ends or corners of shore structures. A distinctive pattern of wave propagation direction and wave heights is created in the vicinity of the diffracting end or corner (Figure 2-7). The result is sheltering in the immediate vicinity of the structure (i.e., a shadow zone). It is common to find debris



Source: Harp, 1983

Figure 2-5
Shore Drift Produced by Wave and Current Action When Waves Approach Shore at an Angle



Source: Downing 1983.

Figure 2-6

Wave Refraction

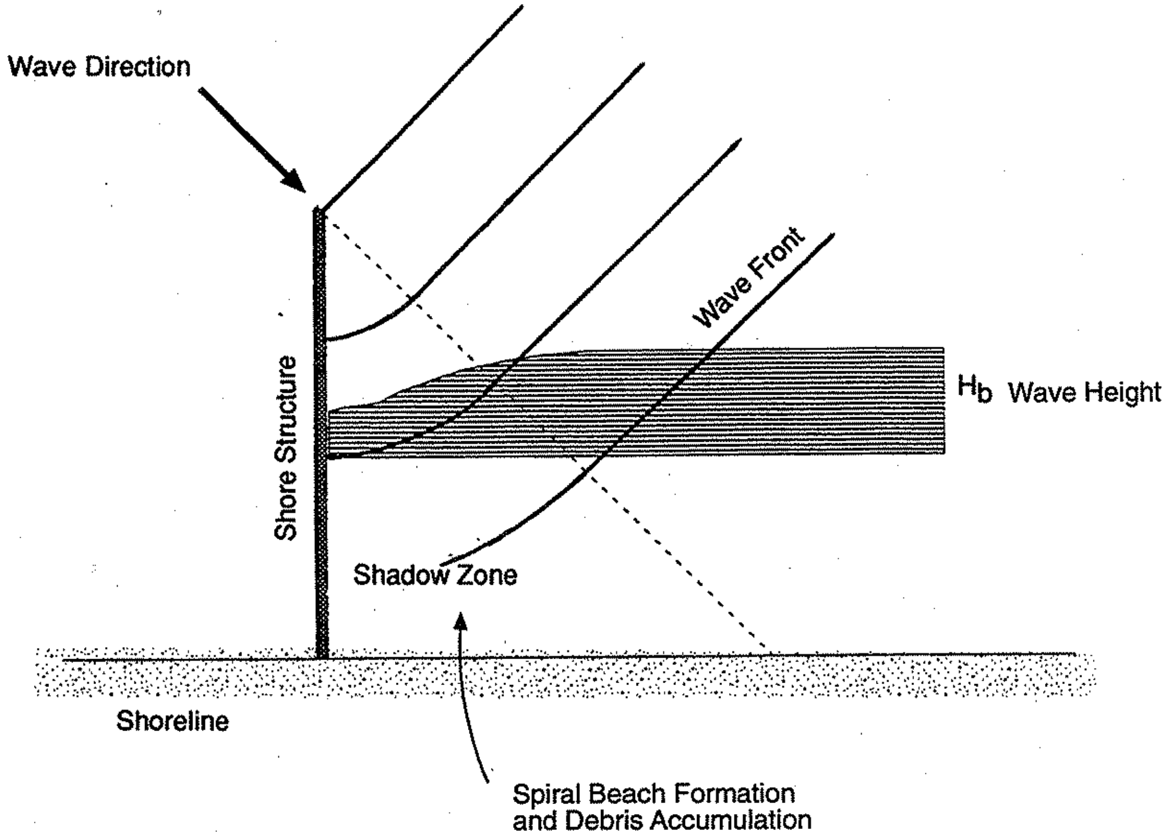


Figure 2-7

Wave Diffraction

accumulation adjacent to, and on the downdrift side of, diffracting structures due to this sheltering effect. This process is also responsible for the formation of spiral beaches—small crescent-shaped beaches created within the shadow zone.

Shore structures reflect waves according to the smoothness and slope of the reflecting surface and the water depth in which the structure is located. The highest reflectivity is achieved with a smooth vertical wall with a submerged toe. Standing waves tend to form in front of such reflecting surfaces, through the superposition of incoming and reflected waves. There is some evidence that the equilibrium depth of scour below the substrate level in front of a vertical wall is approximately equal to the height of the incident wave (Smith and Chapman, 1982). When a wall is located in deeper water, the wave is dissipated less before reaching the structure. Therefore, a greater amount of the initial wave energy is available for driving processes that could modify the shore. Sloped walls, such as rubble revetments, also reflect wave energy, although to a lesser degree than vertical walls do.

Natural beaches can also reflect wave energy. Reflective beach profiles (as opposed to dissipative profiles that absorb wave energy rather than reflect it) have steep beach faces with surging breakers, bedload transport (i.e., sediment rolled along the seabed), and an absence of nearshore bars and rip currents (Mossa, Meisburger, and Morang, 1992). The dominant direction of transport is alongshore, not cross-shore. A beach having an abundance of sand size material can adjust to varying energy states of the surf zone by changing from a dissipative beach to a reflective beach (Nordstrom, 1992). Where beach material is predominantly large, as in much of Puget Sound, the equilibrium condition is the reflective beach. Through time the shoreline has become adjusted to the particular wave reflection and dissipative characteristics of the profiles. Placing structures at the shore might increase reflectivity and cause an adjustment in the system.

The initial reflectivity of typical Puget Sound beaches is greater than the sandy beaches on which most seawall interaction studies have been performed. Therefore conclusions, particularly any quantitative measures, derived from those sandy beach studies are subject to modification before they can confidently be applied in Puget Sound.

Mutual Adjustment of Shore Features and Energy Dissipation Processes

Wave forces are dissipated to zero at the limit of uprush on a sloped surface. Kinetic energy in the water wave is dissipated through generation of heat and transport of solid particles at the boundary and in the water column. Some of the wave energy is reflected from the boundary on which it impinges. Where that sloped surface is made of mobile particles, the magnitude and rate of energy dissipation and the stability of the particles cause a particular geometric form to develop, both in profile and in planform. The boundary form controls, by way of water depth, the rate of energy dissipation and exertion of wave and current forces against the boundary. Where input conditions are relatively steady with respect to the response time of the changing boundary geometry, an approximate equilibrium is established between beach profile shape, sediment transport rates, and wave energy dissipation rates.

Wave-driven and tidally driven currents provide the hydrodynamic forces for transporting individual particles that make up the shoreface and nearshore zone. These currents include longshore currents as well as the runup bore and runback sheet flow of the swash zone. Increased reflectivity of the boundary increases turbulence and wave interference (superposition) in the surf zone, which are thought to alter the intensity and pattern of transport of shore material (U. S. Corps of Engineers, 1981). Beaches are degraded through the net removal of particles transported by hydrodynamic forces. Where the transporting force exceeds a particle's resisting force, that particle is moved, then falls toward the boundary when the transporting force is insufficient to maintain its motion. Sedimentary particles are in motion throughout the coastal zone, with deposition and erosion occurring nearly simultaneously. The summation of particles that are removed or are added to the beach constitute the change in shoreline position and profile shape, which then adjust the beach reflectivity.

Sediment transport mechanisms are strongly dependent on grain size. Sediment cohesion can cause fine-grained silts (<0.1 mm grain diameter) and clays to be resistant to erosion, but once in suspension they are rapidly mixed in the water column and can be carried long distances. Fine sands (0.1 to 0.5 mm grain diameter) are easier to erode and move through a combination of both suspended load and bedload. Coarse sands (0.5 to 2.0 mm grain diameter) and gravels mostly roll or "skip" (saltate) along the bottom as bedload, for they require much greater hydraulic forces for suspension and transport.

A convenient way of viewing the flux of sediment is to apply the principle of conservation of sediment to a control volume. Within a control volume, thought of as fixed in space, when more material enters than leaves, the quantity in storage increases and is expressed physically as an increase in boundary elevation and accretion (shallower depths and progradation of the shoreline). This change in boundary configuration is not accomplished without affecting energy dissipation rates and sedimentary stability of particles adjacent to this specific control volume. When changes in wave forces, water level, sediment supply, or sediment character are imposed on the system, the effects are propagated throughout the beach and surfzone, through the mutual feedback of energy dissipation rate, transport rate, and boundary form. Given time, the entire profile is remolded to a new equilibrium condition.

Episodic Processes

In studying beach processes, one must be aware of the integral role of adjacent bluffs in supplying beach material (Figure 2-8). Likewise, bluff recession is tied to beach characteristics. A bluff contributes material by episodic and localized collapse. The material thus liberated is reworked and sorted for a long time afterwards. Sometimes only a relatively small fraction of the total volume removed from a bluff face is of a grain size suitable

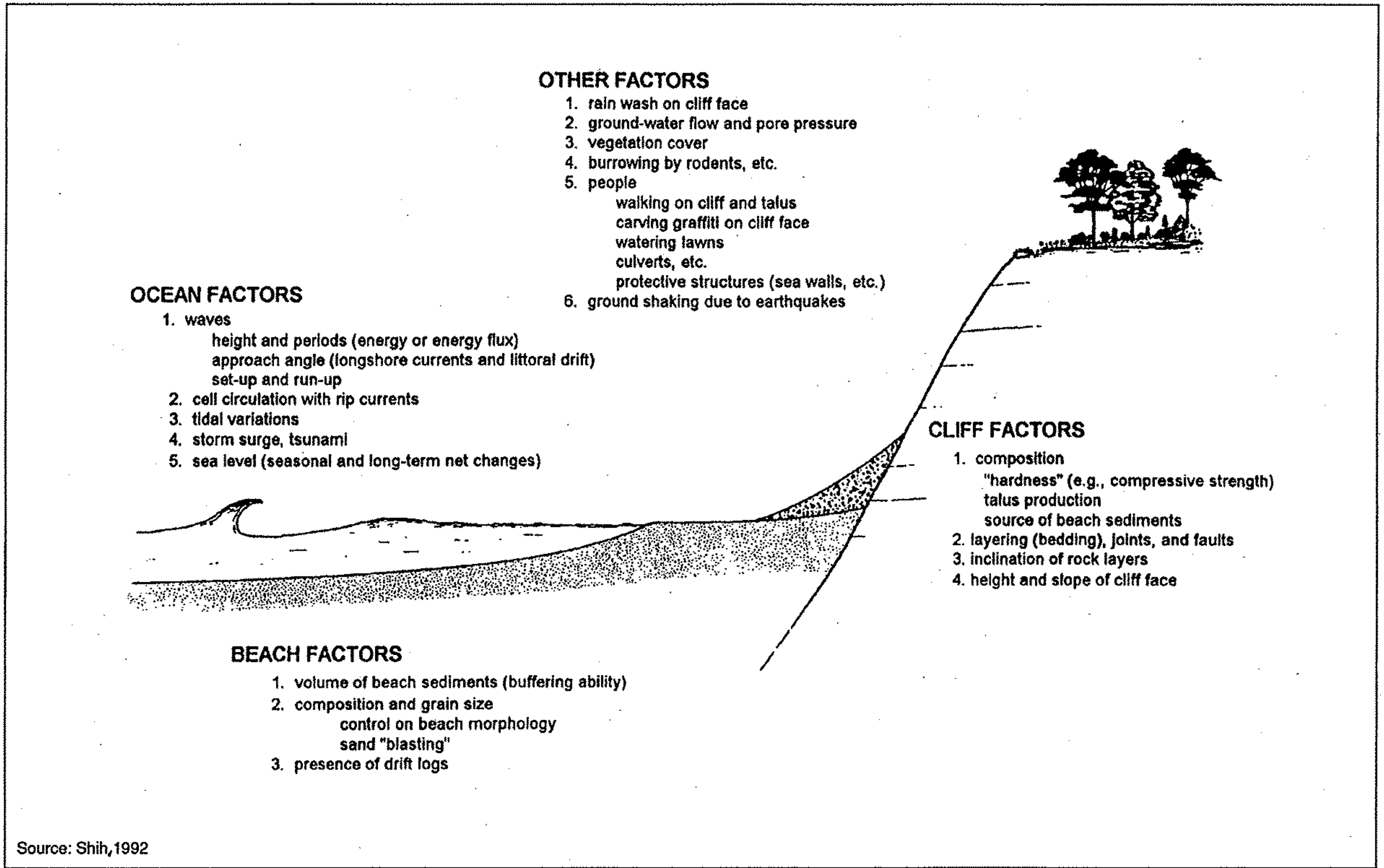


Figure 2-8
Factors Involved in Sea Cliff Erosion

to become mobile beach material. If present, very large size material (boulders, cobbles) remains at the toe of the bluff and eventually scouring occurs around it. Much of the typical glacially derived Puget Sound bluff material is disaggregated into fine particles and lost to deep water by waves and currents. Significant bluff slumping is required to satisfy the shore's natural demand for littoral material. Where bluff material feeds an active littoral stream, the equilibrium condition is one of retreating bluff, retreating shoreline, and constant beach width.

Drift Sector Concept[1]

Sediment processes around Puget Sound can be spatially segregated into hundreds of distinct drift sectors (drift or littoral cells). Headlands frequently delineate longshore zones or sectors in which littoral processes and materials are isolated from other sectors. Material moving in the littoral stream is called drift or shore-drift. The longshore transport rate is often referred to as the drift rate (see Fact Sheet). The sector between headlands in which the drift is isolated from adjacent locations is the drift sector (Figures 2-9 and 2-10). A drift sector can be divided into three longshore areas: a feed or source area that supplies material to the downdrift, a driftway or transport area where there is minimal net loss or gain of material, and an accretion terminal or sink area where the drift material is deposited (see Fact Sheet). The boundaries between source, driftway, and sink can shift locations within a drift sector with changing sediment source conditions, changing water levels, and changing wave height and direction.

Large Organic Debris

Large Organic Debris (LOD)—drift trees, "snags," stumps, driftwood, and all manner of woody debris—is a distinctive and significant feature of Pacific Northwest river systems, coastlines, and beaches. Early visitors to the Northwest describe great quantities of LOD in estuaries and river mouths, as well as on the beaches of Puget Sound and the outer coast (Maser et al., 1988; see Fact Sheet).

In quiescent periods, LOD can act like a berm or breakwater, slowing wave or current action and enhancing the accumulation of beach sediments. Piles of drift logs lying at the foot of a bank or bluff can also provide natural "toe protection," thus slowing erosion. Under high tide and storm wave conditions, however, large drift logs may float free and act as battering rams that can greatly increase local erosion and inflict serious property damage.

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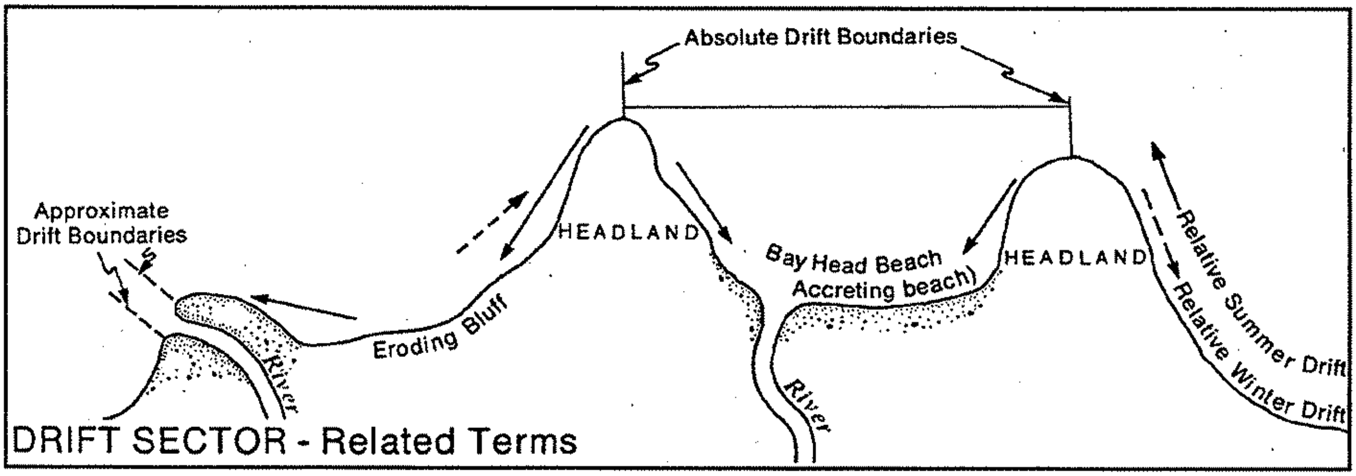
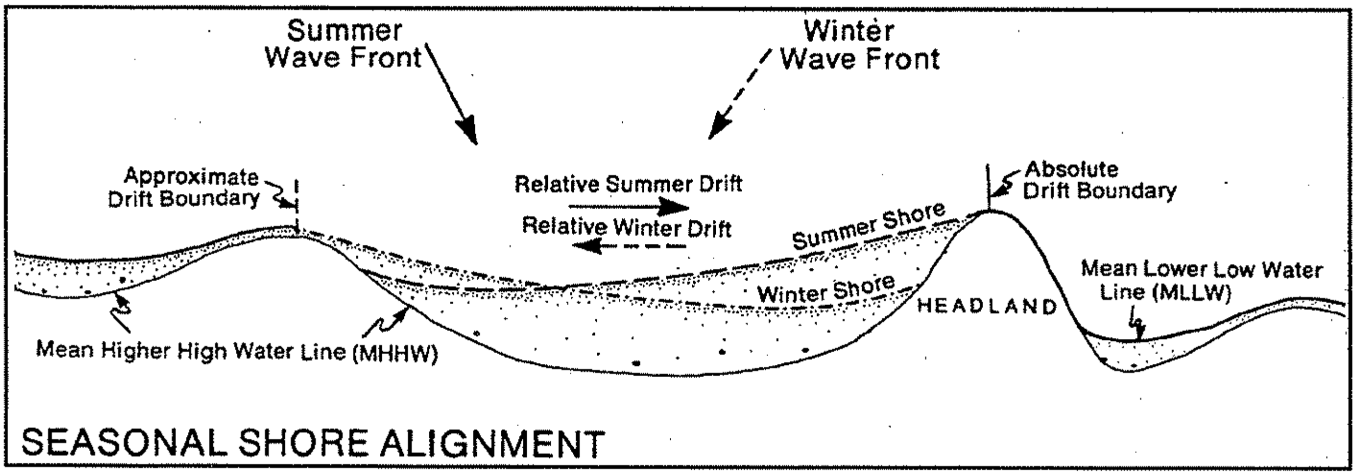
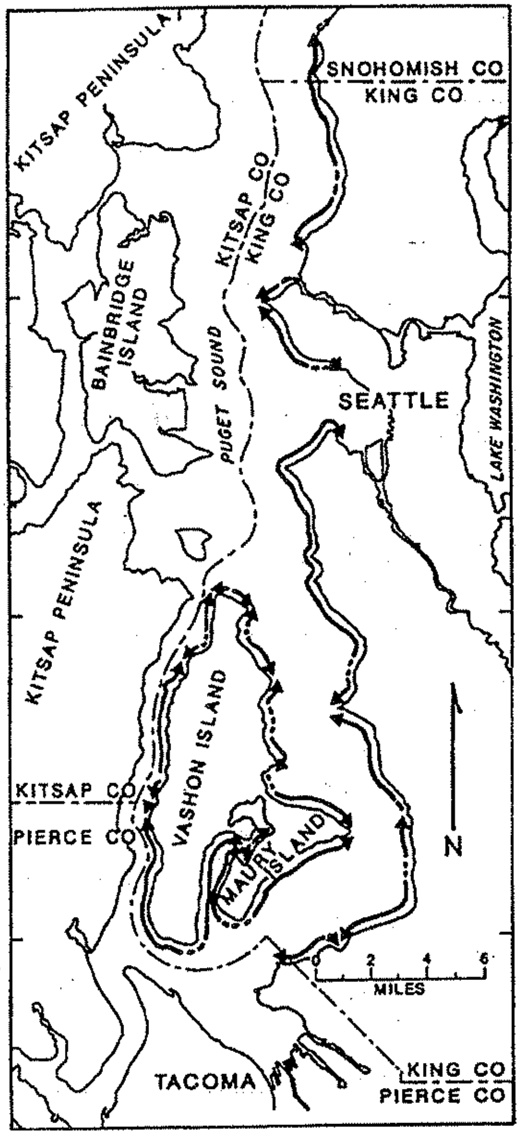
[1]The best information on drift sectors around Puget Sound is contained in a series of Department of Ecology research reports titled Net Shore-drift in Washington State, Version 2.0 (June 1991). These reports are based on master's theses completed under the guidance of Professor Maurice Schwartz, Department of Geology, Western Washington University, Bellingham, Washington. Ecology no longer recommends use of drift sector information in the earlier Coastal Zone Atlas (1977-80) series (Douglas Canning, Ecology, March 1993).





Source: Coastal Zone Atlas of Washington, 1977-1980.

Figure 2-9
Drift Sectors



Legend
Drift Sector

Net shore-drift is the direction in which the majority of sediment moves over a long period of time.

Source: Schwartz, Wallace and Jacobsen, 1989.

Figure 2-10
King County Shoreline
Drift Sectors and Net Shore Drift

Accretion beaches

Puget Sound contains a wide variety of barrier beaches including cuspate forelands (points), tombolos, spits, and bay barriers (Downing, 1983). The term "accretion beach" has been used widely in Washington to describe these features. These landforms range from a few hundred meters in size to several kilometers. Most, but not all, have associated marshes, lagoons, or ponds to the landward. The spits and accretional beaches of Puget Sound share many characteristics with barriers in Chesapeake Bay, on the New England coast, and in the Great Lakes.

Barrier beaches within Puget Sound are built from sediment moved by longshore currents. The abundance of small barrier beaches in Puget Sound is a result of a highly convoluted shoreline and an abundant supply of sand and gravel in adjacent eroding bluffs.

Spits and barrier beaches within Puget Sound are subject to flooding and wave damage during major storms. The berm may be overwashed during periods of high waves and tides. Rafted debris can cause serious damage to houses and seawalls. Developed barriers are vulnerable to storms that cause localized or short-term erosion and which often undermine bulkheads and homes. In addition, long-term erosion may occur in response to reductions in sediment supply from updrift areas (Shipman and Canning, 1993).

Many of the barriers in the Puget Lowland have been developed intensively for both industrial purposes and, more commonly, as residential subdivisions. Most of this development occurred prior to the environmental legislation of the early 1970s and, in particular, the state's Shoreline Management Act (1971). Development of these sites has resulted in extensive filling of wetlands, armoring of shoreline, and dredging of channels.

Barrier sites are also among the most valuable public shoreline in Puget Sound, and many are parks or wildlife refuges. Low bank shoreline is relatively uncommon within Puget Sound, and these locations provide excellent shoreline access for recreation, boat launching, and shellfish harvesting.

The barrier beaches of Puget Sound shelter many small salt marshes, freshwater ponds, and lagoons. They are associated with many small stream mouths. These small estuarine environments within Puget Sound are extremely productive areas. Barriers represent a large part of the low bank shoreline in the Sound, excepting the large, heavily modified river deltas. The sites provide feeding sites for wading birds, shorebirds, and raptors and provide protected shallow water fish habitat.

–Hugh Shipman (1993)

In addition to these roles as shoreline "structural elements," LOD adds important elements of habitat/substrate diversity and habitat complexity to Northwest estuarine and coastal ecosystems.

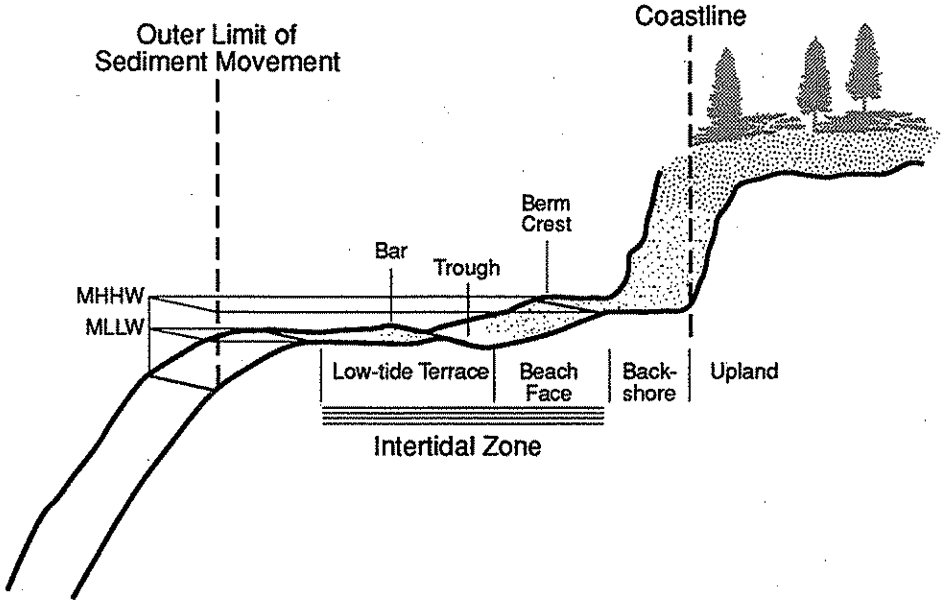
Application to Puget Sound

Ninety to 95 percent of the world's beach sediment is delivered to the coast by rivers (Komar, 1976, p. 235), but Puget Sound beaches are supplied predominantly by erosional products of local bluffs (Downing, 1983, p. 54; Shipman and Canning, 1993). The source material of most Puget Sound beaches is poorly sorted glacial sediments. As a consequence, beach material can be made of mostly sand in some locations and mostly gravel in others. Generally, Puget Sound beach material is characterized by coarse size and poor sorting, i.e., a wide range of sediment sizes mixed together. The porosity and hydrodynamic properties of these sediments produce distinctive beach forms.

The morphology of much of Puget Sound's shoreline is that of a narrow beach fronting steep shore bluffs (Terich, 1987, p. 17). This morphology is illustrated in Figure 2-11. The high tide beach has a steep face and is composed of coarse sediment. The usual slope measured in Skagit County ranged from 4° to 9° (Keuler, 1979, p. 17). Coarse material added to the beach at West Point in King County formed into a foreshore having a 7° to 9° slope and an upslope winter berm having a slope of 14° to 16° (Domenowske, 1987). The low tide terrace is at the foot of the high tide beach and forms an abrupt change in slope at and above the mean lower low water elevation. The low tide terrace lies at a flatter slope than the high tide beach and consists of poorly sorted fine-grained sediments. This morphology is not common on a worldwide basis and can be attributed to the following causes (Keuler, 1979, p. 13):

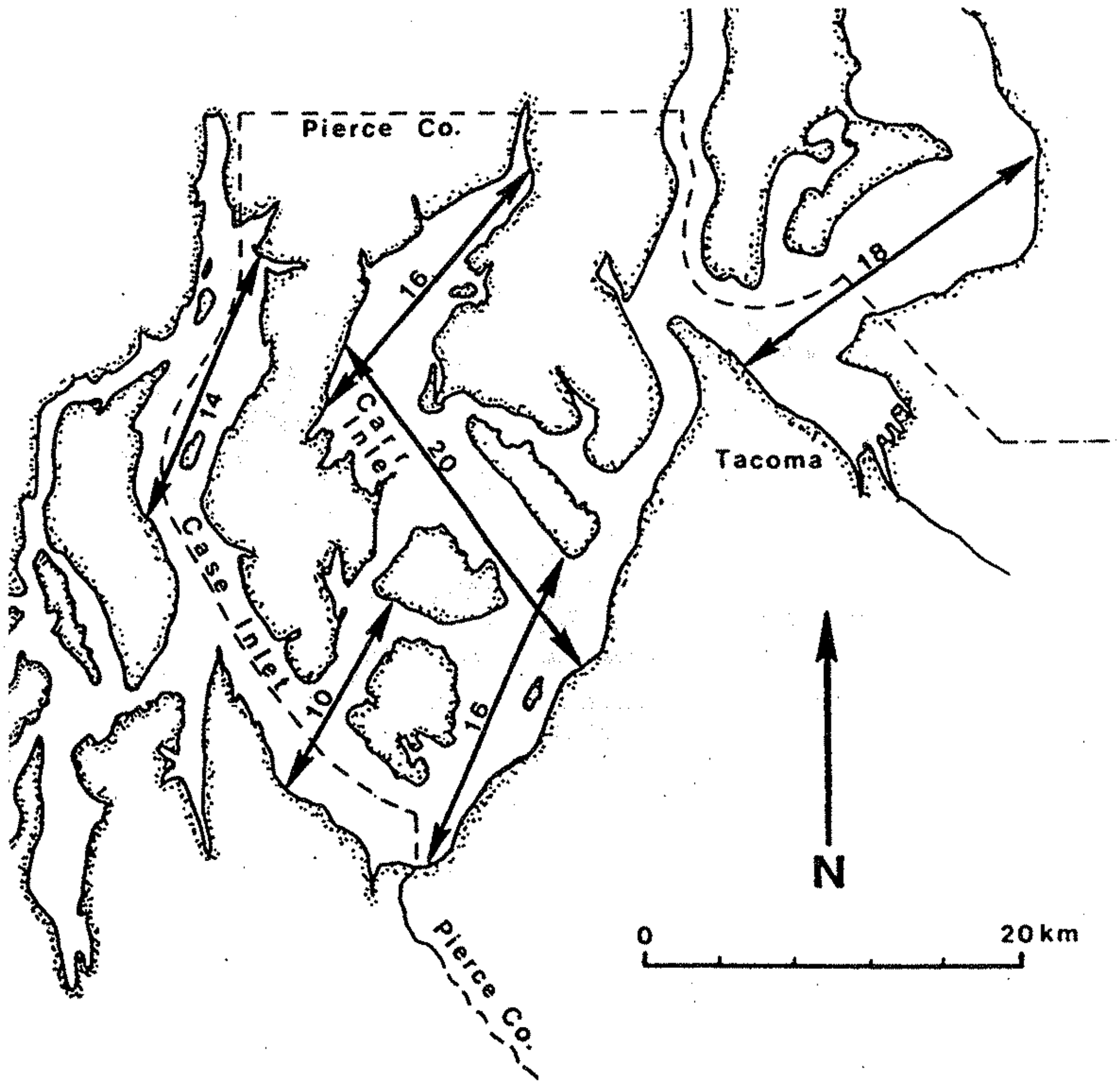
- A large tide range relative to the predominant wave height. (This is probably the primary control of beach morphology.)
- The differing responses of gravel and sand to short-period storm waves. Gravel is piled up on ridges, while sand is withdrawn to the lower foreshore or nearshore bottom.
- The low tide terrace develops by deposition of fine-grained sediments from longshore transport of suspended sediments supplied by cliff erosion or nearby streams.
- Possible cause is a limited supply of coarse material.

The predominant wind direction in Puget Sound is from the southwest to the northeast. However, since many of Puget Sound's deep, narrow channels trend north and south, most of the shoreline, particularly in the central and southern parts, is not directly exposed to long fetches (Figure 2-12). The direction of wave approach, availability of sediment, and the fetch length are the most important factors influencing sediment transport rates in Puget



Source: Redrawn after Dowing, 1983

Figure 2-11
Typical Puget Sound Shoreline Features



Source: Harp, 1983

Figure 2-12
Selected Fetch Distances, Pierce County Coast

Sound and Strait of Juan de Fuca. From their study of net shore-drift rates in Puget Sound and Strait of Juan de Fuca, Wallace and Schwartz (1987) determined that 27 percent of the drift sectors had net shore-drift rates of less than 100 cubic meters per year, 31 percent had rates between 100 and 1,000 cubic meters per year, 38 percent had rates between 1,000 and 10,000 cubic meters per year, and just 4 percent had net drift rates greater than 10,000 cubic meters per year. Drift rates were quantified by a combination of measuring sediment accumulation at obstructions that form total barriers, measuring spit growth from aerial photographs, and by analyzing dredging volumes where applicable (Schwartz, Wallace, and Jacobsen, 1989, see Fact Sheet). By comparison with drift rates measured from sandy beaches on open ocean coasts (100,000 to 300,000 cubic meters per year) or even Great Lakes beaches (30,000 to 60,000 cubic meters per year; USACOE/SPM, 1984, pp. 4-91), Puget Sound beaches clearly exhibit very low drift rates.

Wallace and Schwartz (1987) note that net shore-drift rates are generally lower in southern Puget Sound than in the northern Sound, the Strait of Juan de Fuca, or Georgia Strait. They concluded that development in the South Sound is less likely to cause a major interruption of sediment transport—and, by implication, would have less impact—than comparable development farther north. This is not necessarily correct, however, for impacts are more likely to reflect the <u>proportion</u> of sediment transport interrupted, rather than differences in the <u>absolute</u> volume of sediment transport.

These factors emphasize the difference between the Puget Sound shore environment and the typical fine sandy beaches usually chosen to study the effects of coastal structures on shore processes and morphology. Keuler (1979, p. 28) asserts that Puget Sound's accreted beaches are the product of longshore transport, and that because the coarsest material (larger than 64 mm in diameter) represents less than 5 percent of the accreting volume, the occurrence of transport is very infrequent. High tides and high waves control the timing of erosion and transport. By considering the distribution of occurrences of tides higher than Mean High Water and the pattern of storm waves, it is likely that most shore erosion in Puget Sound occurs during a few days per year between November and January.

Deep water near shore allows wave energy to impact the shores and bluffs of Puget Sound. Steep beaches are associated with coarse particle sizes. The fraction of total bluff source material with grain sizes appropriate for beach deposits is small, however, requiring erosion and disaggregation of larger volumes of bluff material than are indicated by the transport rates reported by Wallace and Schwartz (1987). The overall bluff retreat rate, however, is not high (Keuler, 1988).

Most bluff failures in Puget Sound occur during the rainy November to March period (Tubbs, 1975; Downing, 1983, p. 77). Failure mechanisms are tied to saturation of the soil mass by precipitation and loss of ballast at the toe of the slope. Where the toe is exposed to the water surface in Puget Sound, the bluff is most vulnerable to undercutting by wave erosion. A bluff composed of porous material overlying an impermeable clay layer is most vulnerable to collapse after long periods of heavy rains, even without exposure to waves. Still, a <u>combination</u> of conditions is usually present when a bluff collapses

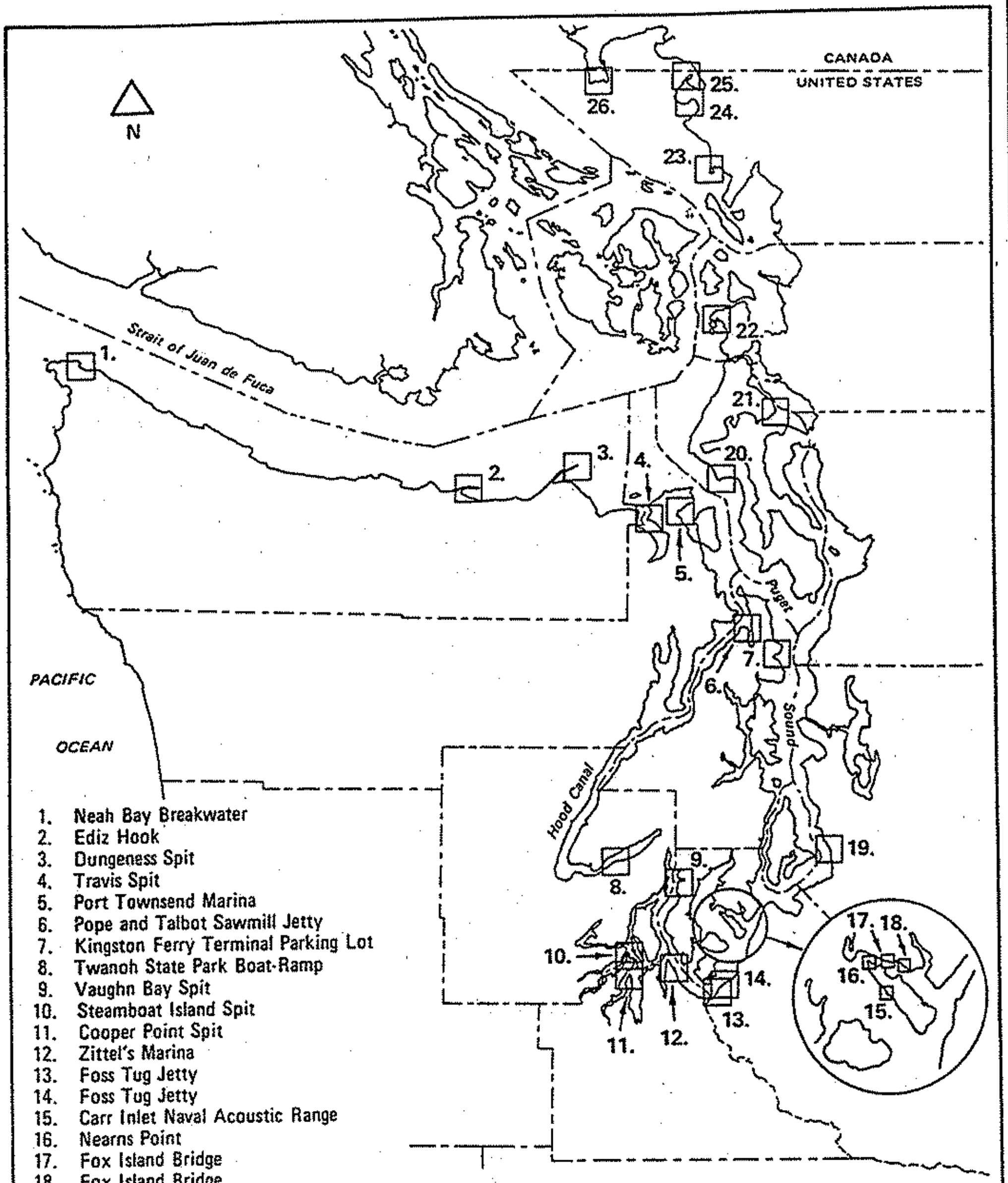
Net Shore-Drift Rates

Fetch Distance

Schou (1952) found that in protected coastal areas, the direction of net shore-drift is most often determined by the direction of maximum fetch. The waterways of southern Puget Sound are oriented in a general southwest-northeast trend. However, the coastline of the southern region is very irregular, with many headlands, coves, bays, and islands. Fetch distances and directions are varied because of these irregularities.

Fetch distances observed in the southern region of Puget Sound were, with the exception of the Des Moines City Marina, all less than 10 km. The mean annual net shore-drift rate for sites #8-18 is 400 cu m/yr.

Puget Sound Central waterways are generally oriented east-west. The main body of water is the Strait of Juan de Fuca, through which wind and waves approach from the west. Drift rates at Ediz Hook and Dungeness Spit, 9,000 and 14,000 cu m/yr, respectively, represent the largest rates in the study area. Both sites are within drift cells having fetch distances in excess of 50 km, among the largest in the Puget Sound area.



1. Neah Bay Breakwater
2. Ediz Hook
3. Dungeness Spit
4. Travis Spit
5. Port Townsend Marina
6. Pope and Talbot Sawmill Jetty
7. Kingston Ferry Terminal Parking Lot
8. Twanoh State Park Boat-Ramp
9. Vaughn Bay Spit
10. Steamboat Island Spit
11. Cooper Point Spit
12. Zittel's Marina
13. Foss Tug Jetty
14. Foss Tug Jetty
15. Carr Inlet Naval Acoustic Range
16. Nearns Point
17. Fox Island Bridge
18. Fox Island Bridge
19. Des Moines City Marina
20. Keystone Harbor
21. Mariner's Cove
22. Skyline Marina
23. Sandy Point Spit
24. Birch Bay Village Marina
25. Semiahmoo Spit
26. Point Roberts Marina

Study Sites of Net Shore-Drift Rates

The east-central region includes six sites (#5-7, 20-22) located east of the Strait of Juan de Fuca. Four have fetch distances in excess of 12.5 km. The mean annual net shore-drift rate for this region is 1,500 cu m/yr.

Four sites (#23-26) in the northern region all have fetch distances greater than 40 km. Consistent with relatively long fetches, these sites have a relatively large mean annual net shore-drift rate of 3,500 cu m/yr.

No.	Site (county)	Waves[a]	Fetch[b]	Cell[c]	Rate[d]
1	Neah Bay Breakwater, Clallam	E	4.0	4.0	860
2	Ediz Hook, Clallam	W	51.5	11.8	9,170
3	Dungeness Spit, Clallam	W	Unlimited	26.0	14,200
4	Travis Spit, Clallam	NE	30.0	5.6	2,182
5	Pt Townsend Marina, Jefferson	SE	8.6	6.0	1,190
6	Pope & Talbot Mill, Kitsap	SW	8.0	26.0	77
7	Kingston Ferry Terminal, Kitsap	SE	12.5	1.2	2,082
8	Twanoh Pk Boat Ramp, Mason	SW	6.9	8.1	215
9	Vaughn Bay Spit, Pierce	S	8.6	3.9	2,013
10	Steamboat Island Spit, Thurston	SW	5.4	4.0	328
11	Cooper Point Spit, Thurston	S	10.0	7.7	808
12	Zittel's Marina, Thurston	N	4.8	0.5	95
13	South Foss Tug Jetty, Pierce	S	1.5	0.6	81
14	North Foss Tug Jetty, Pierce	S	1.5	0.3	95
15	Carr Inlet Naval Range, Pierce	SW	6.4	2.8	634
16	Nearns Point Spit, Pierce	SW	6.4	0.7	93
17	NW Fox Island Bridge, Pierce	SW	7.6	1.5	30
18	SE Fox Island Bridge, Pierce	SE	7.6	2.7	40
19	Des Moines City Marina, King	SW	17.7	2.9	4,912
20	Keystone Harbor, Island	SW	13.7	9.6	4,550
21	Mariner's Cove, Island	SW	14.3	1.5	213
22	Skyline Marina, Skagit	SW	48.3	10.0	830
23	Sandy Point Spit, Whatcom	NW	145.0	13.3	2,115
24	Birch Bay Marina, Whatcom	W	40.0	2.9	600
25	Semiahmoo Spit, Whatcom	W	40.0	6.5	8,210
26	Pt. Roberts Marina	SE	48.0	3.3	3,552

[a]Compass direction of predominate wave approach. [b]Effective fetch distance, km. [c]Drift cell length, km. [d]Net shore-drift rate, m^3/year.

Regression analysis supports the fetch distance-rate relation. If there is no relation between fetch distance and drift rate, computation using regression equations of a critical value (r), with a confidence level of 95 percent, should have a value of 0.33 or less. Data on fetch distance was used to arrive at a value for (r). The critical (r) value was 0.69; thus the null hypothesis was rejected and an increase fetch distance-increase drift-rate relation was inferred.

Drift Cell Length

Drift cells ranged in length from 0.3 to 26.0 km. Four groups were delineated, based on drift cell length. Of the 26 sites, seven were within drift cells of 2 km or less. The mean drift rate in cells of this length was 400 cu m/yr. Within drift cells 2 to 4 km long, there were eight sites, these had a mean drift rate of 1,500 cu m/yr. Seven sites were within drift cells 4 to 10 km long, and the mean rate for these sites was 3,000 cu m/yr. In drift cells exceeding 10 km there were four sites; these show a mean drift rate of 6,000 cu m/yr. These data support the trend of increased drift rates associated with increased drift cell length.

Data on cell length was also analyzed using regression. If the null hypothesis is assumed to be correct (no relation between cell length and drift rate) the critical value (r) should once gain be less than 0.33, to be within a 95 percent confidence interval for the data set. Analysis yielded an (r) value of 0.53. Although not as high as the critical value for fetch distance, this, nonetheless, appears to indicate that there is a relation between the length of a drift cell and the rate of net shore-drift.

Relatively large segments of undefended coastline, under the combined influence of westerly waves, large fetch distances, and relatively long drift cells, exhibit transport of the largest volumes of sediment recorded in this study--eastward, along the south coast of the Strait of Juan de Fuca (west-central region). Northern Puget Sound exhibits the second highest mean annual transport volume. This is due in part to fetch distances in excess of 40 km, combined with predominant, northwesterly wind and waves entering northern Puget Sound through the Strait of Georgia. The east-central region is not directly subjected to westerly waves like those sites along the south coast of the Strait of Juan de Fuca. However, the mean fetch distance for sites in this area is 17.6 km, and the overall drift rates are an order of magnitude greater than those in southern Puget Sound. Southern Puget Sound, with waterways oriented along a southwest-northeast trend, is affected primarily by southerly waves and relatively small fetches to the south, southwest, and southeast. Smaller volumes of sediment are transported in southern Puget Sound due mainly to limited fetch exposures arising from the many islands, bays, and headlands in the region.

Source:
Schwartz and Wallace (1986) and
Schwartz, Wallace and Jacobsen (1989)

onto a beach: rain storm, high tide, high waves, and removal of fronting beach. When collapse occurs, material is supplied throughout the drift sector, providing temporary protection for adjacent bluffs. Bluff retreat is therefore infrequent, and loss of the bluff face at an individual location is an even rarer event.

The width and elevation of the beach control the exposure of the bluff to wave forces and abrasion by sediment particles that leads to bluff collapse (Kamphuis, 1987). Where the transport rate is high, or where localized interference with processes causes a continual narrowing of the beach, it can be expected that bluff recession would be relatively rapid. In Puget Sound, more than 6,000 years ago, sea level rose relatively rapidly. There probably was little or no beach and the bluffs retreated rapidly. As sea level rise slowed, a shallow platform of eroded bluff material developed (Downing, 1983, p. 52). As the rate at which material is carried away from a bluff toe, and the rate of bluff retreat approach a balance, beach width becomes more nearly constant. It is important to realize that in this state of balance, with a constant beach width, the overall shore position will retreat along with the bluff face position.

Longshore transport in drift sectors in Puget Sound appears to be at low rates, (Wallace & Schwartz, 1987) and occurrences are infrequent (Keuler, 1979, p. 28). These observations are consistent with a low rate of bluff retreat. Keuler (1988) estimated long-term erosion rates in central Puget Sound were about 10 cm/year (4 in/year). Keuler (1979, p. 59) determined the erosion rate of unconsolidated deposits on bluffed shorelines in Skagit County was about 5 cm/year (2 in/year).

Sediment discharge by rivers flowing into Puget Sound is not as volumetrically important as bluff erosion, but it also follows episodic patterns. Downing (1983, p. 20) reported that the 12 largest rivers in the Puget Lowland discharge about 1.8 million cubic meters (2.4 million cubic yards) of sediment annually, but only about 10 percent is sand size or coarser. This compares with about 1.5 million cubic meters (2.0 million cubic yards) that come from beach and cliff erosion and is clearly the primary source of regional beach sediment. Griggs (1987a) concluded from his investigation of sediment discharge in northern California coastal streams that this source delivered most sediment to the beach in a few high-flow years. He further concluded that sediment delivery actually occurs during only a few high-flow days in those years.

The result of episodic sediment delivery to a localized spot is a temporary increase in the sediment available for transport and an irregularity in the shoreline, whether at a river delta or at a recent bluff collapse. Wave and current processes rework and sort the liberated material and distribute it throughout the beach profile and alongshore, slowly increasing beach width at more distant locations. The timing and rate of beach growth at a particular location depends not only on the volume and size distribution of sediment episodically delivered at the shore, but also on the distance from where it was delivered. The coincidence of all of these factors may result in temporarily distorted perceptions of shoreline processes—that is, they may appear to be responding faster or slower to change than their true average condition (see Fact Sheet).

Shoreline Erosion Rates

When geologists speak of coastal erosion rates, they usually mean long-term average rates of shoreline retreat. When property owners speak of coastal erosion rates, they usually mean the amount of bluff that slid during the previous winter. Both of these rates are important, and it is critical to understand the distinction.

Shoreline retreat is the rate at which the toe of the bluff moves landward and must be documented over a long enough period so as not to be influenced by short-term variations. Short-term erosion typically refers to slope failures such as landslides, slumps, or simply the sloughing of a layer of soil and vegetation. In the case of slope failures, it is useful to know the frequency and the maximum extent of such an event.

High rates of bluff retreat occur when:

- Wave energy is high. Long fetches in the direction of predominant winds, coupled with deep water close to shore, allow large waves to develop and to reach the toe of the bluff. Energetic waves can break apart rocks more easily and can rapidly remove eroded material from the base of the bluff, exposing fresh material.

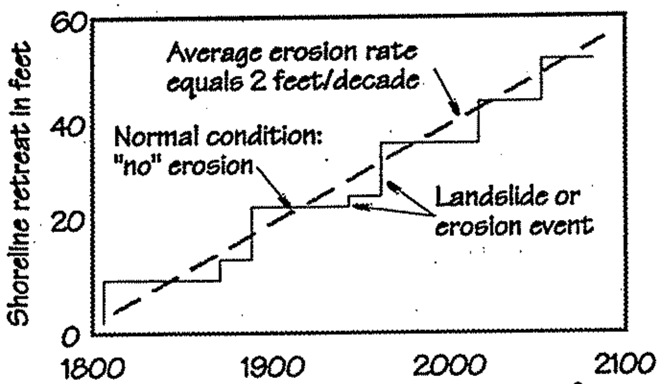


Figure 1. Long term erosion rates are an average of many landslide or erosion events over a period of decades to centuries.

- Bluff materials are weak. Many factors affect the resistance of rock to erosion, including rock type, fractures, and groundwater saturation. The glacial sediments typical of Puget Sound bluffs may erode several inches per year, whereas massive bedrock such as that in the San Juans may erode only a faction of an inch per year.
- Beaches are narrow. Beaches provide excellent natural protection, dissipating wave energy over a broad area and limiting the frequency with which waves actually reach the base of the bluff.

These three conditions are most often met on classic feeder bluffs such as Birch Point in Whatcom County, Scatchett Head on south Whidbey Island, and Green Point south of Gig Harbor. As one moves downdrift within a coastal drift sector, beaches generally become wider, and erosion rates may diminish.

Ralph Keuler, with the U.S. Geological Survey, measured long-term shoreline erosion in much of northern Puget Sound. The fastest rates are over 1 foot per year at Point Partridge on the exposed west side of Whidbey Island, but this rate is unusually high for Puget Sound. Even on exposed feeder bluffs such as Forbes Point near Oak Harbor, the north end of Marrowstone Island, or Yellow Bluff on Guemes Island, retreat rates are in the 4- to 8-inch per year range. On less exposed shorelines, the erosion rates are often much less than 4 inches per year.

Coastal erosion is highly episodic. Long periods during which erosion is negligible are interrupted by short, impressive slumps and landslides. These slope failures are triggered by saturated soils, tree blowdown, or the combination of storm waves and high tides. Although these events may cause the top of the bank to retreat several feet, and may appear even worse since they strip away mature vegetation, the long-term rate at the location may still be very slow. It may be many decades before that portion of the bank slides again.

Shoreline property owners often accelerate erosion rates by weakening the bluff or causing the beach to diminish. The former is easily done by clearing upland vegetation and changing bluff hydrology by misdirecting storm runoff or placing sewage drain fields too close to the bluff.

The latter is best done by armoring the shoreline updrift, effectively starving the beach of needed sediment.

There is a tendency around Puget Sound to exaggerate the rate of long-term shoreline erosion, yet ignore the potential for short-term bluff failure. When developing near marine bluffs, we need to recognize that both slope stability and chronic shoreline erosion affect the safety of the property but that, if the geology of the site is known and the structure is adequately set back, problems will be unlikely.

–Hugh Shipman (1993)

Section 3
Major Impact Categories

To provide a broader context for the specific assessment of shoreline armoring impacts on physical coastal processes that follows (Section 4), this section of the report outlines potential general impacts to both physical and biological processes that can result from shore protection[1]. A summary of these potential shoreline armoring impact categories is presented in Table 3-1.

Impacts to Physical Processes

Direct impacts to physical shoreline processes include excavation and burial effects from the placement of "structures" along the shore—whether they be sand or cobble beachfills (nourishment), rock revetments, or concrete bulkheads—as well as all the temporary impacts associated with their construction (noise, vibration, increased turbidity, work barge impacts, accidental spills, etc.). Depending on their placement relative to the original undisturbed natural shoreline, addition of any such "structures" is likely to result in a direct loss of beach area and possibly a narrowing of the shore drift (sediment transport) corridor.

Possibly the most significant of all impacts resulting from shore protection is a direct impact: the impoundment of potential natural sediment sources behind shoreline structures. A seawall that cuts off sediment supply from a feeder bluff to the beach, or a bulkhead that prevents unusually high tides or storm waves from reaching a reservoir of sediment stored high on the beach, will cause direct onsite impacts, as well as indirect downdrift (and possibly updrift) impacts.

Indirect impacts to physical processes from shore protection include the downdrift impacts of sediment impoundment noted above, changes in local drainage and groundwater regimes, and a variety of hydraulic impacts. The hydraulic impacts result from a general increase in (erosional) energy seaward of the shore protection, caused by reflection of wave energy and increased turbulence. Together with sediment impoundment, it is these indirect hydraulic impacts that are the central theme of Section 4.

Another potentially important but poorly documented category of indirect impacts are "during storm" impacts, when seabed fluidization and scour are much more pronounced than under "normal" conditions (Smith and Chapman, 1982).

Finally, potential cumulative impacts of shoreline armoring need to be considered. In their simplest form, these cumulative impacts will represent small incremental increases in all previously described impacts as additional individual shore armoring projects are completed

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[1]Thurston County Historic Commission expressed the additional concern that significant coastal archaeological resources, Salish Indian shell middens, for example, can be lost or disrupted through bulkheading (Shanna Stevenson, Thurston County, personal communication, May 1993).

Table 3-1
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

IMPACT LINKS TO BIOLOGICAL PROCESSES

1. Direct Impacts
   a. Temporary Construction Impacts
   b. Permanent Impacts
      - Habitat (Substrate) Burial or Removal
      - Change Vegetative Cover/Organic Inputs
2. Indirect Permanent Impacts
   a. Modification of Groundwater Regime
   b. Changes to Shoreline Environment Due to Hydraulic Impacts
      - Loss Spawning/Foraging/Rearing Habitat for Fish
      - Loss Migratory Corridor for Fish
      - Substrate Changes Reflected in Benthos
      - Effects on Shellfish
3. Cumulative Impacts
   a. Incremental Increases in All Impacts
   b. Potential Threshold Effects

around Puget Sound. For example, cumulative increases in downdrift sediment starvation of beaches. When impacts to specific drift sectors are considered, however, it is possible that certain "threshold values" may exist beyond which small incremental impacts either cease to have any further effect or, conversely, suddenly become highly significant. Comparing impacts of armoring a drift sector's transport corridor (driftway), versus its source area, might provide an example of such threshold values.

Impact Links to Biological Processes

Impact links to biological processes from shore protection (Table 3-1) can be broken down in much the same way as for physical processes. Direct permanent impacts to the shore could include habitat (substrate) removal or burial, with its direct loss of onsite organisms; and modification or removal of native plant cover—trees, shrubs, and herbs. Vegetation modification is also likely to alter the availability and type of organic material—whether seasonal leaf fall, trees, or material carried down by bluff collapse—reaching the shore.

Indirect impacts include the biological consequences of modifications to the local groundwater regime and the effects of hydraulic impacts. Narrowing of the dry beach, deepening/steepening of the beach profile, and coarsening of bottom sediments, caused by the hydraulic impacts (increasing shoreline turbulence) noted above, all result in indirect impacts to shoreline biology. Reduced shading, changing substrates and organic inputs, as well as increased turbulence and water depths, all have the potential to impact spawning, rearing, and foraging of fish species, as well as impacting their nearshore migratory corridors. Changes in bottom sediment grain sizes will have a significant impact on the types and abundance of benthic organisms present and will include impacts to shellfish.

Finally, as with the physical processes, there are cumulative impacts to shoreline biological processes to be considered. Once again, small incremental impacts to biological systems from the addition of single armoring projects may be linear in their effect, or they could respond significantly to threshold levels. If local species populations or specific spawning habitats become too scarce, or are separated by too great a distance, for example, biological impacts could increase sharply to more significant levels.

The following quote from Kurt Fresh, Washington State Department of Fisheries (Washington Coastal Currents, Vol. XVI(6), p. 15, December 1991) nicely summarizes interrelationships between physical and biological processes in Puget Sound:

> "During the last 20 years we have learned much about how organisms use our shorelines, including seasonal and temporal patterns of distribution and abundance, food habits, and responses to changes in environmental conditions. We have also become more cognizant of the functions shorelines provide for these animals. Some important functions include foraging, reproduction, refuge from predation, physiological transition zones, and migratory corridors.
>
> One important lesson of the last 20 years is that shorelines are not a series of isolated and discrete habitats but rather are linked by both physical and biological processes into a

system of habitats. Physical processes such as sediment transport, currents, and weather events significantly influence the type of habitat that exists along any particular stretch of shoreline. These processes operate on a broad regional basis. Sediments on a particular beach may originate from a feeder bluff many miles away.

Biological processes also link shoreline habitats over broad distances. Recent work has demonstrated that detritus (*small pieces of particulate organic carbon*) is one of the key elements of nearshore food webs, especially in Puget Sound. Detritus used on one beach may have originated in an estuary or eelgrass bed many miles away.

During the last 20 years we've learned about the effects of shoreline modifications on biological resources. From a biological perspective, shoreline modification is fundamentally a change in habitat. The substrate may be altered, vegetation eliminated, or current patterns modified. When the habitat is transformed, even subtly, resources can be impacted." (Kurt Fresh, 1991)

While the emphasis of this report is on shoreline armoring impacts to physical coastal processes—it is important to understand some of the types of physical/biological linkages that Fresh is referring to. Following is a summary of ecological issues identified by Washington Department of Fisheries (Ken Bates, personal communication, 1993) or identified in the literature as possibly related to physical changes that might be associated with a site-specific beach stabilization project.

Changes (generally losses) in food resources

- Losses of terrestrial- or estuarine-derived organic matter that would have been contributed during episodic erosion. Dexter, et al. (1981) identify that shoreline erosion is one of the major contributors to the detrital pool of Puget Sound's nearshore environment.
- Less likelihood for accumulation of detrital material on steep narrow beaches (logs, drift algae, and associated organic matter).
- Less retention of organic materials in coarser substrates (Kozloff, 1974).
- Change in marine food web (loss of terrestrial inputs, and changes in marine benthic flora and fauna including bacterial communities) due to physical changes.
- Losses of shoreline vegetation and associated estuarine or upland food web in areas filled and developed.

Changes in Habitat

Beaches and the nearshore vicinity can take on entirely different characteristics including substrate type, slope or angle, wave energy, sediment size, and food availability as discussed above. While some nearshore organisms are flexible and can colonize different types of habitats, others are more limited. Following are some relevant habitat impacts that have been identified by Fisheries and others.

- Sandlance, herring, and surf smelt are important bait fish in Puget Sound that all depend upon nearshore/intertidal areas. These species all require specific substrate material and stability conditions for successful intertidal spawning. Rock sole also use nearshore and intertidal sandy areas for spawning.

  - Adult sandlance require sandy nearshore habitat for feeding. They leave the sand to swarm in the nearshore surface water for spawning. If nearshore sand is removed, less habitat will be available for this species.

  - Pacific herring lay their eggs in eelgrass beds and on other types of macrophytic vegetation. Changes to eelgrass beds have occurred from shoreline protection, which resulted in loss of sand substrate.

  - Spawning habitat for surf smelt may be mimicked by berms built up in front of the toe of the structures during storm events. Eggs require 2 to 4 weeks for incubation, and these berms are not stable enough to remain for that length of time. When the berm washes away, eggs are lost. Pentilla (1978) conducted a lengthy study of surf smelt-spawning in Puget Sound and reported that substrate and shade are negatively impacted by bulkheads. Spawning substrate can be lost, and shoreline shade, which protects spawned eggs from desiccation and temperature extremes, may be removed when bulkheads are constructed.

- Juvenile fish rely on the intertidal/nearshore habitat for protection, rearing, and feeding. Species that use this area that are especially important to Puget Sound include salmonids, cod, and flat fish such as starry flounder and English sole.

- Large organic debris such as drift logs provide an ecological niche on Puget Sound beaches for several species including algae, barnacles, isopods and amphipods, terrestrial insects, and bacterial communities. On shallow sandy beaches, logs can create sand traps, thereby providing additional shoreline stabilization. On armored beaches, logs readily slip along the surface and can affect the shoreline (Downing, 1983).

Changes in Seasonal Characteristics of Beach Profiles

Man-made stabilization systems may respond differently to storm waves and building waves and might result in different seasonal responses than natural shorelines.

response to the presence of a seawall), and controls (i.e., the controls that determine the type and magnitude of beach response). All three lists are reproduced in Table 4-1 and provide an important general perspective for the discussion that follows.

Estuarine Beaches Are Not Scaled-Down Ocean Systems

It is notable that, while Tait and Griggs' (1991) literature review considers widely distributed study sites, the majority are sandy beaches, on open ocean coasts—California, Florida, and Oregon, for example. Further, many of the studies reviewed involved the reaction of beaches and seawalls to severe storm or even hurricane conditions. Superficially at least, the general features of these locations—broad, gently sloping beaches characterized by uniform, well-sorted sediments and impacted by large waves, ocean swells, and an active surf zone—seem very different from what we commonly see in Puget Sound.

This view, that Puget Sound beaches are substantially different from those of the open coast, gains support from Nordstrom's (1992) recently published book, *Estuarine Beaches*. Several quotes from Nordstrom (1992) summarizing the distinctive characteristics of estuarine beaches are presented in the accompanying fact sheet. A figure illustrating differences in beach profile response to erosional wave conditions on estuarine beaches versus the open ocean coast is also included.

The distinctive features of estuarine beaches noted by Nordstrom (1992)—particularly the importance of local wind-generated waves as the primary agents of erosion, relatively high tidal range, and predominance of coarser sediments—must all be kept in mind when research results from the open coast studies are transferred to Puget Sound beaches.

Quantitative Information on Beach Responses Remains Scarce

Tait and Griggs (1991) indicate that our present knowledge about the long- and short-term effects of seawalls on beaches is limited and that central to this dilemma is the lack of sufficient field data with which to resolve alternative claims. To quote:

> "It is important to assess the effects of seawalls on beaches under a variety of conditions, using a variety of seawall designs, and in a variety of coastal environments (e.g., cliffed shore versus dunes, eroding shoreline versus stable environment, longshore transport versus no net longshore transport, high energy versus low energy, etc.). It is also important that enough seasons or years of record are available to be able to distinguish between long-term trends and short-term variability."

Table 4-1
Beach/Seawall Interactions: Response, Processes, and Controls
(Tait and Griggs, 1991)[a]

Beach Response to Seawall	Processes Invoked To Explain Response	Basic Controls on Beach Response
Observed in Field		
1. Scour trough—A linear trough or depression fronting a seawall	1. Increased sediment mobilization	1. Long-term shoreline trends (erosion versus stability)
2. Deflated profile—the lowering or erosion of the beach face	2. Wave reflection	2. Position of wall on the beach profile
3. Beach cusps—crescentic or semicircular embayments on the beach face	3. Sediment impoundment	3. Geomorphic shore type (cliffed versus dunes)
4. Rip current trough—a trough or embayment crossing through the surf zone	4. Acceleration of longshore currents	4. Sediment supply/width of beach
5. End scour—erosion of the unprotected beach adjacent to the end of a seawall	5. Rip currents	5. Relative water level (tides, storm surge, sea level rise, land subsidence/emergence)
6. Upcoast sand accretion—the impoundment of sand on the upcoast or updrift end of a structure	6. Wave refraction and diffraction	6. Sediment properties (grain size, fall velocity)
Hypothetical	7. Edge waves	7. Offshore gradient/width of surf zone
7. Steepened slopes—increased beach face slope in front of a seawall		8. Wave characteristics (height, period, breaker angle)
8. Downcoast shoals—shallow water depositional features downcoast from a seawall		9. Exposure of coast
9. Reflection bars—shore parallel bars offshore from seawalls		10. Wall design (height, permeability or dissipative characteristics, slope)
		11. Length of wall

[a]No relationships are implied by the sequence of numbering of the three columns. See text for additional explanation.

FACT SHEET

Estuarine Beaches

Waves and Currents

The primary agents of erosion on estuarine beaches are waves generated within the estuaries by local winds in association with passage of low pressure centers and fronts, although ocean swell waves entering through inlets, tidal currents, wind drift, and human-induced process are important on some sites. Process controls and shoreline characteristics differ over short distances in irregularly-shaped estuaries, and there is considerable local variability between sites due to differences in fetch length, exposure to winds from different quadrants and ocean waves.

Waves generated by local winds in estuaries have low wave heights and short periods.... Tidal range affects the vertical distribution for wave-energy over the profile, determining the width of the beach and the duration that waves break at any elevation. Beaches with high tidal range relative to wave height are characterized by a steep upper foreshore with a broad, flat low-tide terrace. At low tide, spilling waves break in a broad surf zone across the gently sloping low-tide terrace, but the energy in the waves is low. At high tide, waves reach the upper foreshore with little loss of energy and break as plunging waves. During storms, spilling waves pass over the low-tide terrace at both low water and mid-tide levels. There is a lack of energy for transport of sediment from the low-tide terrace to the upper foreshore during periods of low wind velocities.

Wave refraction is less effective on short-period waves, and locally generated estuarine waves often break at a sharper angle to the beach that refracted ocean waves....

Longshore currents are predominantly generated by the breaking of local wind-waves but refracted ocean waves, tidal flows and wind drift are important. Currents induced by refracted ocean waves and tides may flow opposite flows generated by local wind-waves. Tidal currents are important near channels, projecting headlands and constrictions in the bay, and they may be the dominant agent of sediment transport on the low-tide terrace....

Ship and boat wakes are higher on estuarine sites than on ocean sites because vessels can pass close to beaches, and the wakes account for a greater proportion of the total energy. The size of wakes varies largely with vessel speed and distance from the sailing line, but ship length, beam, draft, and hull geometry are important. The average energy of boat wakes is usually only a small percentage of the average energy of wind waves in all but the smallest estuarine basins. The shorelines most susceptible to erosion from boat wakes are in narrow creeks or coves, are composed for easily erodible material, have a steep nearshore gradient and have a high rate of boat passage close to shore.

Shoreline Characteristics

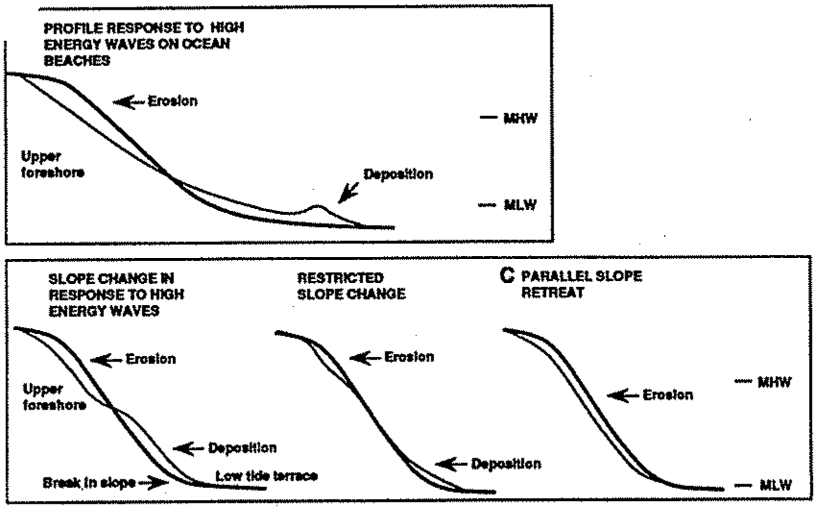
Only a fraction of the material eroded from coastal formations is found in the mobile layer of sediments on the upper foreshores of estuarine beaches. Cobbles form an immobile layer under sand and pebbles, and fine sand and smaller particles are winnowed from the beach. Surface sediments are usually coarser on estuarine beaches than ocean beaches, due to the absence of long, flat waves that normally deliver fine sediments from offshore and through preferential elimination of fine particles....

Gravel beaches are common in formerly glaciated estuaries, and they can exist in low-energy environments. A small rate of delivery of gravel is sufficient to form a beach through time because there are no offshore losses. Some gravel beaches are immobile lag surfaces, but many are characterized by high rates of change.

The depth of mobilization of sediments on the upper foreshore is small, and the active beach may be only a thin veneer of unconsolidated material overlying an immobile layer of coarse sediments, clay, peat, or a wave cut platform. Mobilization of sediments on the low-tide terrace by waves may only occur to depths of 10 to 30 mm, and biological activity may play a greater role than wave processes in altering the characteristics of the surface and subsurface.

....Vegetation plays a greater role in influencing morphological change on estuarine beaches than on ocean beaches because of the greater abundance of vegetation and the reduced ability of low-energy waves to move it....

Estuarine shorelines are often composed of numerous isolated beaches with different orientations. They have high variability in morphology and rate of erosion over small areas resulting from local differences in fetch, wind direction, stratigraphy, inherited topography, resistant outcrops on the foreshore, variations in submergence rates and amounts of sediment in eroding formations. Irregular shoreline orientations result in a great length of shoreline within an estuary. Beach compartments are isolated into longshore drift cells defined by deep coves or headlands formed by resistant rock, marsh, or human structures.



Profile response to erosional wave conditions on ocean and estuarine beaches. (MHW and MLW are mean high water and mean low water.)

The net rate of longshore transport on estuarine beaches can be an order of magnitude less than the rate on ocean beaches. Net rates vary with orientation, fetch distance, and size of each drift cell and range from tens of cubic meters to tens of thousands of cubic meters. Rates of transport are low, but the magnitude of erosion can be high because the quantities of sediment in transport represent a sizeable fraction of the total unconsolidated sediment in the active beach....

Beach Dynamics

Conspicuous cycles of cross-shore sediment transport bayward of mean low water appear to be rare on estuarine beaches characterized by short fetch distances and appreciable tidal ranges. Conspicuous change on meso-tidal (tidal range <1.0 m to >4.0 m) estuarine beaches is confined to the upper foreshore above the low-tide terrace....

High-energy waves on meso-tidal estuarine beaches remove sediment from the upper foreshore and deposit it on the lower foreshore with a change to a concave upward profile. Onshore-offshore transport is usually confined to a few meters bayward of the former break in slope between the upper foreshore and the low-tide terrace. Recovery involves transport of material up the upper foreshore with eventual restoration of the previous linear slope across the entire upper beach. The sediments that are moved offshore form only a thin veneer over the surface close to the break in slope instead of forming the bar that is prominent on many ocean sites. A small swash bar may form, but it is not under water at low tide. Permanent offshore losses may occur on estuarine beaches that have large amounts of fine sand.

....Landward displacement of the entire foreshore profile may occur while the profile slope is maintained. This parallel-slope retreat appears to be the result of losses of sediment due to longshore movement on the upper foreshore associated with changes in wind direction and wave approach, and it can occur as a result of either high-energy events or prolonged periods of unidirectional longshore currents. The effect is most pronounced near one end of a drift compartment. Recovery involves return of sediment from longshore sources with little or no change in beach slope.

Many gravel beaches in estuarine settings are steeper than sandy beaches because of their permeability, but flatter slopes may occur on non-equilibrium beaches where sediments are too coarse to be reworked by waves or where a thin veneer of mobile gravel overlies a wave cut terrace. Gravel beaches are morphodynamically reflective, and cusps, berms and storm ridges are prominent. Cross-shore cycles of transport on gravel beaches are rare; bar forms are usually lacking, and differences in slope between the upper foreshore and low-tide terrace are pronounced.

Source: Nordstrom (1992)

For now, these field data simply do not exist. Thus, while qualitative descriptions of beach response, processes, and controls are increasing in scope and reliability, quantitative data describing the magnitude of these beach/seawall relationships clearly still remains beyond our grasp.

It is worth noting that quantifying beach/seawall interactions and process rates—toe scour, erosion, and sediment transport, for example—is a difficult task. Professionals familiar with the field regard data points that agree within a factor of two as "precise," while agreement within an order of magnitude is still considered good (Steven Costa, personal communication, August 1993).

Shoreline Erosion Is an Important Element in Natural Coastal Stabilization

There is a widespread tendency to regard shoreline erosion as something "bad" that needs to be stopped. This is understandable if your house is located close to the shoreline, especially if you have just experienced a powerful winter storm and an episodic erosion event! Yet, in fact, trying to halt erosion is not only likely to prove unsuccessful, at least in the longer term, but it may actually aggravate the perceived erosion "problem" you are trying to solve.

As the energy contained in waves is dissipated on the shoreline, sediments are in a continual state of flux as erosional and depositional processes strive to reach a dynamic equilibrium. Wave erosion, smoothing out shoreline irregularities, contributes sediment to the adjacent beach. These beach sediments are continually reworked and transported by wave-driven alongshore currents until they are eventually lost to some depositional sink. This "river of sand" (or more often, coarser materials in Puget Sound), continually moving along the shoreline, provides a critical natural defense of the land against the waves. Structural intervention along the shore often disrupts this natural line of defense, resulting in increased, rather than decreased, erosional problems.

The purpose here is to stress that erosion along the shore is not inherently bad—indeed the feeding and nourishment of the shoreline with an adequate supply of sedimentary material provides the best natural defense against excessive erosion. Further, awareness of the inevitability of coastal erosion and its generally episodic nature—especially here in Puget Sound—provides a more rational framework for long-term management of both coastal resources and coastal development (Bascom, 1980; Downing, 1983; Silvester and Hsu, 1993).

Major Physical Impact Categories

Potential physical responses of a natural, undisturbed, shoreline system to the placement of different forms of shore protection have been organized into six categories. These categories are as follows:

- Sediment impoundment (leading to downdrift impacts)
- Modification of groundwater regime
- Narrowing of the beach
- Lowering of the beach profile
- Modification of beach substrates
- Loss of beached organic debris

Impacts of shore protection features on the shore vary according to the type of shore protection, wave energy régime, and site geology (i.e., landform and sediment type; Table 4-1). In the following discussion we make the distinction between "hard" and "soft" approaches to shore protection. Examples of hard structures are bulkheads, sea walls, and revetments, while soft solutions to shore protection include dynamically acting or compliant approaches such as beach nourishment or replenishment. Shoreline vegetation management is also often viewed as a soft solution, however, functionally vegetation is a "hard" structure intended to hold the sediment in place rather than allowing adjustment. Vegetation does offer a soft solution in the sense that it can "grow" with slowly changing site conditions; it also offers greater potential for shore (and bluff) protection in the more protected habitats of Puget Sound than on the open coast.

Because hydraulic forces acting on a volume of sediment at the shore are the primary determinant of the character of a beach (given a particular source material), the impact of shore protection on the beach is scaled according to the degree of modification to the hydraulics and sediment supply caused by the shore protection. The location of shore protection within the beach profile is widely recognized as a critical factor in determining impacts, for this controls the extent of its interaction with waves and currents and, therefore, its potential for modifying sediment transport in the littoral zone (Weggel, 1988; Tait and Griggs 1991, p. 23).

In this section, structures are analyzed for physical impacts according to whether they are high in the beach profile and only stabilize material upland from them, or whether they are lower in the beach profile and impinge on wave energy dissipation and sediment transport processes. The alongshore location of shore protection within a particular drift sector also determines the extent to which it interacts with sediment transport.

Each of the six physical impact categories listed above is identified in the form of a question, which is then answered—pro and con—from available literature and other data sources. Where data are available, physical impacts of placing hard- or soft-shore protection landward (above) and waterward (below) of Ordinary High Water Mark (OHWM, see Section 2) are described separately. For clarity, each impact discussion begins on a new page; conclusions sections assess our current state of knowledge of each major impact.

Does Shore Protection Cause Sediment Impoundment That Has Downdrift Impacts?

Impoundment of sediments behind some form of shore protection system is the most broadly acknowledged, least controversial, and possibly the most significant physical impact of shoreline armoring (Tait and Griggs, 1991). Sediment impoundment—typically the long-term or permanent removal of sedimentary source material from the dynamic longshore transport system—can result from two different basic mechanisms.

The principal mechanism for impoundment, and certainly the one most commonly seen in Puget Sound, is simply the permanent loss of sediment from a beach system when it is "locked up" behind a seawall, bulkhead, or revetment. Depending on the seawall's location within the beach profile, this loss can include (a) sediment from the active beach, (b) sediment "stored" in backshore areas, that is usually only activated into the longshore transport system during severe storm events, and (c) sediment from adjacent upland sources (feeder bluffs, for example) that previously reached the beach, but is now trapped behind the seawall structure, out of reach of the waves.

The second mechanism for sediment impoundment is a "groin effect." If shore protection structures extend out onto the beach profile where they can be impacted by waves and currents, they can behave like groins. Sediment moving alongshore can become trapped updrift of the projecting armoring (Dean 1986; Tait and Griggs, 1991). Impoundment would not seem to be as permanent in this case as for material enclosed <u>behind</u> shore protection, and major storm action is likely to remobilize this updrift material into the longshore sediment stream.

The obvious impact of sediment impoundment is potential starvation of the adjacent beach. This typically leads to increased erosion immediately in front of the seawall or other shore protection structure involved, as noted above (Dean 1986, Everts 1985).

A secondary but equally important impact is potential starvation of beaches <u>downdrift</u> from shore protection structures.

Variables Controlling Impacts

Tait and Griggs' (1991) literature review suggests three factors that are particularly important to determining the overall impacts of sediment impoundment (see Table 4-1). The overriding factor is the long-term trend in the position of the shoreline. If a segment of regionally eroding shoreline is fixed by shore protection, the beach will eventually disappear in front of the shore protection. Sediment impoundment will only accelerate beach retreat. If the shoreline is either stable or accreting, sediment impoundment behind shore protection structures will only effect the beach during major storm events, or if major (seasonal) fluctuations in the position of the shoreline expose the armoring to wave attack.

The second major factor is the landward/waterward location of the shore protection. The following quote from Tait and Griggs (1991) summarizes several relevant studies:

> "The basic concept is that the more often and the more vigorously the waves interact with the wall, the greater the potential magnitude of beach response. This assessment has been echoed by numerous researchers. In their 20-year study of the effect of coastal protection structures on an Australian coast, McDonald and Patterson (1985) conclude that the impact of a seawall on the beach is 'largely dependent on its position on the profile.' Sato, Tanaka, and Irie (1968) came to the same conclusion based on laboratory studies of scour at a seawall in a prototype-scale wave basin.
>
> Kraus (1988), after a thorough review of the literature, comments that the position of a seawall with respect to the surf zone is 'a critical parameter controlling the amount of erosion and the beach recovery process.' He also cautions that 'this distance is variable because the boundaries of the surf zone shift according to tide, surge, and period and height of the waves.' To the extent that a wall projects into the surf zone, it may serve to constrict longshore currents as well as increase upcoast sand impoundment and the accompanying downcoast scour. The position of a wall on the beach profile may also affect water depth and wave heights in front of the wall, could increase.
>
> In their study which compared several seawalls, Griggs and Tait (1988) comment that the wall which projected furthest seaward was the first to lose the beach in front of it with the onset of winter waves, experienced the greatest scour or deflation, and was the last to recover during the summer months."

The third factor influencing the effect of sediment impoundment is the local sediment supply and beach width. In general, the more limited the sediment supply and the narrower the beach, the greater impact sediment impoundment is likely to have on increasing local and downdrift beach erosion. Conversely, where ample beach sediments exist and/or longshore drift rates are large, the potential impacts of sediment impoundment are likely to be reduced.

Downdrift Impacts of Impoundment

Where there is a retreating shoreline material eroded from one location supplies the littoral stream that maintains the beach width downdrift, even if that width is also decreasing in time. Shore armoring placed so as to prevent shore material from entering the littoral stream (i.e., impoundment) will cause the rate at which sediment arrives at a downdrift location to diminish. The rate of sediment leaving that location, however, will be unchanged and the deficit (i.e., starvation) will take the form of beach narrowing. This process occurs whether the supply material is fed from a beach of low height or a high bluff that episodically slumps onto the beach. In the extreme case, the beach downdrift from shore armoring could recede to a bluff and lead to removal of material at the toe of the bluff and eventual bluff instability.

At the updrift end of a drift sector the amount of sediment being carried in the littoral flow is at a minimum. The flow is farthest from "capacity" at the updrift headland and the tendency to erode the shore is usually greatest there. The rate of loss of material from the shore to feed the littoral flow is proportional to the difference between the capacity and the actual transport rate. The pattern of varying erosive tendency (assuming uniformly erodible material) is expressed by an exponential relationship.[1]

The implication of this exponential relationship is illustrated in Figure 4-1. If a portion of the updrift sediment source of a drift sector is impounded behind a bulkhead, the difference between the "capacity" of longshore drift to transport sediment and the amount of sediment actually available to be carried downdrift, will be at a maximum in front of the bulkhead. Longshore drift will continue to remove material in front of the bulkhead, the beach will be lowered, and the shoreline will rapidly retreat.

As the difference between the actual and potential transport rates drops off exponentially downdrift, successive locations, A and B, experience lesser degrees of sediment starvation. The rate of beach erosion (still related to the updrift bulkhead) declines and the rate of shoreline retreat diminishes. Addition of a second bulkhead, and impoundment of more source material, incrementally increases both downdrift erosion and shoreline retreat as shown in Figure 4-1.

Hard Shore Protection (Armoring)

Armoring Landward of OHWM. Shore protection and sediment impoundment located totally landward of Ordinary High Water Mark (OHWM) would not be expected to impact the adjacent beach during times of normal wave, tide, and current action—as noted above, beach impacts result from <u>interactions</u> between shore armoring, waves, and sediments.

During major storms, however, especially if they coincided with high spring tides, waves might reach such structures. Impoundment of substantial sediment sources that might be "needed" for immediate beach nourishment under such storm conditions, could result in rapid erosion both in front of the shore protection structures and at downdrift locations.

Armoring Waterward of OHWM. Shore armoring that projects onto the beach waterward of OHWM obstructs the longshore flow of sediment. The lower in the beach profile the armoring is situated and the more seaward it projects, the greater the interruption of

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[1]At any distance x, downdrift from the headland: $Q_x = Q_{equilib} \cdot (1-e^{-kx})$,
where k is the proportionality constant between the longshore gradient of erosion and the difference between the actual and potential transport rates.

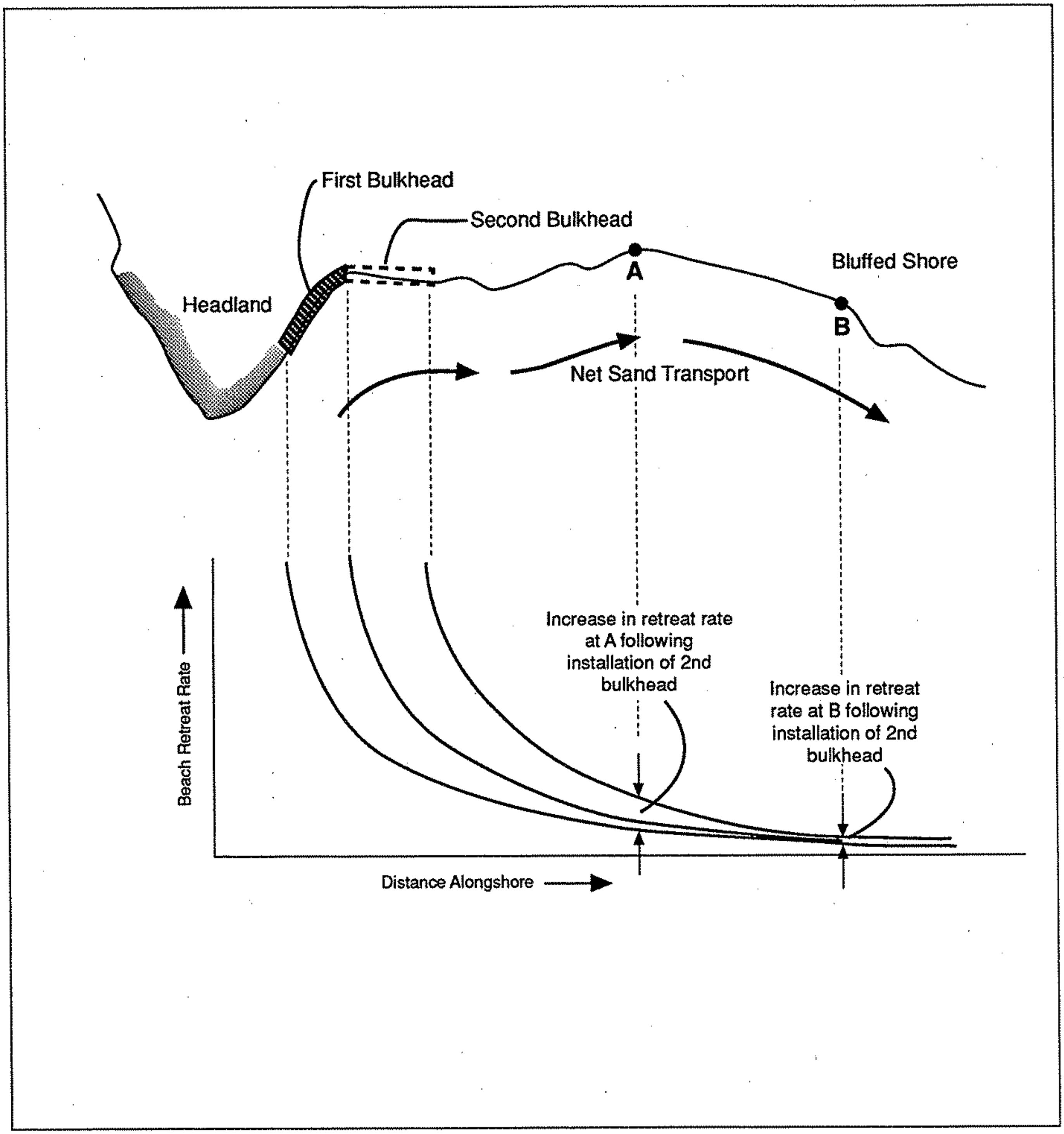


Figure 4-1
Alongshore Change in Beach Retreat Rate as Actual Sediment Transport Approaches Capacity

longshore transport. Sediment removal on the downdrift side of the obstruction continues at the rate it would have before the obstruction was emplaced. Whereas a balance was previously maintained with the sediment carried into that location, there is now a deficit in the flow of sand until the impoundment on the updrift side grows to the point where sand is again flowing around the obstruction at a rate to balance the removal rate. During that time the downdrift shoreline experiences accelerated shoreline retreat, first in the localized area at the end of the armoring, but subsequently over a greater length of shore depending on the amount of updrift impoundment.

The balance of the dynamic shore environment requires a sediment supply to replace that removed by waves and longshore currents. Where armoring is installed along eroding bluffs—thus impounding the former supply behind the structure—the supply is diminished for a downcoast location. The result is that more sediment is removed than supplied. The volume of beach material in that location is therefore decreased and the beach is narrowed. A location where this process is both active and quantitatively documented between Elwha River and the tip of Ediz Hook (U.S. Corps of Engineers, 1971; Galster and Schwartz, 1990; see Section 5). Another excellent example is provided by Good's (1992) study of the cumulative impacts of shoreline armoring along the Siletz littoral cell on the central Oregon coast (see Section 6).

A field study at the southeastern end of Lake Michigan, reviewed by Kraus (1987), documents measured longshore currents at a 579-meter-long seawall, depth along the wall, and erosion both at the wall and along neighboring beaches. Combining field evidence with aerial photographic interpretations, Kraus concluded that the volume of material eroded from the unprotected portion of beach downdrift of the seawall was approximately equal to that removed from the littoral system by impoundment behind the wall.

Retreat of the downdrift shoreline at West Point, Seattle, while the reveted sludge lagoon was in place (see Section 5), extended over a distance of approximately 260 feet, or 30 percent of the reveted shoreline length. This provides further confirmation of the balance between impounded shoreline sediment sources and associated downdrift impacts.

Soft Shore Protection

Beach nourishment fills and stabilization with vegetation can have similar effects of narrowing downdrift beaches as would a bulkhead, if placed at a site that usually feeds the longshore drift system. Similar effects also result from interception of runoff that usually saturates a bluff, or other forms of bluff stabilization. Any measure that leads to retention of sediment that would otherwise supply the littoral zone changes the balance of supply and removal, with the result of altering the rate of change of shoreline position downdrift. In the case of shore protection using beach nourishment, however, impoundment losses of back-beach sediments may be partially offset by the nourishment material itself entering the active longshore drift stream.

Observations at Ediz Hook near Port Angeles are instructive with regard to soft as well as hard shore protection measures. They show that beach nourishment can feed and protect downdrift locations in both the upper part of the beach and the lower shore profile. After hard structures were installed along the base of an eroding bluff, starvation and narrowing of a downdrift spit occurred (Galster and Schwartz, 1990). The cutting off the sediment supply from the bluff interrupted the longshore sediment balance. One component of the selected method to control erosion on the spit was to add cobble size beach material at locations along its length. Tracer material was placed with the beach nourishment. Monitoring the performance of the beach nourishment showed that the rates of movement in the downdrift half of the spit varied from 0.6 to 7.6 m/day with an average of 2.5 m/day for the first 2.5 years. Six locations had material added to them and were monitored for downdrift redistribution of placed material. Material from all the sites migrated toward the distal end of the spit at varying rates. Based on monitoring information, an estimated two-thirds of the nourishment volume from the largest placement area moved into the nearshore area in about 6 years. There was considerable deposition along the central and distal portions of the spit to a depth of nearly 5 meters. This is one of the few cases of performance monitoring of a "soft solution" to shore protection in the vicinity of Puget Sound.

Conclusions

1. Impoundment of sediment, or sediment sources, that would otherwise be available to feed adjacent and downdrift beaches is the most broadly acknowledged, least controversial, and possibly most significant, impact of installing shore protection structures.

2. Sediment impoundment landward of OHWM is unlikely to result in beach impacts except under unusually high water and severe storm conditions. At such times the "unavailability" of the impounded material could lead to rapid beach erosion.

3. Impoundment of sediment sources at progressively lower elevations across the beach profile is likely to result in increasing "shortfalls" in longshore sediment transport required to maintain an equilibrium beach profile. Erosion will increase, both immediately in front of the shore protection, and at downdrift locations, and the beach front will retreat.

4. Hard and soft shore protection approaches can both act to impound sediments and sediment sources that might otherwise supply local longshore transport needs. Soft solutions, if designed to incorporate "sacrificial" fill, could partly offset impounded sediment losses.

5. Overall, this impact is well documented. Some limited quantitative data relating source impoundment to downdrift beach erosion (Downing 1983, Galster and Schwartz 1990, Good 1992) are also available.

Can Modification of the Groundwater Regime Impact Beach Erosion?

Installation of shoreline armoring, particularly if characterized by low permeability, can result in modification of local groundwater conditions landward of the armoring that may, in turn, impact the adjacent beach.

A beach directly seaward of shoreline armoring installed above OHWM might become narrower if a higher water table forms behind the armoring than at unarmored locations. The higher water table increases the pore water pressure in the beach material and increases its mobility under wave action (Figure 4-2). This results in increased sediment transport and erosion.

This impact is most likely to be significant at sites with fine-grained sandy beaches, where groundwater seepage will tend to "fluidize" the sand. Although the mechanism will still be present at coarser-grained sand or gravel beaches, the greater stability of these sediments will reduce the actual impact.

In Plant and Grigg's (1992) Aptos Seascape, Monterey Bay, California, study, groundwater elevations were measured at various locations on the shore profile both in front of a seawall and at adjacent natural beach locations. Swash mechanics were closely observed. During times of higher tides, the water table was higher in the beach backed by a seawall than in the natural beach. This is important to infiltration into the beach from the uprushing wave and subsequent downrushing sheet flow, with the effect of permitting swash actions to occur at a higher elevation on the seawalled beach than on the natural beach. This could cause an adjustment to coarser sediment, a steeper profile with a more landward shoreline position, and a quicker change from summer to winter profiles.

To our knowledge, this potential impact has not been explored or documented during previous Puget Sound shoreline protection studies. Modification of groundwater regimes does play an important and well documented (Tubbs, 1975) role in the stability of banks and bluffs that lie behind many Puget Sound beaches and provide their principal source of sediments. Task 6 of this study, *Coastal Bluff Management Alternatives for Puget Sound*, will explore these issues in more detail.

Fisheries staff note that a change in groundwater regime is itself a physical impact. This is especially important for beaches that front marshes around Puget Sound (see Accretionary Beaches Fact Sheet). Hydraulic and hydrologic continuity between the water dependent marsh habitat and adjacent Sound waters must be maintained for the habitat to remain viable. Clearly any shore protection proposed at such a location must take these potential groundwater impacts into account (Ken Bates and Neil Rickard, personal communication, May 1993).

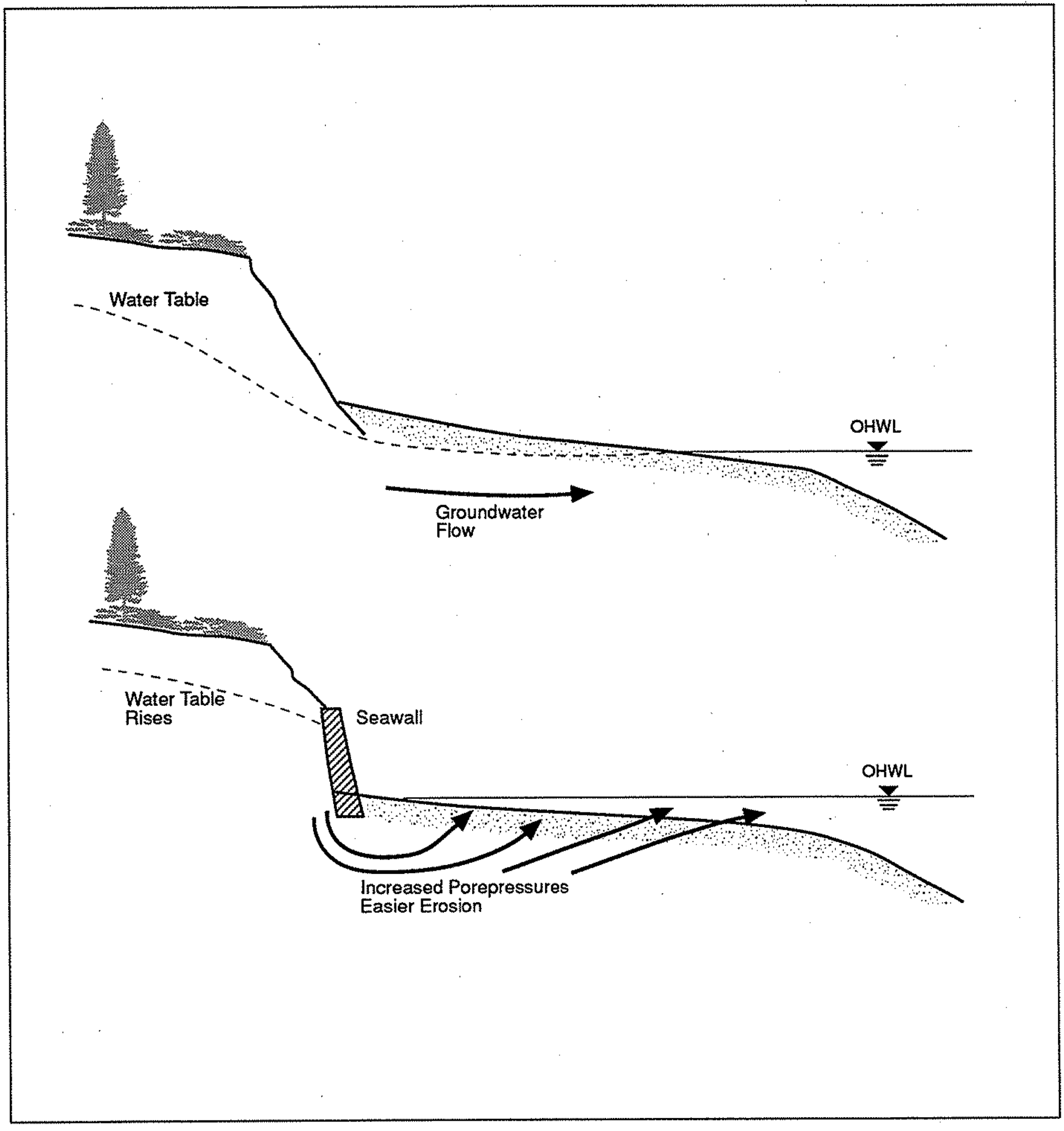


Figure 4-2
Armoring Impact on Water Table and Beach Erosion

Conclusions

1. If shoreline armoring raises the watertable behind a beach, increased pore pressure in the beach material can accelerate erosional processes.

2. This impact is most likely to effect fine-grained sandy beaches and thus may not be common in Puget Sound.

3. Fisheries staff have noted that this impact may be of special importance where beaches separate marsh/wetland habitats from the Sound.

4. No documented regional examples of such groundwater impacts have been identified during this review.

Does Shore Protection Cause Narrowing of the Beach?

Hard Shore Protection (Armoring)

Armoring Landward of OHWM. Shore impacts are caused by the interaction of shoreline armoring with the waves and sediment. Weggel (1988) states that the location of a structure relative the shoreline is an important parameter in defining the degree of interaction of the two. If the toe of the armoring structure is located landward of OHWM and the water table is not elevated in front of the armor, the structure will in general not cause narrowing of the fronting beach.

A vertical sheetpile seawall 662 feet in length was installed at Ocean Beach, San Francisco in 1941 (Berrigan, 1985), causing no apparent loss of beach width. The structure, with a top elevation of 7.2 feet above Mean Higher High Water (MHHW), is normally covered with sand to the extent that most people are unaware of its presence. It was uncovered in the severe storms that struck California in the 1982 to 1983 winter, but by October 1984 it was nearly covered again. Obviously, this vertical wall is not responsible for beach narrowing.

A quarrystone revetment was installed at Seadrift, northwest of San Francisco under emergency conditions in 1983 to prevent damage to beach homes after storm erosion removed the beach and frontal dunes. Since that winter the beach has returned. Wind-blown sand and dune grass now cover much of the revetment (Wiegel, 1992). This is another example of positive coexistence of armoring and the beach.

Plant and Griggs (1992) documented beach profiles at Aptos Seascape, a location in northern Monterey Bay, California, and reached the following conclusions about the profile in front of shoreline armoring: (1) the bermed profile that develops during summer when wave steepness is low is similar to the profile for the adjacent natural beach, (2) at the start of the storm season, as wave energy intensifies, the beach in front of the armoring transforms to the winter profile sooner than at adjacent unarmored locations, but (3) once the beach has adjusted to more erosive winter waves, the profiles of the armored beach are indistinguishable from those of the adjacent natural beach. Upon return of low-steepness summer wave condition, profiles of both the armored and unarmored reaches respond similarly.

It should be noted that the three examples cited above, Ocean Beach, Seadrift, and Aptos, are all locations with generally finer sandier sediments and higher wave energy regimes, than is typical of many Puget Sound locations.

It has been generally assumed that breakpoint bars that form low in the beach profile during storms are built with material from the upper beach profile, and that removing that material from the littoral system by shoreline armoring induces adjacent erosion to compensate for the volume loss. Preliminary results of monitoring revetments and seawalls in Oregon (Kraus and McDougal, 1992, p. 85) do not indicate that the beach is narrowed at unprotected properties adjacent to shore armoring (i.e., no flanking effects), although no information was given regarding location of the structures in the profile.

The assumption that armoring induces adjacent erosion, is further questioned by model test results of Toue and Wang (1990). In their model, the seawall toe was set at the mean water level and both normal and oblique incident waves were tested. For normally incident waves no flanking effects could be detected. The beach eroded nearly identically both with and without the seawall. Under oblique wave conditions the seawall acted as a groin and caused erosion downdrift of the structure, but that effect was confined to a region spanning three to four times the length of the seawall. It is obvious from the debate that in some cases shore retreat occurs in front of armoring and in other cases there is none. Other factors besides the presence of the seawall must influence beach response.

Armoring Waterward of OHWM. Observations of net removal of the beach fronting shore armoring, both in laboratory experiments and after hurricanes on the Gulf coast (Walton and Sensabaugh, 1978; McDougal, Sturtevant, and Komar, 1987), are in marked contrast with the previous examples of minimum impact of armoring placed high up the shore. The opinion appears often in the literature that wave agitation increases in front of a seawall. Armoring that extends waterward of OHWL will interact with waves when the toe of the armoring is below water. The common explanation for increased scour in front of a wall is as follows: Waves reflected by the structure back into the surf zone combine with the incoming waves and produce increased water oscillations at the bed (Tait and Griggs, 1991). Smooth vertical bulkheads and seawalls reflect nearly all the incoming wave energy. Sloped rubble revetments dissipate much of the energy of an uprushing wave, but also reflect some energy. This reflected energy mobilizes the sediment more than under conditions of no reflection, and makes the sediment available for transport out of the area by currents. The more reflective the armoring surface, the greater this effect and the greater the loss of material from in front of the armored section. The result is narrowing of the beach in this location (see Fact Sheet, Geomorphologists versus Engineers, Differing Perspectives).

At the toe of reflective faces, the structure and beach material are exposed to larger hydraulic forces. When the beach disappears, shore armoring with a shallow foundation is at structural risk. Toe scour is a common cause of failure for seawalls (USACOE, 1981; Silvester and Hsu, 1993, p. 282).

A quasi three-dimensional experimental and theoretical study reviewed by Kraus (1987), predicted that maximum erosion would occur in the vicinity of the toe of the seawall, and maximum net erosion would occur when the seawall is located about three-fifths of the distance from the wave breakpoint to the still-water line. These findings are in agreement with some experimental flume results. However, in Supertank experiments conducted at Oregon State University, two-dimensional tests of beach sections with and without a seawall indicated that the presence of the seawall had no noticeable effect on the overall profile shape (Kraus, personal communication, June 10, 1992; Pollock, 1993).

Geomorphologists Versus Engineers
Different Perspectives

Forces, not walls, move sediment. Those forces are present in the coastal environment with or without shoreline armoring. Armoring affects the beach and nearshore zone to the extent that the armoring surface interacts with wave and current forces or that the structure affects stability of beach material.

Thieler, Young, and Pilkey (1992) support their conclusion that shoreline armoring causes narrowing of beaches by correlating historical measurements of dry beach widths with the presence or absence of armoring. Others (Dean, 1988; Basco, 1992; Kraus, 1987) have countered that shore erosion was likely occurring at these sites before armoring, thus the perceived need for armoring the shore.

It is important to understand the philosophical reference frame of the authors to understand the appropriateness of applying their conclusions to Puget Sound. The "geomorphologist camp," which Pilkey's views represent, attaches little significance to the fact that the beach profile might be migrating landward–as in the case of barrier islands–through removal of material on the seaward side and deposition on the lee side. As long as the dry beach width is maintained, the recreational value is preserved. Loss of resources or investment in the path of the translating beach profile is of little relative consequence. When a fixed structure is emplaced on the beach, a reference point is then established from which distance to the water line can be measured. From this Legrangian point of view, the narrowing of the beach in front of the structure is due to the presence of the structure. Whether hydrodynamic processes are altered by the structure or not, narrowing would not occur were it not for the presence of the structure. This is illustrated in Figure 1.

The "engineer camp," whose views are reflected by Basco (1992), for example, often equates "narrowing of the beach" or "loss of the beach" with "erosion"–overlooking the aspect of the shore that is the dry beach width–while focusing on sediment budgets, changes in reflectivity, and alteration of momentum fluxes in specifying details of hydrodynamic effects of armoring.

The geomorphologist view is valuable for planning an investment at the shore. One should be aware of shoreline change rates for the site, the locale, and the region to analyze environmental and economic outcomes fully. However, valid engineering decisions can be made to armor the shore. A correct basis for those decisions is a quantification of the physical processes that lead to shoreline change. The "anything-that's-not-natural-is-not-good" argument of some geomorphologists is inconsistent with the historical and philosophical basis that drives humans to improve their living conditions.

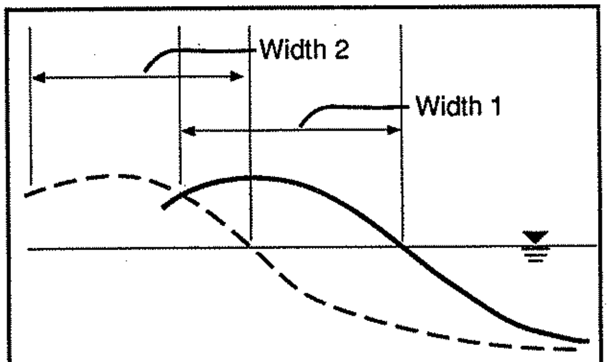


Figure 1. **Geomorphologist Camp.**
Shoreline is moving but dry beach width stays the same.

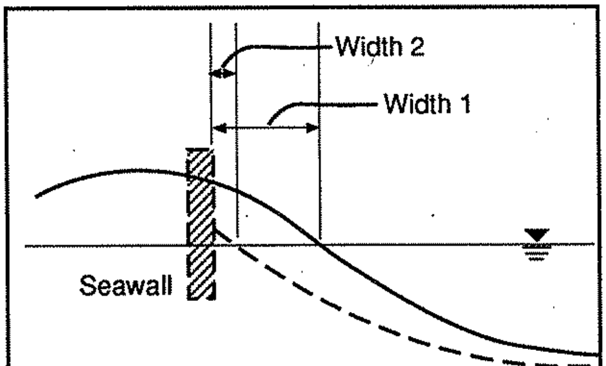


Figure 2. **Engineer Camp.**
Shoreline is moving - what caused the dry beach to narrow?

There is some local evidence from Puget Sound that there may also be a lower boundary to interactive effects between shore structures and the associated beach profile. A rock revetment built at West Point with its toe at Mean Lower Low Water (MLLW) created no modification to the existing bottom profile over a 20-year period (Domenowske, 1987). Potentially, shore protection caused modifications to beach profiles may be limited to a zone between MLLW and OHWL; this, of course, includes virtually all shore protection around Puget Sound.

End Wall Effects. When located waterward of OHWM, end walls or return sections of shore armoring structures (i.e., walls that anchor the armoring structure to the upland) present reflective surfaces to waves. If the return section is oriented perpendicular or nearly so to the beach, reflected waves are directed to the adjacent beach and reinforce incoming waves. The resulting increased transporting forces remove beach material adjacent to the ends of shore armoring (Figure 4-3). The further an end wall extends waterward of OHWM, the greater will be its impact on local beach erosion.

Abrupt corners and ends of armoring exposed to waves also form defracting points, causing wave crests to radiate outward from the point. Crests that strike the adjacent beach can cause localized shore erosion similar to that from reflected waves (Figure 4-3).

Erosion caused by reflection of oblique waves from the hardened surfaces of the return wall onto the beach, or by waves diffracted at the corner of the armoring, is a function of only the height and direction of waves arriving at the eroding beach. Diffracted and reflected waves impinging on the shore are functions of incident wave height, angle and structure characteristics.

Observations from a scaled model study (McDougal, 1987) suggest that the alongshore extent of the eroded shoreline adjacent to an armoring structure continues downdrift for approximately 70 percent of the armoring length. Griggs and Tait (1992 p. 30) observed at one field location (Aptos Seascape, Monterey, California) that the length of eroded shoreline was about 50 percent of the adjacent structure's length. Data from Seattle's West Point sewage lagoon revetment (Section 5) suggest shoreline erosion extending approximately 30 percent of the revetment length. While a generalized relationship is often sought between some armoring structure dimension and the extent of beach effects, it is questionable to link seawall length with the length of shoreline erosion, because of the added complexities of the end-wall effects noted above.

It is evident from the literature (Smith and Chapman, 1982; Tait and Griggs, 1991) that a beach profile containing a seawall responds differently to moderate waves than to intense storm waves. Those who see no universal danger of seawalls usually refer to observations of processes under moderate wave conditions, while opponents of seawalls point to beach changes on a retreating coast or after unusually large storms in which material has been lost from the shore. Dean (1988) reports laboratory tests show that the additional scour volume near the base of a seawall is about 60 percent of the upland volume that would have been eroded if the seawall were not present. These tests were to simulate the

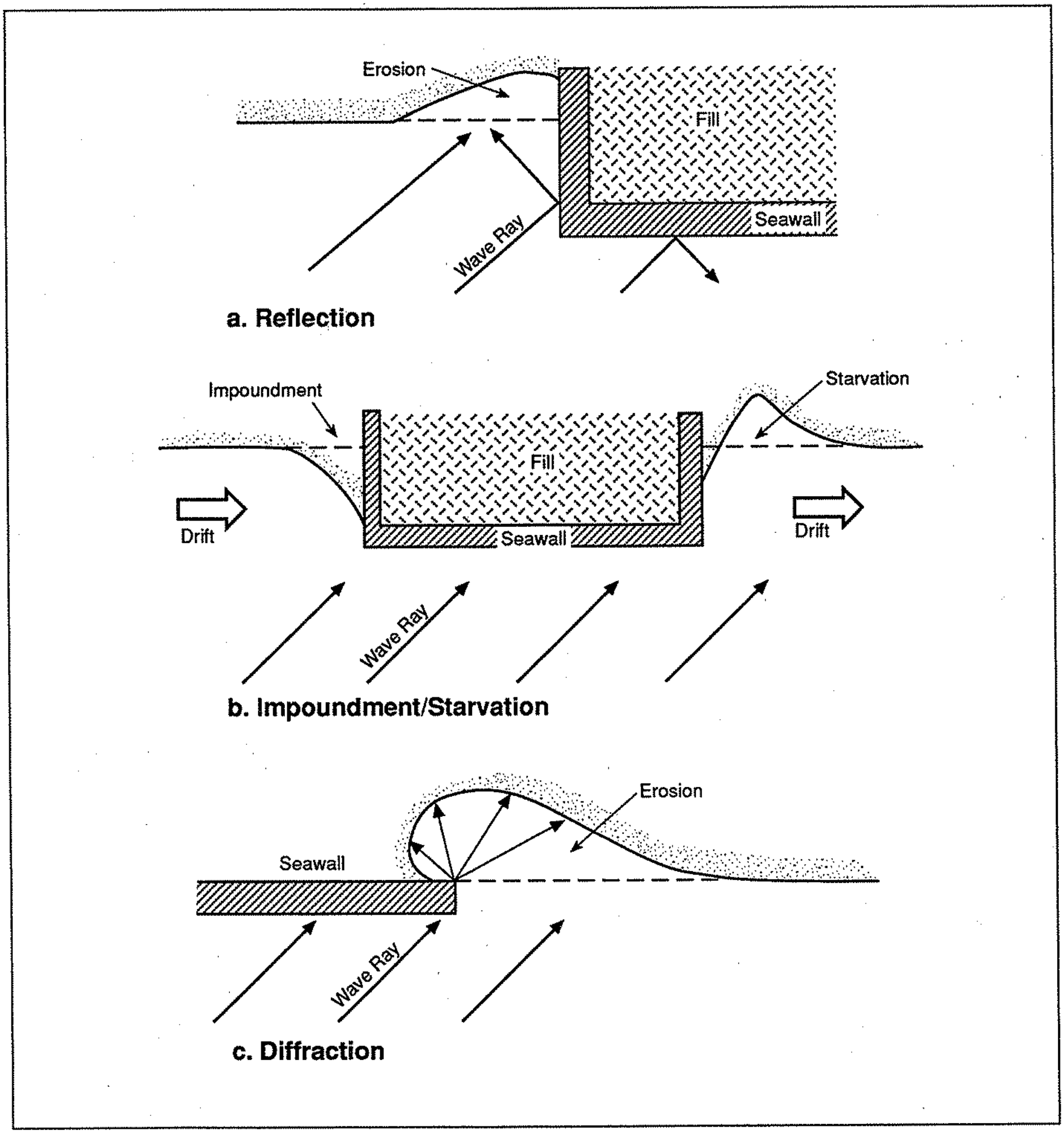


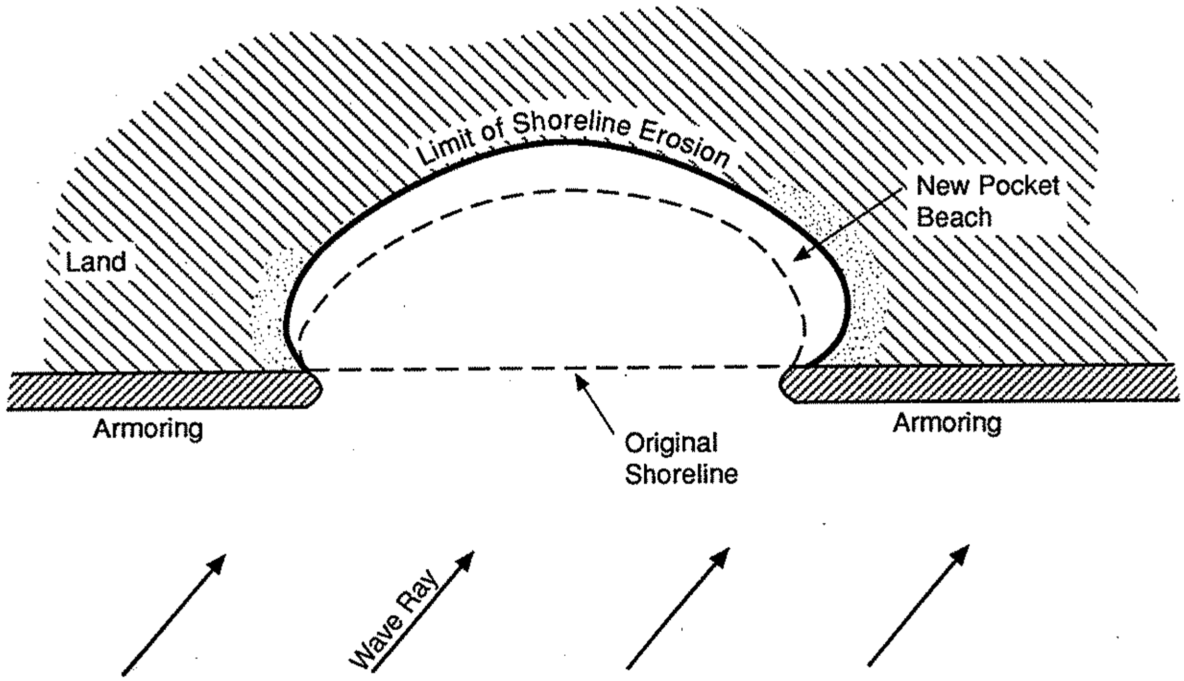
Figure 4-3
End Wall Effects

adjustment made in a beach during a storm when there is a "demand" for sand from the dry beach to be transported offshore to build a storm bar. This is a *cross-shore* dominated adjustment. This study revealed how retaining sand (behind a seawall) on the dry beach affects the profile, and was not a study of structure end effects.

Dean (1986) proposed that the beach profile seaward of an armored segment does not depend on the presence of the armoring but on the amount of sand available to form the profile. Large incident waves at a shore require a surf zone having dimensions suitable to dissipate the incident wave energy. If adequate beach material is available, the profile will attempt to form the dimensions that provide for a uniform rate of energy dissipation across the surf zone during a storm event. If beach material is inaccessible because it is impounded or "locked up" behind shore protection structures, storm waves will attempt to "borrow" the necessary beach material from another unprotected location. The amount of material borrowed from the unprotected beach depends on the wave height (the "demand") that alters the profile, but also on the amount of material kept from availability (impounded). After the storm event, in a climate of constructive waves, if the redistributed material is still in the shoreline reach, the beach profile will again be remolded to provide for the required energy dissipation rate. If the material is inaccessible, however, because it might have been transported alongshore or offshore down a steep slope, the profile will remain altered permanently.

Shore retreat immediately adjacent to a seawall is another form of beach narrowing. Erosion that begins to occur in the unprotected gap between two adjacent shore protection installations convinces the owner of the eroding property that they too should place a structure at the shoreline. Erosion in the gap, however, will progress to only a certain extent—and then stop—without engineering intervention (Figure 4-4). Studies by Hsu, et al. (1989 and Silvester and Hsu, 1993, p. 229)) of the geometric form of numerous headlands and bays are pertinent to the response to discontinuous shore armoring. Their studies indicate that shoreline retreat within the gap (given uniform readily erodable sedimentary material) will not exceed 30 percent of the gap distance between adjacent sections of armoring, for most reasonable angles of wave approach.

Fulton-Bennett and Griggs (1986) state that no systematic observations have been made to provide a generalized answer to the question of whether or not the presence of a seawall results in increased erosion of adjacent areas. Factors influencing the answer certainly include how far seaward the wall extends, the type of coastal environment, and the type of wall involved. They confirm that as the amount of continuously armored coastline increases, outflanking becomes a problem in the unprotected gaps. Two concrete walls they studied were on shores backed by dunes and no accelerated wave-caused erosion was observed along the flanks of the walls. Riprap at another site settled much more around gaps in the continuous riprap revetment than elsewhere, during 1983 California coast storms. It could not be verified that the settlement was caused by outflanking, or by some other factor.



Note: Maximum shoreline retreat equals about one-third of armoring- gap distance

Figure 4-4
Shoreline Erosion Between Armored Segments

Soft Shore Protection

Beach nourishment and other shoreline forms that can dramatically adjust to changing wave conditions have similar effects of retaining upland material that might otherwise be contributed to the littoral stream. These methods of shore protection do not present reflecting surfaces or diffracting points to the waves. One effect of placing beach nourishment is to widen the beach locally. If extremely coarse material (shingle, cobbles) is placed, the steep, high-tide beach morphology which forms only above the MLLW elevation might be mimicked (Keuler, 1979, p. 13).

Beach material added in an area experiencing shoreline retreat acts as an additional "supply" for a littoral system that is not transporting material at capacity for the prevailing energy level in the littoral zone. Periodic maintenance of the beach—i.e., fill renourishment—will be necessary until either, an adequate supply rate is provided by an updrift source or, the energy level is lowered at the nourishment site. The latter is accomplished by creating a flatter, shallower beach profile. The visible beach often narrows after beach nourishment has occurred. Some people interpret this as loss of beach material and loss of the beach itself—and therefore a loss of the investment in nourishment. In fact, however, if the beach is in equilibrium, the added material fills the profile below the water level, where it functions as an energy absorber to some extent and protects the upper profile.

Compliant shorelines typically occur as small pocket beaches between "hardened" headlands and will self-adjust both along shore and cross-shore, sustaining a dynamic equilibrium. At any point in time and space, the shoreline position, profile, and orientation may differ, but the time and space-averaged shoreline remains constant.

Shoreline vegetation can act as a sediment trap and cause accretion of the backshore and might resist erosion in moderate storms. It is nevertheless vulnerable to attack in extreme storms. On an eroding beach, if non-storm intervals of sufficient duration exist between the erosional events, vegetation might be developed enough to halt shore retreat in the moderate events. If the newly vegetated area was previously contributing sediment to the littoral stream, the stabilized area will diminish the rate of introduction of upland and/or littoral material to the drift cell. This may lead to downdrift impacts from sediment starvation.

Conclusions

1. It is widely stated that hard shore protection—seawalls, bulkheads, and revetments—reflects wave energy back into the breaker zone, increasing water oscillation and turbulence in front of the armoring, and particularly at the toe of the armoring (Kraus, 1987). This reflected energy mobilizes both finer suspended and coarser bedload sediments, making them available for transport out of the area. One result is narrowing of the beach in front of armored shorelines.

2. It is important to distinguish beach narrowing due to regional shoreline erosion and retreat from narrowing due to hydraulic impacts from shore armoring.

3. Armoring located landward of OHWM has no impact on the beach until unusually high water levels or storm conditions allow waves to reach the armoring. Rapid beach erosion can then occur.

4. Armoring located waterward of OHWM will cause increasing impacts as armoring, waves, and sediments interact more frequently at successively lower elevations across the beach. Kraus (1987) predicts maximum net erosion when the seawall is located about three-fifths of the distance from wave breakpoint to the still-water line.

5. End wall effects—in which shore protection juts onto the beach waterward of OHWM, and behaves like a groin—can cause significant additional beach erosion.

6. Increasingly reflective armoring (e.g., smooth seawalls) will have a greater impact and result in more pronounced beach narrowing, than less reflective shore protection (e.g., sloped rock revetments or gravel beach nourishment).

7. A quantitative relationship between length of shoreline armoring and length of downdrift erosion (i.e., later equals 70 percent of former) has been postulated, but has not been widely tested nor generally accepted.

8. Another quantitative relationship suggests that the volume of sediment scoured in front of a seawall equals 60 percent of the "upland" volume that would have been eroded in the absence of the seawall. This too remains to be adequately tested.

9. Soft solutions, particularly beach nourishment, can minimize the potential for beach narrowing. This is because such approaches do not present reflecting surfaces or diffraction points to the waves, and because the nourishment material itself can increase sediment supply to the littoral transport system.

10. Beach narrowing in front of shoreline armoring, and related end wall effects, are the most widely accepted, best documented hydraulic impacts caused by armoring. To date, however, most studies have examined the responses of sand beaches to shoreline armoring during severe storms, rather than more "normal" wave conditions.

11. Beach narrowing in front of armoring is common in Puget Sound. Generally coarser beach sediments and lower wave energy may minimize impacts, but severe winter storms, such as seen in 1990-1991, can cause serious episodic impacts.

Does Shore Protection Cause Lowering of the Beach Profile?

Hard Shore Protection (Armoring)

Observations in the field, as reviewed by Tait and Griggs (1991), indicate that scouring a trough locally in front of a seawall high in the beach profile occurs in response to large storm waves and the beach sometimes recovers. Recovery might take a year or more and meanwhile the integrity of the seawall is at greater risk. Profile deflation is a slightly different process and results in a general lowering of the beach profile in front of a wall. Monitoring by Griggs and Tait (1988) at Monterey Bay showed that with the onset of erosive winter conditions, but before the waves had reached the seawalls, the beach was initially cut back uniformly alongshore. Profile lowering began when waves reached the wall. The wide summer berm in front of the wall was eroded sooner in front of the seawalls "due to scour from reflected waves." The contours of the beach face migrated landward in front of the wall, while the berm profile persisted seaward of the position of the wall on the adjacent natural beach.

If armoring is placed on a retreating shoreline, even initially landward of OHWM, the beach profile will eventually lower to the point where waves will reach the armoring, unless beach material is artificially added to the profile. If the toe is not buried deeply enough, the structure will be undermined. If the armoring is not undermined, the previously described reflection and scouring conditions will develop. This is one case when armoring placed high in the profile does not remain there because the profile translates shoreward. The sand level becomes lower at a fixed location. Translation of the shoreline initially is caused without influence of the armoring, but rather by increased erosion in a sediment starved system. Without the armoring, the profile would lower to the level for waves to erode the upland backing the beach and liberate new shore material. Instead, the armoring has fixed the shoreward boundary and has become the fixed point for referencing shoreline movement.

As was discussed in relation to beach narrowing, a shoreline that is regionally retreating is starved of beach material. There is insufficient material to maintain the equilibrium profile, it translates shoreward, and depth increases at a fixed location. If there is an adequate amount of material available to fill the profile, general profile lowering would not result from the presence of the armoring. Few locations in Puget Sound have an abundance of beach material. It is usually at the location where individual bulkheads are constructed that the effects of sediment starvation are manifested. Localized scouring immediately in front of the armoring should be expected.

An observation of field conditions at one East Coast location has relevance to Puget Sound. FitzGerald (1980) describes beach changes in response to an intense February 1978 storm. A beach backed by a seawall showed a general profile trend of accretion where gravel was predominant and erosion where sand was predominant. The most severely damaged beaches were those exposed to direct wave attack, had relatively little or no high tide beach, and had a relatively steep offshore gradient. This points up the difference in the behavior of sandy beaches and gravelly beaches under similar wave conditions, and qualifies conclusions drawn from studies of sandy beaches. The gravel content in high tide beaches of Puget Sound is important to maintaining the beach width and protecting the bluffs.

Kraus (1987) reviewed a field study of interactions of seawalls and beaches at Seabrook Island, South Carolina, before and after the 1979 Hurricane David. Although the hurricane was judged to be marginal upon landfall, moderate erosion (10-15 cubic meters per meter of beach length) was experienced by central beaches backed with structures. The beach adjacent to a concrete seawall was lowered 0.64 m. All profiles exhibited recovery over the 5-week monitoring period, although the recovery of the profile at the wall was slower than average.

Kraus, Gravens, and Mark (1986) analyzed survey data from a 12-mile stretch of north New Jersey coast that is protected by a rubble seawall. The profile shape has remained stable over the past three decades. Individual profiles dated 1953 and 1985 were compared with the equilibrium profile shape described by Dean (1977). (The equilibrium profile is computed with a factor for sediment fall velocity and a power law relationship based on distance offshore.) The comparison suggests that the profile along a seawall-backed beach tends to be in equilibrium with the coarser grain sizes comprising the beach sediment. This implies that a lower profile develops in front of shore armoring after installation than was present prior to armoring. It might also mean that the beach retains only the coarser fraction in front of the armoring, which is consistent with the notion of greater competence of combined incident and reflected waves to move sediment particles and the winnowing of sand from the beach material fronting the armoring.

Posey and Dick (1987) conclude from a study of 50 years of monitoring data at Tybee Island, Georgia, that "seawalls or bulkheads will cause lowering of the beach profile due to reflected wave energy providing little, if any, energy absorption or dissipation." There was no documentation presented on which to base the conclusion, however this belief is commonly expressed in the literature.

Because material tends to be coarser in Puget Sound than other study areas, detailed wave measurements and profile surveys should be accomplished during storm events in the vicinity of shore armoring. Whether wave forces exerted on the substrate are amplified in front of a bulkhead to the point of moving the coarser material from this part of the profile needs to be determined. The lowering of beach levels (up to 3 feet or more) observed in front of some armoring (Shipman and Canning, 1993) reflects decades of landward translation of a sloping beach profile, rather than the impact of any single storm event. Localized deepening by shifting the profile is also described by Dean (1991).

Soft Shore Protection

Soft shore protection solutions do not cause local deepening of the beach profile. Their function is generally to fill the profile with placed material. Widening a sloping beach also increases the elevation of the beach. That has important benefits for protection against wave runup. Mossa and Nakashima (1989) reported results of monitoring seawalled and nearby natural beaches at Bayou Lafourche, Louisiana, over a period of 3 years that included impacts of Hurricane Gilbert. The seawall was fronted by beach nourishment.

One conclusion was that the one powerful hurricane was responsible for 70 percent of the volumetric loss of the beach, measured after a 3-month recovery interval. Thirty percent of the loss could be attributed to long-term shoreline retreat factors. This reinforces the notion of episodic erosion events. A second conclusion was that, "beach nourishment was an important component of project performance and should be repeated every three years as planned in order to protect the seawall." The recommendation is that soft solutions should be used in combination with hard solutions on shores experiencing long-term retreat, so that any profile lowering that might be caused by the structure is ameliorated by the artificial beach fill.

Conclusions

1. A shoreline that is regionally retreating is starved of beach material. Since there is inadequate sediment to maintain an equilibrium profile, the entire beach profile moves shoreward and depth increases at a fixed location.

2. Only armoring that continually interacts with waves and sediment can cause permanent profile lowering. In areas of coarse beach material (not capable of maintaining an elevated water table) armoring must be positioned waterward of OHWM to influence the beach in that way.

3. Due to both sediment impoundment and hydraulic impacts from wave reflection, beaches in front of shoreline armoring waterward of OHWM are likely to become both narrower and lower.

4. As with narrowing impacts, studies of beach lowering mostly come from sand beach/storm wave interactions. Few quantitative data are available.

5. Beach lowering and scour at the toe of shoreline armoring are commonly observed in Puget Sound, but only very limited systematic, quantitative survey data describing such features are available (see Section 5).

Does Shore Protection Cause Coarsening of the Substrate?

Hard Shore Protection (Armoring)

As stated above, armoring that interacts with waves and sediment can increase the rate of energy dissipation and turbulence at the toe of the armoring. As beach material is mobilized in the turbulence and currents resulting from wave impact, the smaller more easily transported particles, will be preferentially transported leaving the coarser material in the upper layer.

Transport relationships show that, above the fine sand size class, the stronger the current the larger is the particle that can be carried in the flow. Pilkey and Neal (1988) assert that shore-parallel structures (bulkheads) tend to increase offshore-directed velocities by wave reflection during storms and increase the intensity of longshore currents. No measurements are presented nor other studies referenced. The assertion, although appearing logical on the surface, is in contrast to findings of Jones (1975). He derived analytical expressions indicating that the amount of scour and the speed of longshore currents are reduced in proportion to the reflection coefficient. If a portion of the incident wave flux is reflected offshore, rather than being transferred to the bottom to drive the current, then a physically reasonable argument can be made against coarsening of the substrate in front of shore armoring. Photographic and sediment sampling data are needed to conclusively state the effect of shore structures on substrate size distributions.

A longshore current, by itself, flowing near the toe of shore armoring is not expected to sort or transport larger particles of the size found on most Puget Sound beaches. Wave forces and turbulence generated during wave breaking would move beach material, through a combination of both (finer) suspended load and (coarser) bedload transport. Once suspended in the water column, even if for a very short time, the smaller particles would be translated (winnowed) with the mean current. Where wave breaking is induced by shore armoring, or when structures are located so as to be struck by breaking waves, the substrate could thus be modified to coarser sizes.

There is apparent evidence at Sunnyside Beach, Steilacoom, of coarsening of the beach in front of a bulkhead structure (Figure 6-9). Coarse cobbles are found in front of the bulkhead, but not on the flanking beaches.

Field observations by Puget Sound Fisheries staff suggest "during storm" impacts related to sediment sorting and coarsening. Increased water turbulence close to shoreline armoring may result in winnowing and settlement of sand and pea gravel that "mimics" ideal spawning habitat for some fish species (Ken Bates and Neil Rickard, Fisheries, personal communication, May 1993). Without the armoring and added turbulence, the pea gravel would provide a stable habitat for egg laying and larval fish development. With armoring, however, subsequent storm waves will resuspend and re-sort the pea gravels, destroying any fish eggs present. No quantitative measurements or independent verification of these general observations are available to date.

Soft Shore Protection

Beach nourishment can cause coarsening of the substrate directly by the placement of material that is coarser than that of the native beach. In some instances the deliberate intent is to place material that is not compatible with the native, because the later would not offer the protection needed. Such was the intent of constructing a gravel-cobble beach on a rapidly retreating shore of Flathead Lake, Montana, to stabilize the shore for protection of upland habitat (Da Costa, Scott, and Simpson, 1992).

Beach nourishment containing a mixture including fine grain sizes that is placed on an energetic shore will be reworked and sorted according to particle size. If the littoral flow has the capacity to carry all the fine material exposed to it at the nourishment site, it will be selectively removed. On gently sloping beaches, the finer material is removed to the offshore to form a bar (Bird, 1991) and contribute to the longshore transport system at depth.

Conclusions

1. Armoring that interacts with waves and sediments increases water turbulence. The resulting increase in sediment suspension and transport will preferentially remove finer material, leaving coarser sediments (e.g., gravels, cobbles) on the beach surface.

2. "During storm" impacts may produce substrates in front of armoring that "mimic" fish spawning gravels. Resuspension of the pea gravels by storm waves and increased turbulence may subsequently destroy any fish eggs present.

3. Soft solutions may intentionally coarsen beach sediments in order to increase their stability under given wave conditions.

4. While some general observations are available (see Section 5), no systematic, quantitative data from Puget Sound describing these impacts have been located to date.

Does Shore Protection Cause Loss of Large Organic Debris at the Shore?

Hard Shore Protection (Armoring)

Large organic debris (LOD) can take the form of beached logs that have floated to a site, as well as living or dead vegetation that falls on the back beach throughout the year, or from slope failure or a more gradual contribution through soil creep. Historically, the most significant role of LOD—especially the massive accumulations of drift logs and stumps at river mouths, backshores, and bluff toes (see Fact Sheet)—was the protection of these locations from excess wave and current action, and thus the slowing of local erosion.

Large organic debris also forms both a microhabitat and food source that is a very important in the overall shoreline food web. LOD can be prevented from accumulating at a site if the beach is either too steep, or the profile is too low for LOD to become beached. To the extent that profile steepening and lowering can be attributed to shore armoring (and it will be situation specific) armoring can cause loss of LOD.

Again, Sunnyside Beach offers an interesting example in that drift logs have accumulated at both the northern and southern ends of the beach but not immediately in front of the bulkhead (see Section 5).

There is reportedly much less log debris on the shores of Puget Sound now than there was 30 years ago, however, the effects other practices far outweigh those of shore armoring in this decrease. A spokesman for Bainbridge Marine Services stated that years ago a row of logs 20 feet wide could be seen all along the beaches of Hood Canal, but logs are scarce today (see Fact Sheet). Reasons for the decline certainly include the fact that stumps are no longer pushed over the bank and log rafting is not practiced as much as decades ago (Bainbridge Marine Services, 1992). The sources of much LOD have been removed due to development of uplands, river impoundments, riverbank armoring and logging (Neil Rickard, Fisheries, personal communication, May 1993).

Soft Shore Protection

Soft shore protection solutions, by their nature, provide a beach at least temporarily. Where the profile has been remolded by wave action, a slope is produced conducive to beaching of floating debris. An exception is if the beach fill is of such coarse material and the waves so energetic that a very steep slope naturally develops. When soft solutions buffer a bluff or upland vegetation from the destabilizing forces of the waves, introduction of organic debris from those sources into the shore zone may be slowed down or cut off by the placed material. Soft solutions therefore invite greater waterborne LOD accumulation but inhibit land originating debris.

Conclusions

1. Large organic debris can be prevented from accumulating at a site if the beach is either too steep, or the profile is too low for LOD to become beached. To the extent that profile steepening and lowering can be attributed to shore armoring, and it will be situation-specific, armoring can cause loss of LOD.

2. Since soft solutions, by their nature, provide a beach, they are more likely to increase, rather than diminish, the beaching of LOD.

3. While some general observations are available (see Section 5), no systematic, quantitative data from Puget Sound describing these impacts have been located to date.

FACT SHEET

Wood in Northwest Estuaries and on Coastal Beaches

U.S. Government reports and early visitors' journals of the Pacific Northwest documented great amounts of large wood in the estuaries and on the beaches at river mouths. These mid-1980 accounts describe the quantities and size of the drift trees, also called "snags," that significantly exceeded present amounts of woody debris in the lower portions of river systems and beaches.

Coast survey reports in the 1850s recorded that many of the drift trees in the lower Columbia River were as large as 150 feet long by 13 to 18 feet in circumference; the largest was 267 feet long (Secretary of the Treasury, 1859). Swan (1971) also reported drift trees as large as 250 feet long by 8 feet at the base, with a root span of some 20 feet, on the beach near the mouth of the Quillayute River in Washington Territory.

For several years after the coastal areas were settled in the 1850s and 1860s, roads were limited and land travel was impractical, especially in the winter. The coastal rivers were under the influence of tides for 12 to 40 miles from their mouths and had a low-gradient, deep channel along which commercial boats and log rafts could travel. Slowing currents and stormwind patterns, however, created zones of wood deposition in the estuaries. Many snags and sunken driftwood presented major obstacles for river traffic. The Corps' responsibility on many rivers during the late 1800s was to improve and maintain the navigability of the portions of the rivers deemed to be economically important.

The wood-removal operations by the Corps represented only a portion of the total wood pulled from the lower river systems. Gill-net fishers formed teams to remove wood that threatened to tear fishing nets. Local landowners and, later, port authorities also worked to maintain channel navigability.

Driftwood deposited in marshy areas between the main channel and the shoreline in the lower Nehalem estuary is estimated to have 50 percent fewer pieces and 60 percent less volume than in 1939. Stranded wood in the marsh in 1939 probably included many escaped lumber company logs that had been floated downriver or held in booms.

Watersheds annually replenished wood in the lower portions of the river basin and often floated wood into the ocean, from which it washed up onto the beaches. The lower river and estuary banks (riparian corridor) probably were the most common sources of the largest driftwood in the bays. In the 1860s the banks of the upper half of the Coquille estuary were lined with mature hardwoods that made travel on the Coquille like walking "dim aisles in ancient cathedrals" (Dodge, 1898). In the Tillamook River system in 1904, the U.S. Army Corps of Engineers cut down all overhanging trees along the banks of the estuary in an attempt to alleviate the woody debris problem (report of the Secretary of War, 1904-05.

The woody vegetation along many river corridors was cut in the 1800s to clear land and for a local source of wood. Upstream, the riverside forests were among the first to be commercially harvested because the logs could be floated down the river to the ports at a time when no other transportation was available (Sedell and Duval, 1985). Major sources of large wood for estuaries and beaches along the Northwest coast were exhausted by 1920.

The ocean is another source of driftwood in estuaries and on beaches. Winter storms blow ocean-transported wood into river mouths and onto coastal beaches, generally north of the debris' origin. Some of the woody debris may be buried for long periods by river-bottom sediments in the estuaries or in sandy spits on the coast, but much of the wood probably remains fairly mobile. Other driftwood is deposited on the marshes and along the higher ground of the estuary boundaries where it remains until it decomposes.

Fallen trees influence the estuarine portion of the ecosystem, mainly through their physical properties as large masses; they form heavy, solid objects and firm substrates in an environment where the bottom consists mainly of fine sediment. Fallen trees in the tidal river segment of coastal stream systems create riffles and provide shelter from predators for upper reach fishes. Examples of common fishes in this section of Pacific Northwest estuaries are stickelback, sturgeon, starry flounder, and juvenile and adult salmonids. Fallen trees can also affect local waterflow patterns by creating turbulence and thereby affecting the sedimentation pattern and the formation of bars or mudbanks. Emergent parts of fallen trees stranded in the channel or partly or wholly on tidally exposed banks are used by water birds as refuge perches during daily rest cycles or by predatory birds, such as herons and eagles, as hunting perches.

–Chris Maser, Robert Tarrant,
James Trappe, and Jerry Franklin (1988)

Impact by Shore Protection Method

The previous impact assessments describe several significant changes to the shoreline that are likely to result from hydraulic responses to shoreline armoring. Relatively little has been said, however, about the degree to which these impacts change when different methods of shore protection are considered—beach nourishment versus riprap versus bulkheads, for example.

While there is an extensive "engineering literature" on the structural design (i.e., stormworthiness) and effectiveness of different shore protection methods—the physical and ecological impacts of shore protection to coastal zone processes and habitats are rarely addressed (Tait and Griggs 1991; Nordstrom 1992). To our knowledge, no systematic, quantitative studies relating different shore protection methods to specific levels of beach or shoreline impact have been conducted. Studies such as Tait and Griggs (1991) and Smith and Chapman (1982, on boulder revetment walls) represent an important beginning.

Despite very scarce quantitative data, the literature suggests broad general agreement that differing impacts among shore protection methods largely result from differences in the degree or efficiency with which they either absorb and dissipate incoming wave energy, or reflect it back out into the nearshore zone. At one extreme, a long stretch of undisturbed sand beach—its slope in natural equilibrium with local wave conditions—dissipates incoming wave energy highly efficiently. Little or no energy is reflected back offshore, and beach impacts would be minimal. At the other extreme, a smooth-faced, recurved, concrete seawall, extending into intertidal depths, can reflect almost all of the energy from incoming waves back out into the nearshore zone resulting in substantial hydraulic impacts.

Tait and Griggs (1991) cite several studies that support this general relationship, quote:

> "Walton and Sensabaugh (1979; studying seawalls on the Florida Coast). . . point out that reducing the reflection coefficient of the wall (e.g., by sloping the surface or by placing a rip-rap apron at the toe) should reduce scour. Everts (1985) postulates energy concentration at the toe of a seawall is a function, in part, of the type of wall. 'A smooth vertical wall without a sloping rock toe in front reflects the most energy and dissipates the least.' Since a sloping, rough-surfaced or permeable wall should dissipate more of the incident wave energy, there should be less energy available for scour. In his review of the literature, Kraus (1988) finds that laboratory, theoretical, and field studies all support the notion that there is less scour when the wall is less reflective.
>
> An engineering field study by Toyoshima (1984) on the Pacific coast of Japan relates the changes in the shoreline subsequent to the replacement of an older, vertical seadike with a newer, sloping, rougher wall. The wall was replaced in 1982. In 1984, the author reports, 'the shoreline has

advanced substantially and the sand beach has grown extensively.' It should be noted that no description of regional or long-term trends was provided."

In contrast, Griggs and Tait (1988) examined the juncture of a vertical concrete seawall and a sloping rip-rap revetment at a Monterey Bay site. Both walls were further seaward on the beach profile and were hit frequently by waves during winter months. Two years of biweekly surveying indicated the beaches in front of both walls generally had indistinguishable profiles. In other words, although they would be expected to have considerably different reflectivities, there was no indication of this in the resulting beach profiles. Frontal wave reflection was observed at both walls at high tide.

Among different shore protection types, as the level of reflected wave energy increases (and energy dissipation declines), shoreline hydraulics are likely to be increasingly affected and all of the potential impacts noted above—beach narrowing, profile lowering and steepening, sediment winnowing/coarsening, loss of large organic debris, and increasingly pronounced downdrift effects—will become increasingly significant.

With this reflected wave energy/beach impact relationship in mind, different shoreline protection methods can be ranked in terms of their relative potential for increasingly serious impacts to shoreline hydraulics and beach characteristics (Figure 4-5).

While no Puget Sound data are available to quantify the relationship illustrated in Figure 4-5, a curvilinear pattern is more likely than a simple straight-line relationship. Beach strands, beach replenishment, and sand and gravel nourishment all effectively absorb wave energy and create minimum impacts. As soon as large solid objects—rocks, riprap, revetments, bulkheads—are introduced into the shoreline, energy absorption declines and wave reflection sharply increases. As increasingly reflective structures are placed on the shore—and especially lower in the profile—impact levels rise further, but the rate of increase slows as maximum levels of wave reflection are approached.

Impact by Location in Drift Sector

Just as changes in shore protection method are likely to result in different levels of hydraulic and shoreline impacts—so, differences in the specific location of an armored shoreline site within a drift-sector are likely to result in different levels of impact. No published data have been found to quantify these differences. However, a general understanding of shoreline processes (Section 2), drift sector characteristics (Schwartz, Wallace and Jacobsen, 1989), and armoring impacts (preceding sections) has been combined to produce the preliminary summary impact matrix presented in Table 4-2.

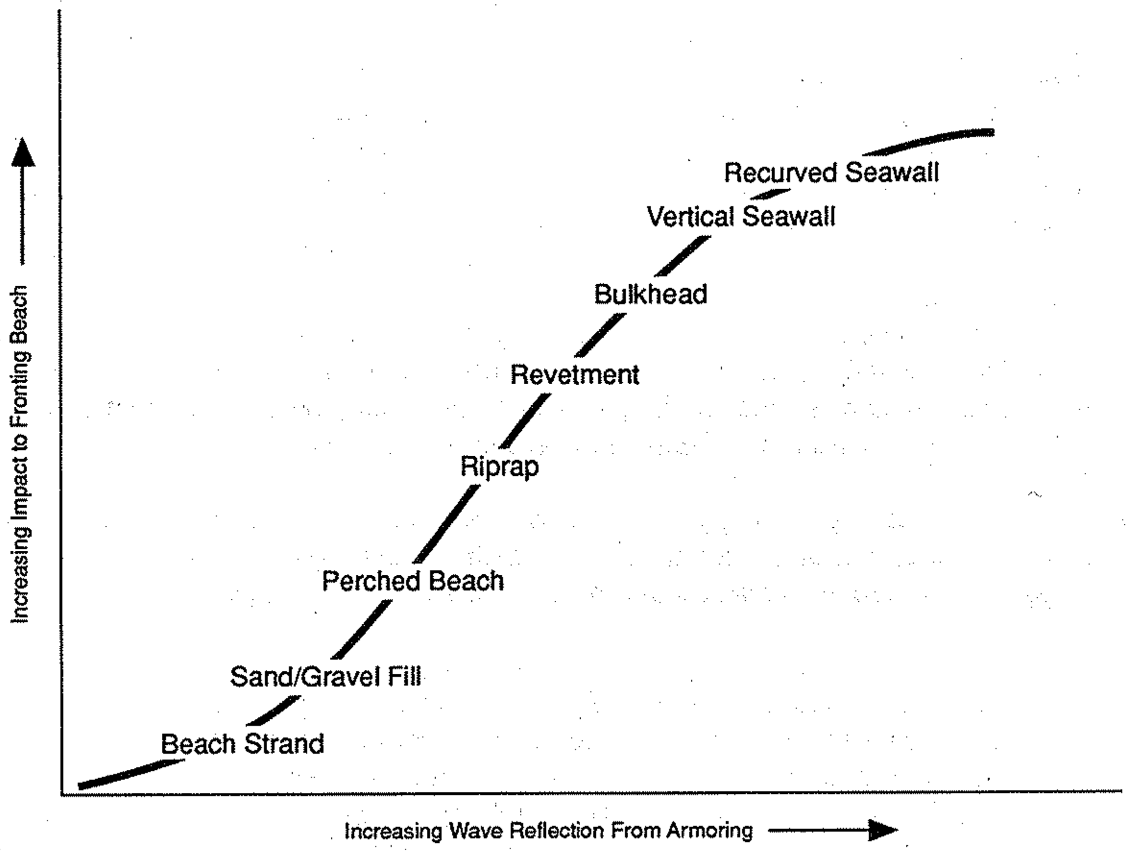


Figure 4-5

Relative Beach Impact by Shore Protection Method

Table 4-2 Drift Sector Summary Impact Matrix						
Drift Sector Location	**Source**		**Transport**		**Sink**	
Shore Protection Type	**Hard**	**Soft**	**Hard**	**Soft**	**Hard**	**Soft**
Downdrift Impacts of Sediment Impoundment	H	M/L	M	L	L	L
Higher Groundwater	H	L	H	L	H	L
Beach Narrowing	H	M	M	L	L	L
Profile Lowering	H	M	M	L	L	L
Substrate Coarsening	H	M	M	L	L	L
LOD Loss	H	H	H	H	L	L
Impact level: H = High, M = Medium, L = Low.						

The matrix presents a qualitative comparison of relative impacts—i.e., low, medium, and high levels of shoreline impact—that are expected to result from using "hard" versus "soft" shore protection methods within the source (feeder bluffs), transport (drift way) or sink (accretion terminal) areas of an idealized drift sector.

Within the drift sector source area, the principal impact of shoreline armoring will be to impound potential sediment sources, leading to beach starvation both at the armoring site and downdrift. The "hard" solution will also cause significant hydraulic impacts leading to further beach narrowing, lowering, coarsening, etc. This combination—source area/hard solution—presents the worst-case scenario in which all impacts are most likely to be highly significant. A "soft" solution used in the same situation—some form of beach nourishment for example—will partially offset both the impoundment of source materials and armoring hydraulic effects, thus lowering overall impact levels. Loss of LOD may remain significant as beach nourishment can bury or cut off existing supplies of organic debris from the feeder bluffs.

The downdrift impacts of (partially) blocking off the drift sector's sediment source will be high with an armored shoreline, but could be ameliorated with a "soft" solution, to the extent that any artificial beach nourishment could replace impounded natural (feeder bluff) sediment sources.

Within the driftway or transport area of the drift sector sediment impoundment would not be as serious a concern as in the source area, for the driftway is receiving sediments from the updrift source. Hard solutions would still cause medium to high hydraulic impacts onsite however, while soft solutions would again ameliorate local and downdrift impacts by feeding new sediment into the system.

Use of either hard or soft shore protection solutions should not be needed within the drift sector accretion terminal or sink, as erosion should not be a concern here. Should shoreline armoring be installed, however, hydraulic impacts can still be expected to occur. Since sediment is being received from updrift sources, all impacts would be relatively low-level.

Modification of groundwater relationships is likely to be more closely tied to armoring approach—increasing with wall height and impermeability—rather than location within the drift sector. Higher groundwater levels will tend to increase opportunities for sediment transport at all locations.

Obviously the matrix is idealized and, as noted elsewhere (Figure 2-9), seasonal changes in sediment drift direction as well as other specific features of an actual drift sector may substantially complicate the final outcome. As noted by Schwartz and Wallace (1986), referring to Puget Sound drift-sectors, "the potential for damage at any given proposed site must be evaluated and dealt with on an individual basis."

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Section 5
Puget Sound Case Studies

The original goal of the Puget Sound case studies was to locate regional study sites where specific impacts of shoreline armoring have been quantitatively documented. Ideally, sites were to be selected where both primary physical shoreline impacts and secondary biological effects could be documented.

The search for sites involved a broad-based literature review, a telephone survey of County shoreland planners, and extensive contact with the following recognized Puget Sound shoreline management experts:

- Eric Nelson and David Schuldt (U.S. Army Corps of Engineers Seattle District)
- Douglas Canning and Hugh Shipman (Ecology, Shorelands and Coastal Zone Management Program)
- Ken Bates and Neil Rickard (Washington State Department of Fisheries)
- Professor Richard Sternberg (University of Washington)
- Professors Maurice Schwartz and Thomas Terich (Western Washington University)
- John Downing and Ron Thom (Battelle Marine Laboratory, Sequim
- Wolf Bauer (private consultant, beach nourishment expert)

Each of these sources separately confirmed that the physical and biological effects of armoring on Puget Sound shorelines have <u>not</u> been extensively studied—especially not quantitatively—and only a very small body of relevant quantitative information exists (e.g., beach profiles, sediment grain size, erosion rates). Only one site was identified—Lincoln Park Beach, in Seattle—where reasonably extensive physical and biological impact data are both available.

This section, therefore, presents chronological histories for those few sites in Puget Sound with available physical data where primary impacts resulting from shoreline armoring (e.g., beach narrowing, profile lowering, downdrift effects) may have occurred. The effort focuses on selected sites in order to complete a site-specific, quantitative assessment rather than a generic, qualitative one.

Ediz Hook, Clallam County

Ediz Hook is a large sand spit (nearly 3.5 miles long, 90 to 900 feet wide) that protects the natural harbor at Port Angeles. Although located on the Washington shore of the Strait of Juan de Fuca, rather than in Puget Sound proper, the spit provides our best regional case history of coastal erosion and rehabilitation. Shore protection work at Ediz Hook dates back to at least 1930 and is well documented in three publications: USACOE (1976), Downing (1983), Galster and Schwartz (1990), and included references.

Ediz Hook is composed entirely of sand, gravel, and cobbles, derived by dominant eastward littoral transport of sediments discharged by the Elwha River to the west, and from glacial till feeder bluffs that form the coast between the river and the hook. Despite its large size, the hook only rises about 15 feet above MLLW; tide range at the hook ranges from -3.3 to +11.2 feet MLLW (Galster and Schwartz, 1990).

In 1911, Elwha Dam was constructed on the Elwha River, impounding as much as 50,000 cubic yards annually of sand, gravel, and cobbles that previously contributed to the littoral system feeding Ediz Hook.

A second major impact occurred in 1930, when an industrial waterline was buried along the toe of 3.3 miles of eroding feeder bluffs just west of the sand spit's landward base. Initially, 2,400 feet of wooden bulkhead was installed to protect the pipeline. Between 1958-61 additional steel pilings and riprap was added, such that a total of 6,000 feet of the bluffs were impounded behind shore protection structures. Galster and Schwartz (1990) indicate that impoundment reduced the bluff-related sediment supply from approximately 270,000 cubic yards per year in 1911 (the natural, predisturbance condition), to 95,500 cubic yards per year in 1930, and to 40,500 cubic yards pear year in 1961. Together, construction of Elwha Dam and placing shore protection at the toe of the bluffs (causing sediment impoundment), reduced the supply of sediment to the Ediz Spit littoral drift system by 88 percent.

During this period of declining sediment supply, the end of the spit grew some 350 feet, but at progressively slower rates:

Period	Growth Rate (ft/yr)	Sediment Added (yd^3/yr)
1870 - 1917	4.3	39,200
1917 - 1948	3.3	34,000
1948 - 1970	2.0	17,000
Source: Galster and Schwartz (1990).		

As noted in the impacts section, when actual sediment transport falls below the "capacity" for transport, the deficit will be made up by increased beach erosion. At Ediz Hook the reduced sediment supply was reflected not only in slower spit elongation, but also in steepening of the beach profile and significant erosional losses from beaches at the western/landward end of the spit. Galster and Schwartz (1990) note shore-zone depth changes, between 1940 and 1970, indicative of erosion of 82,300 cubic yards per year from the foreshore west of the spit, 26,100 cubic yards per year lost from the western portion of the spit, and 39,200 cubic yards per year added to the tip of the spit.

As erosion problems grew worse, between 1937 and 1970, a wide variety of piece meal shore protection measures—timber and pile bulkheads, riprap, timber and rock groins, steel sheet pile walls faced with riprap, and log crib bulkheads—where installed by different property owners. As the beach profile along the spit continued to lower, most of these installations failed.

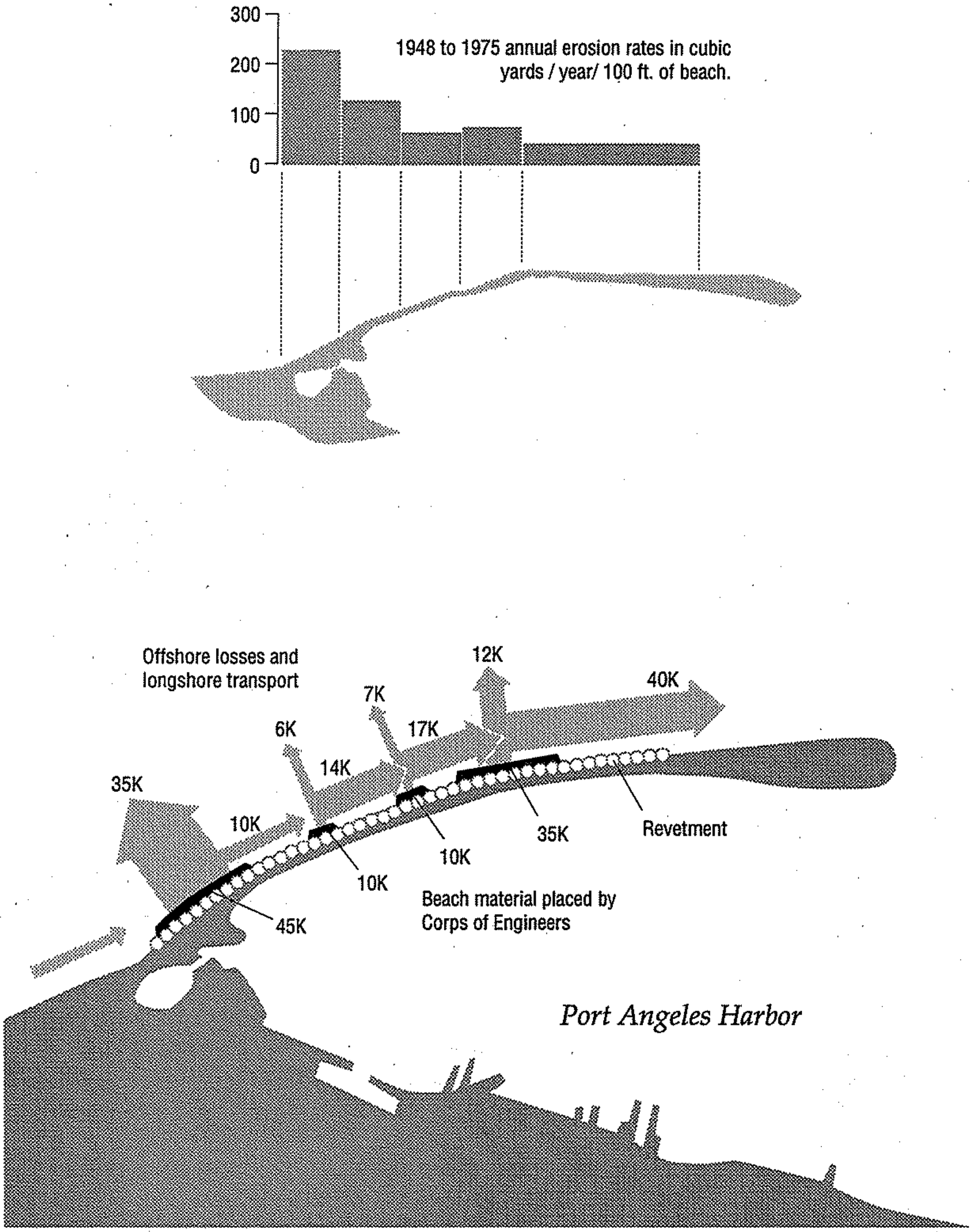
In 1977 to 1978, after extensive studies and tests (summarized by Galster and Schwartz, 1990), the Army Corps of Engineers implemented a comprehensive regional shoreline protection/beach renourishment program, at a cost of $5,600,000. The project included redesign and reconstruction of a continuous rock revetment along much of the spit's length, and placement of five stockpiles (totalling 100,000 cubic yards) of beach nourishment material at intervals along the spit (Figure 5-1).

The results of project implementation were subsequently monitored in a variety of ways—e.g., direct observations, aerial photos, hydrographic surveys, side scan sonar and sea bottom sampling. Distinctive "tracer cobbles" were released with the beach nourishment material to allow quantitative tracking of sediment movements within the longshore drift.

The general behavior of several separate stockpiles of beach nourishment material is illustrated in Figure 5-1. More detailed results are included and discussed in both Downing (1983) and Galster and Schwartz (1990). An additional 30,000 cubic yards of beach nourishment was added to two areas of the spit during 1985, and general repairs were made to the rock revetment. A long-term maintenance program recommends 20,000 cubic yards of beach replenishment be added at 5-year intervals.

Figure 5-1 shows that stockpiled nourishment material was reworked and transported by longshore drift, both offshore across the beach and alongshore, down the spit. Downing (1983) notes that the relative amounts of material moving offshore versus downdrift, is a result of differences in wave energy produced by wave refraction and the orientation of the beach with respect to the direction of wave approach.

Tracer cobbles placed on the beach midway along Ediz Spit exhibited rates of movement from 0 to 25 feet per day, with an average of 9 feet per day for the first 2.5 years, when they reached the end of the spit (Galster and Schwartz, 1990).



Source: Redrawn from Downing, 1983.

Figure 5-1

Ediz Hook: Erosion Rates and Longshore Transport

Summary

1. Ediz Hook provides the best regional example of direct and cumulative physical impacts, from both shoreline armoring and beach nourishment on the adjacent beach.

2. Quantitative data relating bulkheading to reduced sediment supply, narrowing and steepening of the beach profile, and slowing of spit extension are all available for known timeframes.

3. Data from tracer cobbles also provide field measurements of longshore drift rates.

Sunnyside Beach, Steilacoom
Pierce County

Data

- Beach profiles (1979, 1980)
- Historical photographs (1980)

The primary sources of information for this site are the Army Corps of Engineers (Seattle District) and the Town of Steilacoom Public Works Department. The site is located near the south end of Puget Sound within the town of Steilacoom, approximately one-half mile south of Chambers Creek (Figure 5-2).

Sunnyside Beach was formed during the late 1800s and early 1900s from waste sand deposited by adjacent gravel recovery operations located at was then known as the Thompson Gravel Pit. Construction of the Northern Pacific Railroad along this section of the shoreline was completed in 1910. Long-time area residents recall that there was a conveyor-belt system that transported the sand and gravel downhill from the adjacent upland bluffs, over Chambers Creek, and down to the Puget Sound shoreline (Steve Fischer, Town of Steilacoom Public Works, personal communication). The gravel was then loaded onto a barge from a dock for transport to other areas in Puget Sound. Remnants of the old barge dock are still visible at the site today. The waste sand was discarded after separation from the gravel and formed the fill material (the 1935 ground line is depicted in Figure 5-3). By 1930, all sand and gravel operations had been moved about one mile north to the Lonestar and Glacier Gravel Pits, leaving behind over 250,000 yd^3 of waste sand. This waste sand formed artificial "headlands" that extended about 1,500 feet north and south along the shoreline and projected nearly 600 feet into Puget Sound. The headlands are visible as two shoals (one in front of the bulkhead, the other slightly south) shown in an aerial photograph of the site taken in the late 1970s (Figure 5-4).

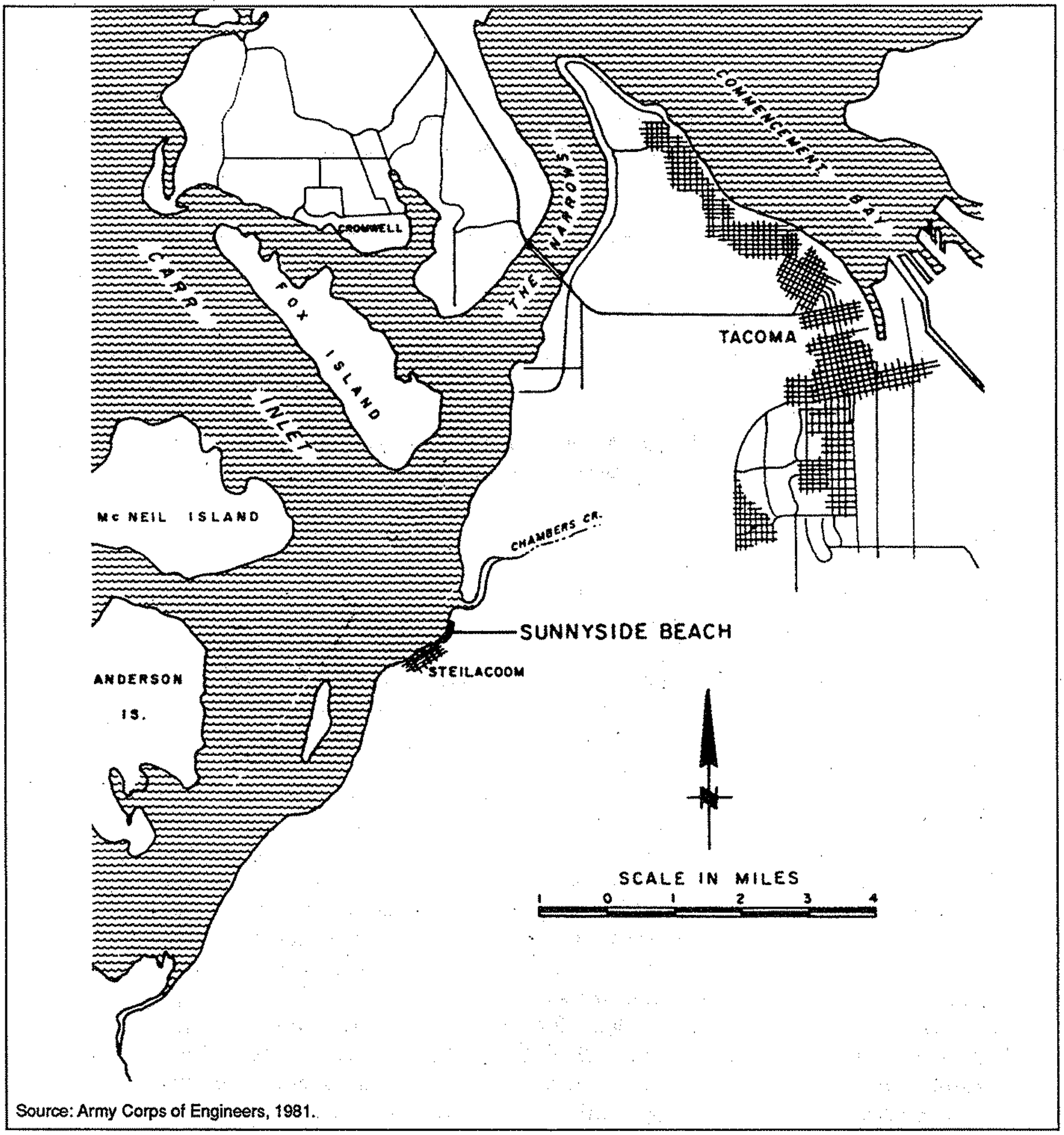
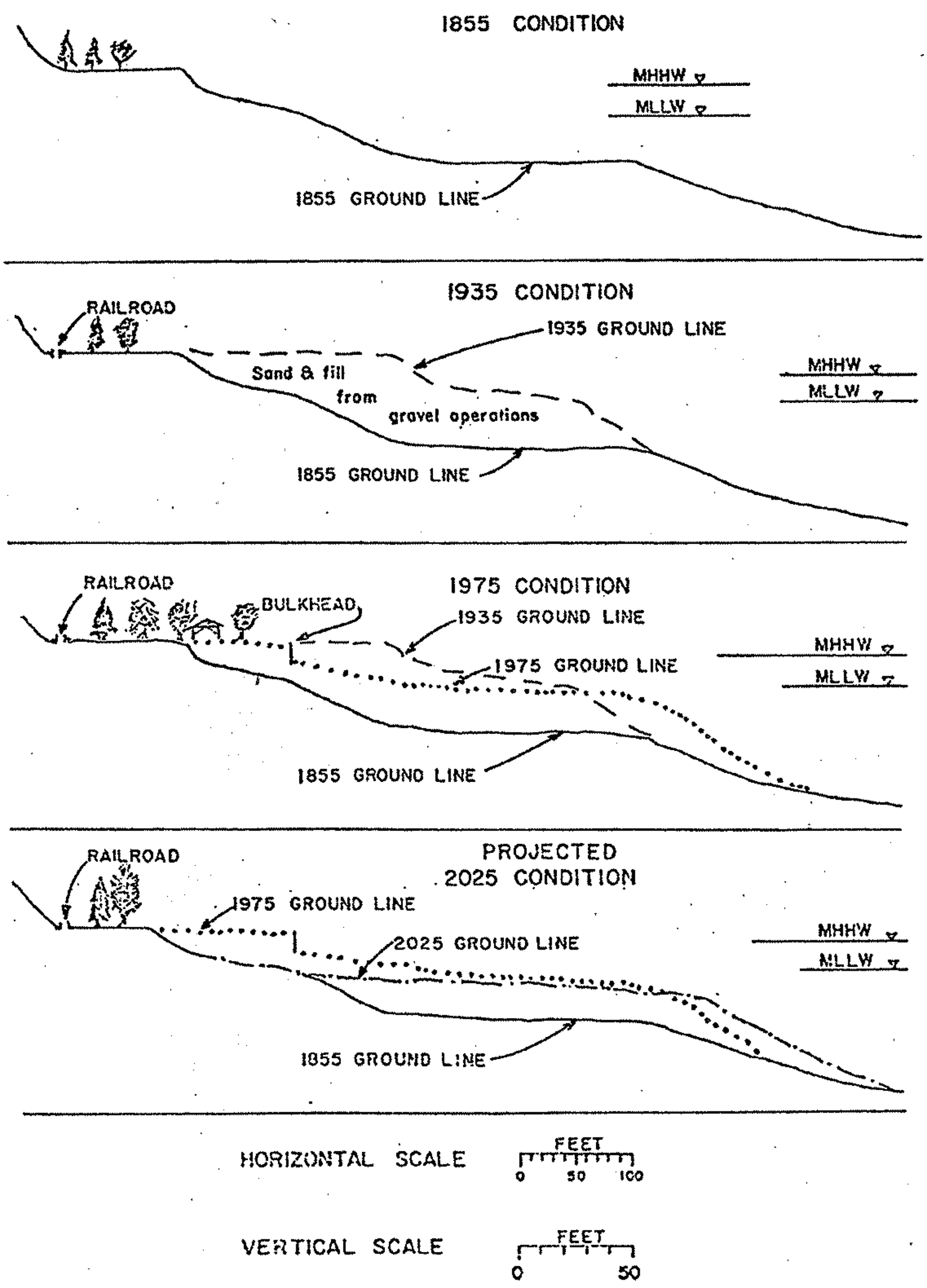
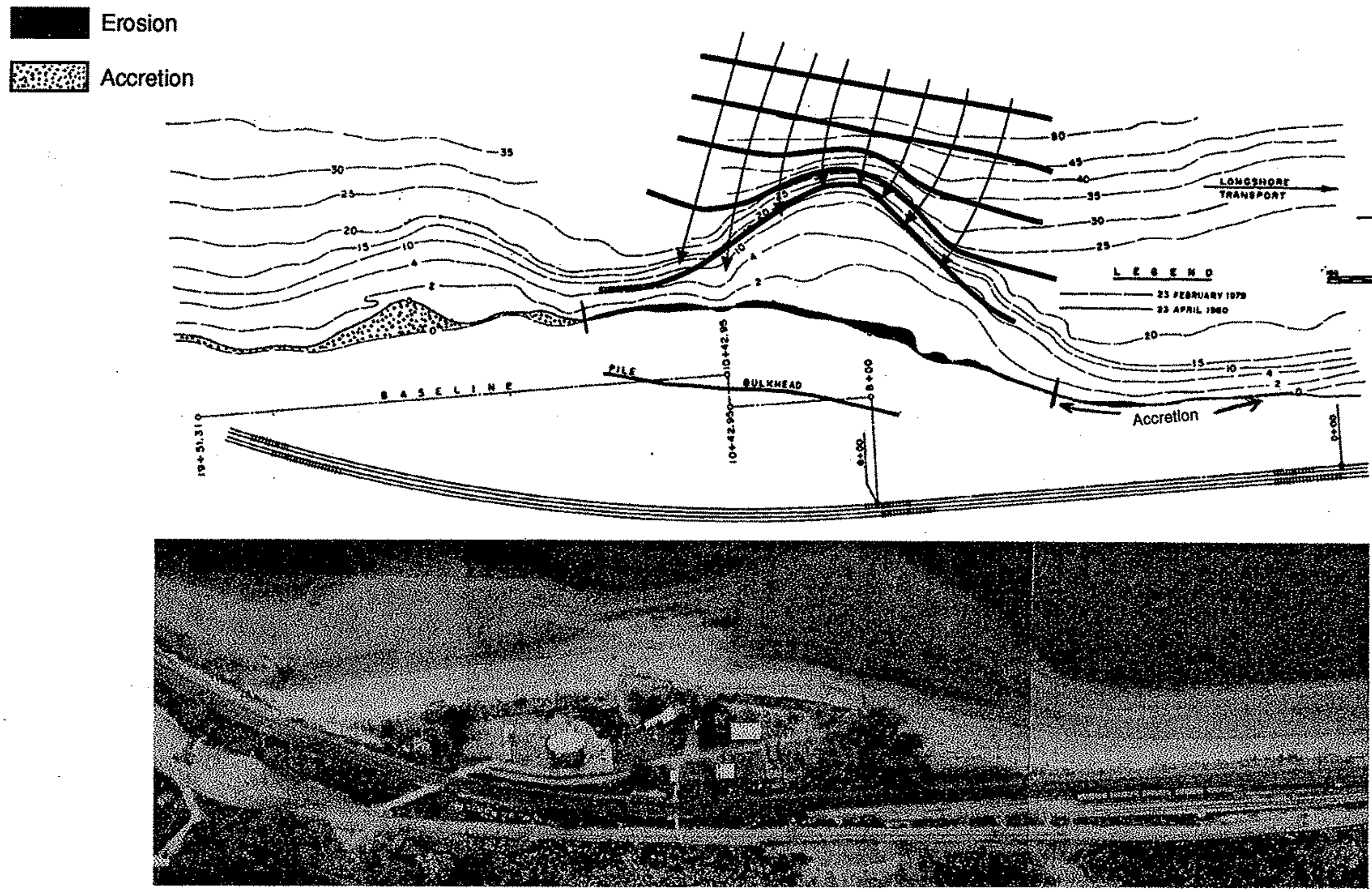


Figure 5-2.
Sunnyside Beach Monitoring Site



Source: Steilacoom Public Works Dept.

Figure 5-3
Sunnyside Beach
Actual and Projected Profiles



Source: Army Corps of Engineers, 1981.

Figure 5-4
Sunnyside Beach Bulkhead: Wave Refraction, Erosion, and Accretion Patterns

Natural erosion of the fill material at Sunnyside Beach went unchecked for a number of years (Figure 5-5) but measures were eventually instituted to protect the backshore area from further erosion. To slow the rate of erosion and protect the shoreline from further damage, a 550-foot long timberpile bulkhead was constructed in 1967 along a portion of the shoreline (Figure 5-6). The beach at this time was actively eroding at an estimated rate of 1 to 2 feet per year. Erosion rates in the vicinity of the old Chambers Creek wastewater treatment plant (located at the south end of the site) during this same period were on the order of 3 feet per year. (Since 1988 to 1989, the wastewater treatment plant has been relocated to a site north of Sunnyside Beach).

The need for the timberpile bulkhead becomes evident based on the local offshore bathymetry. The shoals noted above cause waves approaching from the west to refract, concentrating wave energy in the area of the shoal. Construction of the bulkhead responded to the wave-induced erosion along this portion of the site. The wave refraction pattern in the area seaward of the bulkhead (assuming a due westerly wave approach) is shown in Figure 5-4.

In 1974, Steilacoom asked the Army Corps of Engineers to investigate the cause of erosion and to develop alternatives for shore protection. In the early stages of the project, the Army Corps decided to utilize some type of "hard" shore protection structure (e.g. a vertical wall or revetment) as a solution to the erosion problem. However, it was learned that the Lonestar/Glacier gravel pits had waste sand available that could be used to nourish Sunnyside Beach and plans for the bulkhead were abandoned. The change from a "hard" engineered solution to "soft" beach nourishment was primarily due to budget considerations. The Corps believed beach nourishment to be the lowest cost solution and the one having the least environmental impact.

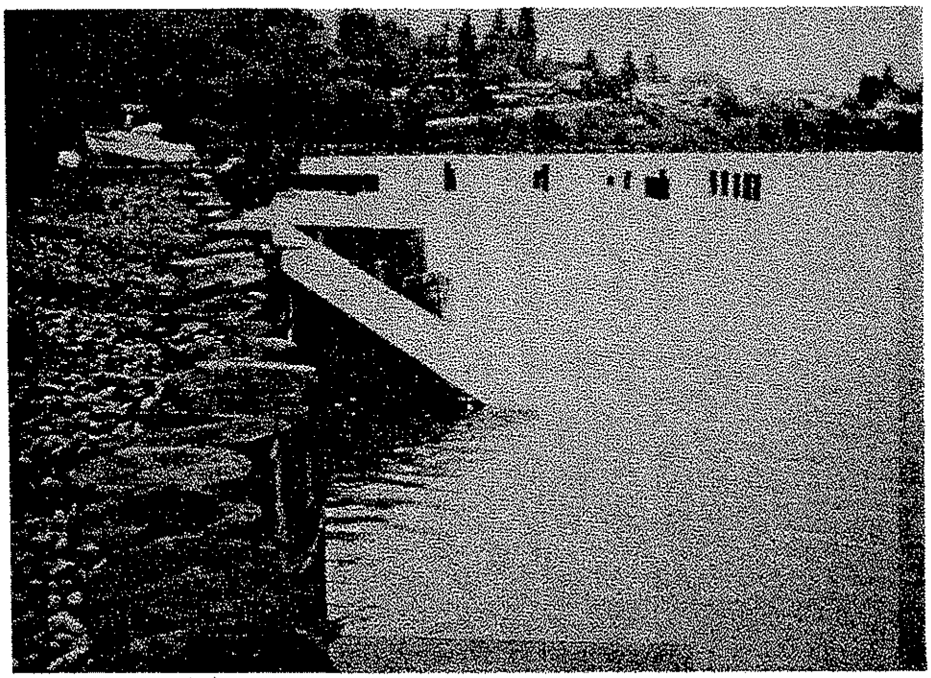
The Corps placed and graded approximately 18,000 yd^3 of waste sand as beach nourishment in December 1975. The sand was off-loaded from a barge at high tide by washing it overboard with a jet of water. The material was then graded at low tide using earthmoving equipment. Drift logs that had accumulated on the beach prior to the nourishment program were removed, then replaced after construction was completed. The project was completed in December 1975, at a total cost of about \$1.00/yd^3 (Eric Nelson, Army Corps of Engineers, personal communication).

In early 1979, the Corps conducted the first surveys at Sunnyside Beach. As part of an informal monitoring program, the Corps conducted site visits, accumulated photographs, tide records, and made beach profile and distance measurements from still water line to the bulkhead. Nails were driven into the pilings at several locations to determine elevation changes in the beach. Based on contemporary measurements, beach erosion was continuing at a moderate rate. A volumetric analysis of beach profiles using 1979 and 1980 data was conducted to calculate net erosion or accretion at the site.

Other than observations that some material appeared to have moved northward as a result of local longshore transport, no other information was collected for about 3 years. In July

Source: Steilacoom Public Works Dept., 1967

Figure 5-5
Sunnyside Beach
Shoreline Erosion, 1967



Timber Bulkhead Shown Flooded at High Tide

Source: Steilacoom Public Works Dept., 1967

Figure 5-6
Sunnyside Beach
Timberpile Bulkhead, 1967

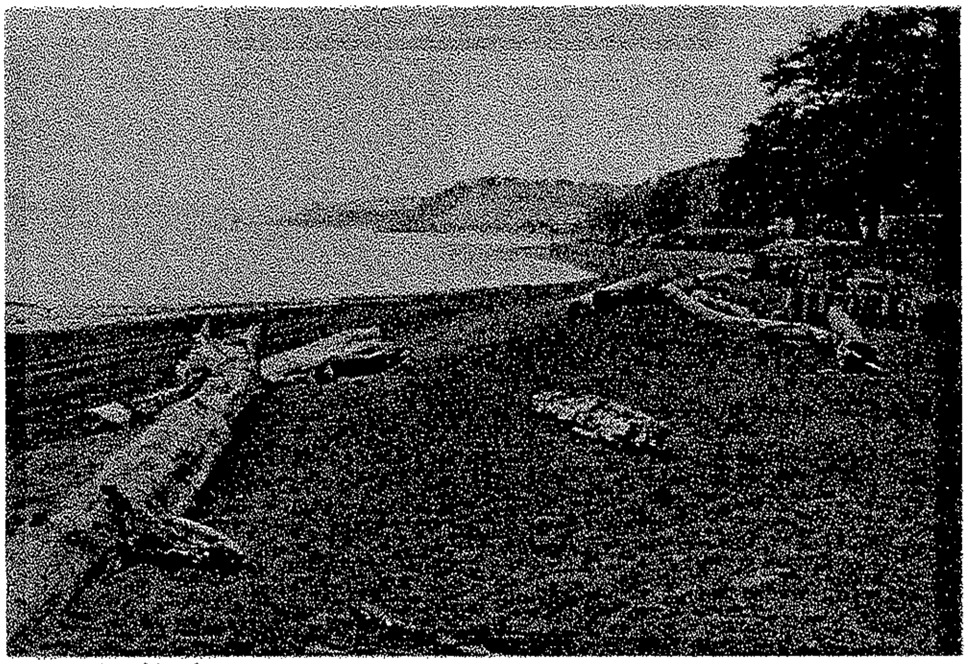
of 1978, 4,200 yd^3 of waste sand was placed as additional renourishment material. According to the Corps, the Town of Steilacoom had no plans for any future beach renourishment. In 1980, the beach was observed to be nearly 1,000 feet long and was about 100 feet wide at MLLW, and scattered with drift-logs (Figure 5-7).

Following the brief monitoring program, the Corps concluded that the eroded beach material was transported offshore, redistributed, and later carried back onshore again. No observations were noted regarding the size of material moved or the amount of redeposition. Fluctuations between erosion and accretion were observed to occur in as little as one month's time. A small longshore transport component carrying material to the north was also noted. Other observations about longshore transport and redistribution of material indicate that the sediment did not follow the direction anticipated, based on knowledge gained about local transport processes (Eric Nelson, Seattle District Army Corps of Engineers, personal communication). However, evidence for a generally northerly net shore-drift is supported by evidence such as the accumulation of sand on the south side of foreshore obstructions (i.e., rocks, drift-logs) and by erosion on the downdrift (north) side of the bulkhead (Harp, 1983).

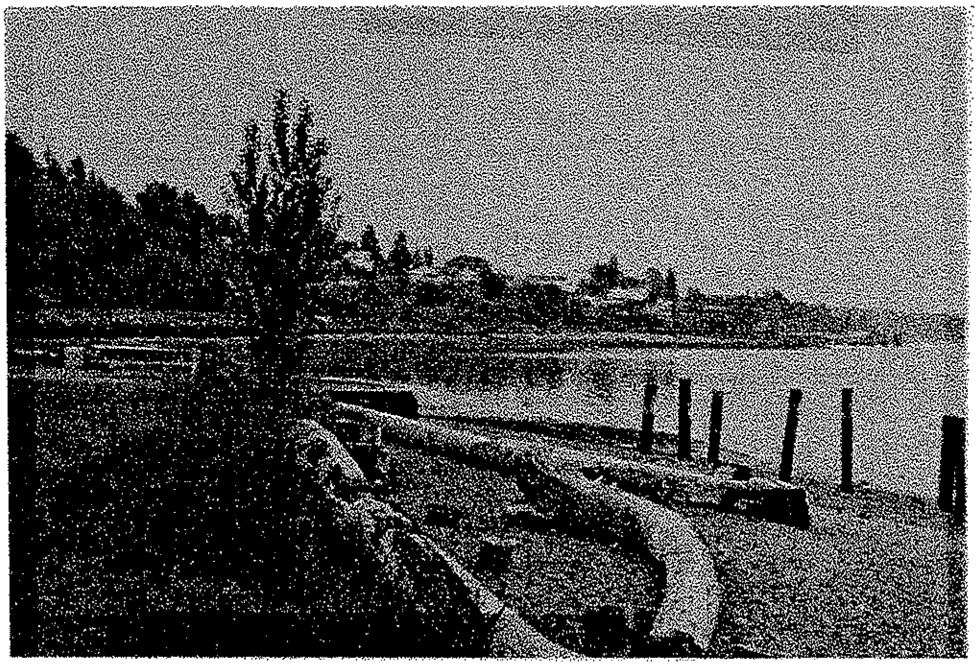
After analyzing the available survey information, a pattern of erosion and accretion relating to the location of the bulkhead can be inferred. The accuracy of the 1979 and 1980 surveys must be taken into consideration, however. From the limited amount of information (when areas of accretion and erosion are compared), the first signs of erosion are evident within about 20 feet of the south end of the bulkhead (Figure 5-4). Erosion is evident for the whole length of the bulkhead (550 feet) and beyond the north end for about 150 feet, at which point slight accretion is again evident. In contrast, substantial accretion can be observed for the beach in front of the southern shoal area (Figure 5-4). One year's survey data is not enough to confirm definitive conclusions about the effect of the Sunnyside Beach bulkhead, but there is enough data to suggest several impacts.

Based upon photographic evidence and field observations, a case can certainly be made that the beach has narrowed at Sunnyside, but not enough data are available to state conclusively whether this is a result of bulkhead construction. The same can be said about lowering of the beach profile. Beach profiles from 1979 and 1980 Corps surveys (Figures 5-8 and 5-9) indicate that both net accretion or erosion were observed, depending upon location along the shoreline (Army Corps of Engineers, 1981). Some transects exhibited both accretion and erosion (Station 4+00, Figure 5-9). Other than observations from photographs taken since 1978 (when the beach was last renourished), there is no evidence among available data to indicate whether there has been a net gain or loss of beach material from the site. Photographs and anecdotal evidence from local residents indicate that the beach is still narrowing, particularly since recent severe storm events (i.e., winter 1990-91).

Changes in substrate type and/or size (alongshore or cross-shore) were not recorded by the Corps nor in information available from the Town of Steilacoom. Downdrift effects in the prominent direction of the littoral transport (north) have been noted and result in the



a. Looking North

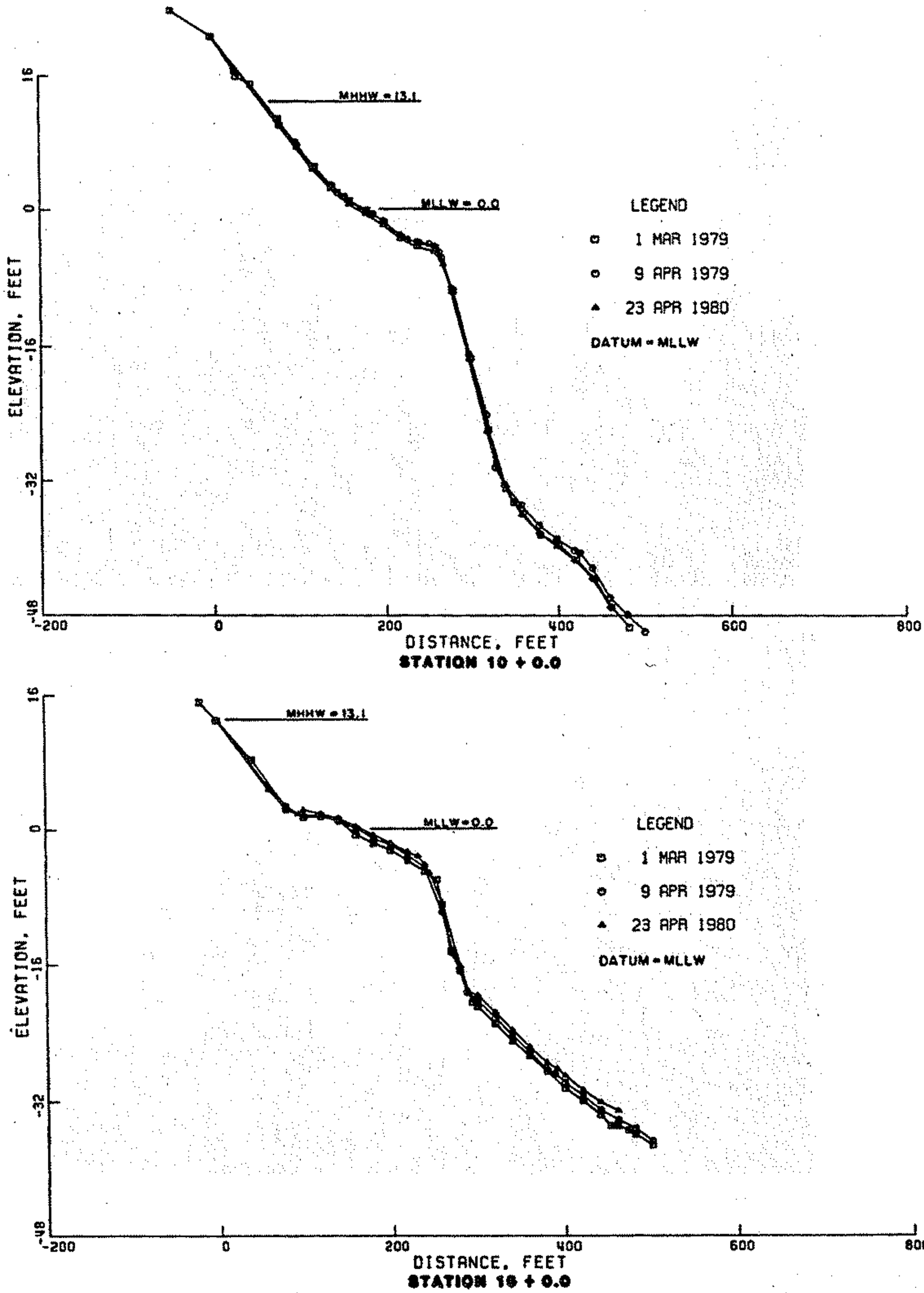


b. Looking South

Views after Corps beach nourishment project completed; LOD placed by Corps.

Source: Steilacoom Public Works Dept., 1980

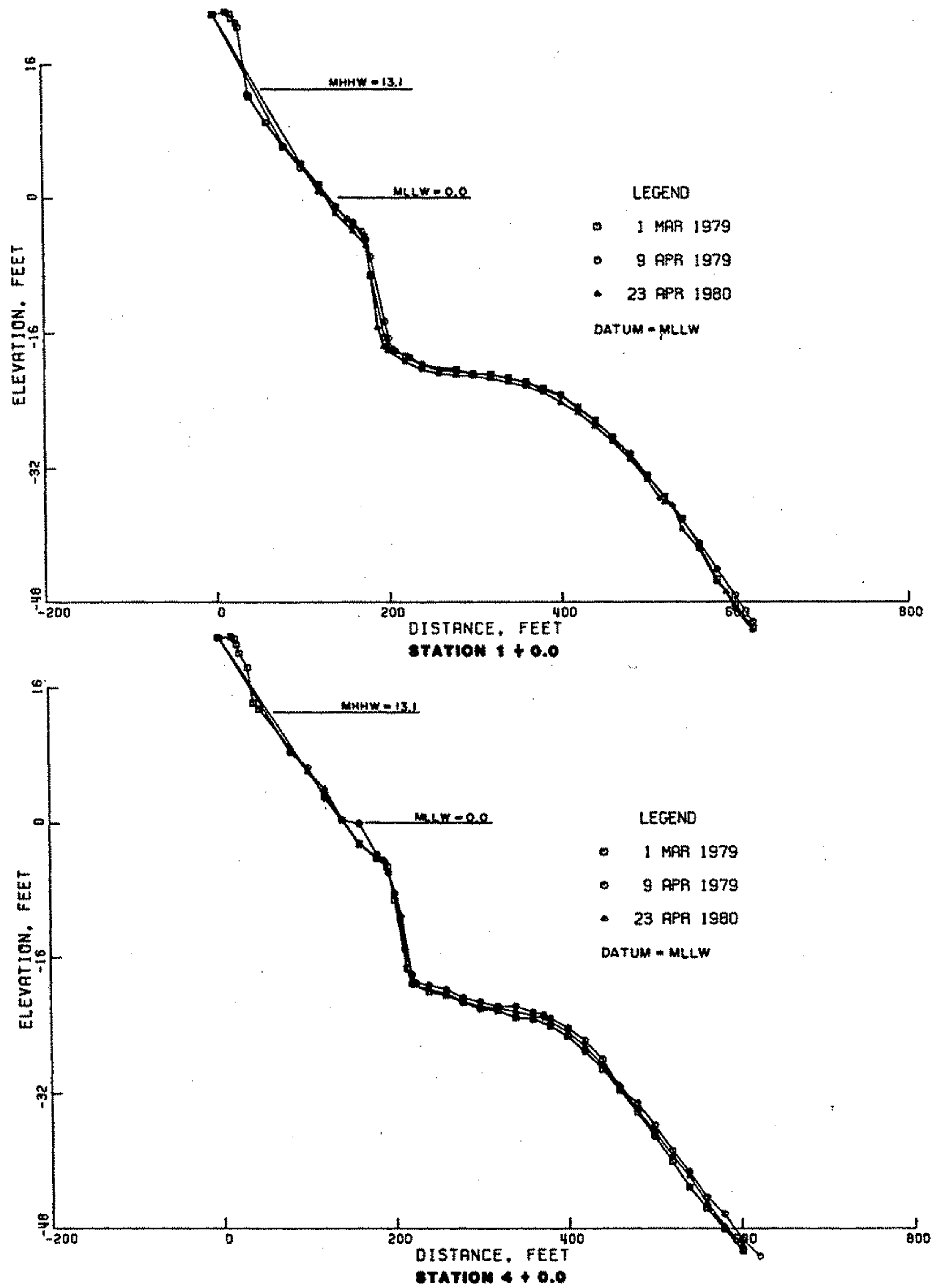
Figure 5-7
Sunnyside Beach, May 1980



See Figure 5-4 for transect locations.

Source: Army Corps of Engineers, 1981.

Figure 5-8
Sunnyside Beach, Typical Profiles (Stations 10 and 16)



See Figure 5-4 for transect locations.

Source: Army Corps of Engineers, 1981.

Figure 5-9
Sunnyside Beach, Typical Profiles (Stations 1 and 4)

redistribution of beach material both north and south of the site. During the winter months, this redistribution of material forms a sizeable beach at the southern end of the site (Steve Fischer, Town of Steilacoom Public Works, personal communication), but this is likely to be at the expense of the beach at the north end of the site. This observation is best explained by seasonal variations in the shore alignment that are caused by differences in wind-induced wave direction and magnitude.

Seasonal accretion on the south end of the site was substantiated by a site visit in March 1993. The presence of very coarse material–cobbles and coarse gravel–directly in front of the bulkhead was also noted; no similar material was seen along other sections of the beach (Figure 5-10). The area in front of the bulkhead also appeared to exhibit a slightly higher elevation than the beaches north and south of the bulkhead. This feature can be seen in the top photograph in Figure 6-9. It is possible that some of this coarse material was derived from the material that constitutes part of the backfill behind the bulkhead or that it is part of the original fill material. Observations about loss or gain of organic debris on the beach have not been made and are restricted to information that can be inferred from site photographs. Drift-logs have accumulated along some portions of the site, particularly at both the northern and southern ends of the beach, but not immediately in the area of the bulkhead.

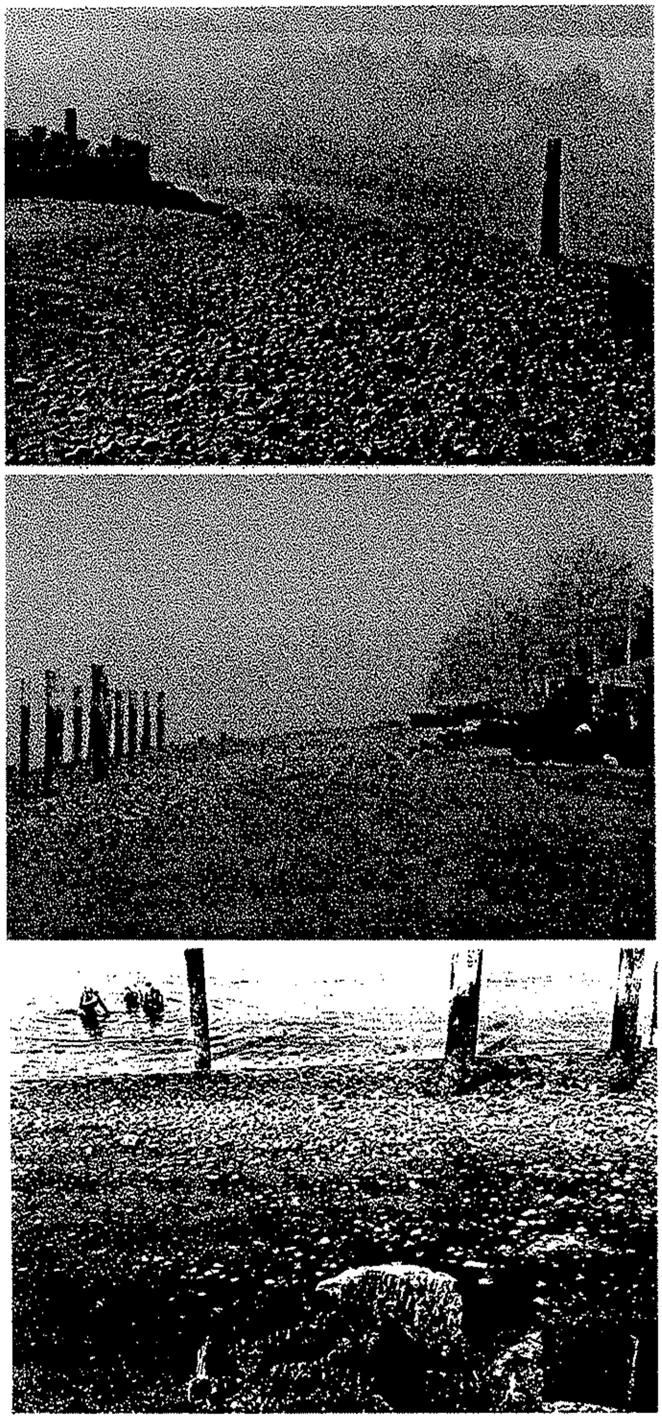
Summary

1. The good site history for Sunnyside Beach—together with an absence of natural sediment sources to the site—permit quantitative calculations of sediment movement and losses over known timeframes.

2. Sunnyside is undoubtedly a "starved" system where the beach is undergoing steady, broad retreat.

3. The presence of a timber bulkhead in the center of a uniform beach is ideal for comparing physical changes in front of the bulkhead with those beyond the ends of the bulkhead. Increased beach erosion—including lowering and narrowing in front of the bulkhead—during the 1990-91 winter storm season was dramatic.

4. This site provides some evidence for both the coarsening of sediments in front of a bulkhead and the loss of LOD.



Source: Brad Paulson, March 1993

Figure 5-10
Sunnyside Beach:
Coarse Gravels Fronting Bulkhead

Lincoln Park Beach, Seattle
King County

Data

- Beach profiles (1974, 1981, 1984 data)
- Substrate data (1983 foundation exploration)
- Erosion rates (1932 to 1974 estimated average)
- Historical photographs (1934, 1936, and present day)
- Biological monitoring (various reports)

The sole source of data relating to physical processes at this site is from the Seattle District Army Corps of Engineers. Some additional historical photographs were available from the City of Seattle Department Parks and Recreation. This site is unique, however, in that it also has been the subject of fairly extensive marine biological monitoring.

The site is located in central Puget Sound within the City of Seattle at Williams Point (Figure 5-11). Lincoln Park was created in 1922 when the City of Seattle acquired 130 acres at Williams Point. In 1925, the park was opened to the public, with the majority of the grounds development occurring in the 1930s. The Works Progress Administration (WPA) constructed a number of facilities on the site, including hiking trails, playgrounds, picnic shelters, tennis courts, and a saltwater swimming pool. As a means to protect the newly constructed park facilities from wave attack, a cobblestone and mortar seawall was constructed in 1936 which extended along the length of the park's shoreline (Figure 5-12). A rock revetment was built along nearly 250 feet of Williams Point to protect it (and the Colman Pool) from particularly severe wave energy.

The mile-long park shoreline can be divided into three distinct areas: a 2,400-foot northwest beach, a 200-foot beachfront at Williams Point, and a 2,600-foot southwest beach (Figure 5-13). The southwest beach and Williams Point have suffered the most damage from wind-induced wave attack, drift-log attack, and beach scour (Figure 5-14). These areas are directly exposed to prevailing southwesterly winds and waves. The northwest beach is relatively well-sheltered from south/southwest storms, and consequently, wave erosion is not considered a problem at this location. Northerly-directed storms have only occasionally necessitated minor seawall repairs along the northwest beach.

Twice in the 1950s, large sections of the southwest seawall failed because of undermining of the seawall toe, requiring replacement of broken portions and the addition of concrete reinforcement to the toe. Backfilling and repairs to the asphalt service roads were also required frequently. Despite continual stopgap measures, the erosion problems persisted as the seawall continued to age. In the winter of 1981, storm waves broke and dislodged a 90-foot section of seawall at Williams Point, while along the southwest beach, backfill was washed out from the seawall after having been breached in several locations (Figure 5-15). The extent of this damage is well-documented by the Corps in the Lincoln Park Beach

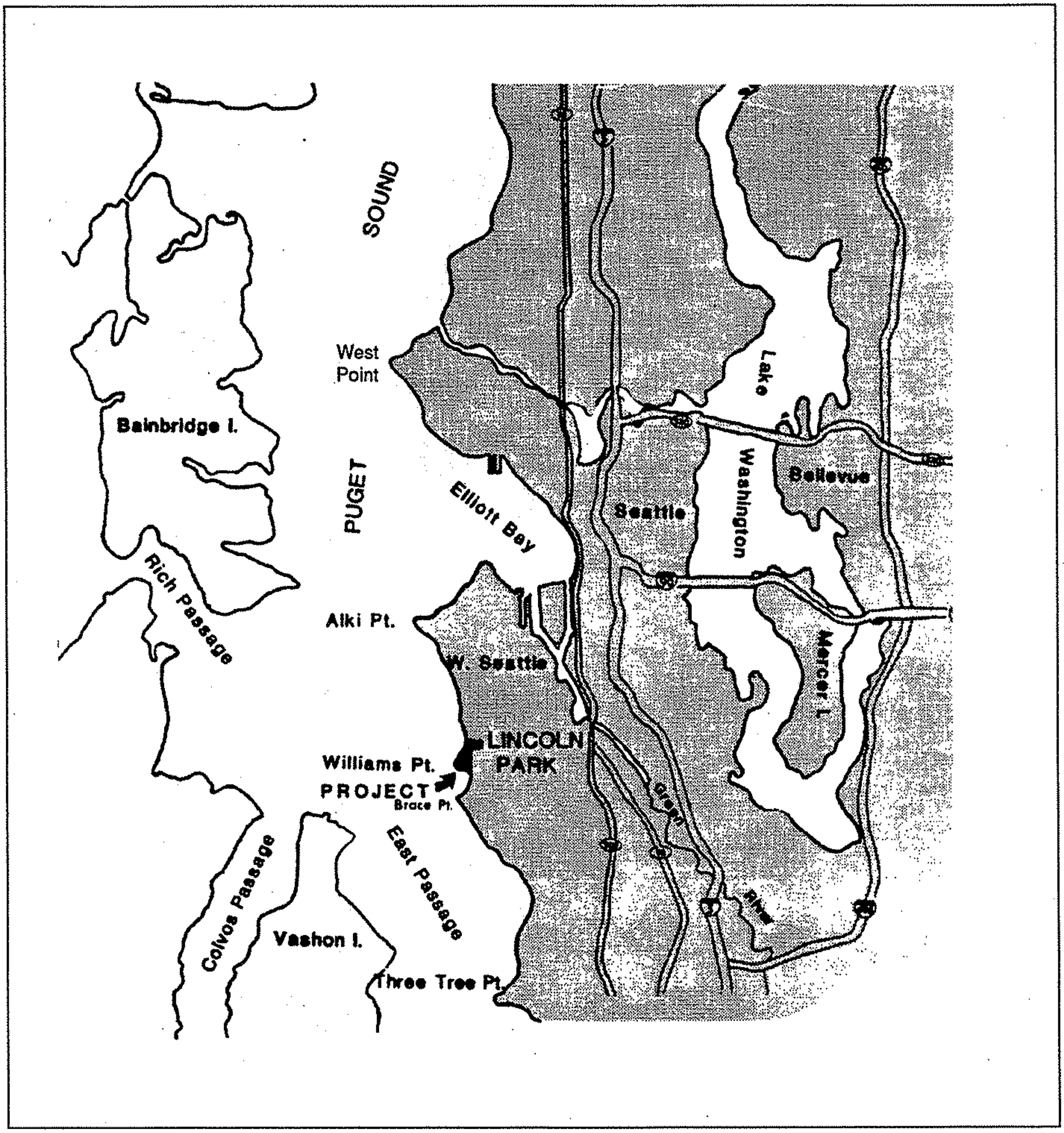
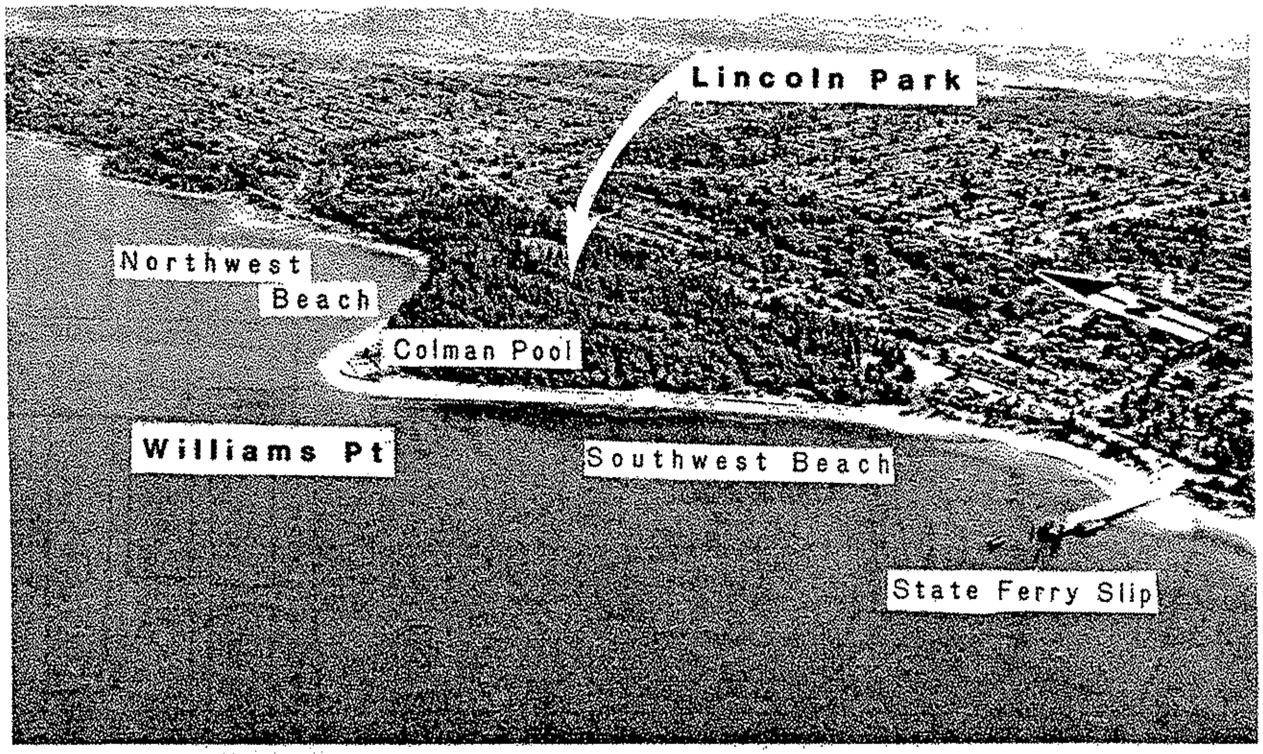


Figure 5-11
Lincoln Park Beach Site

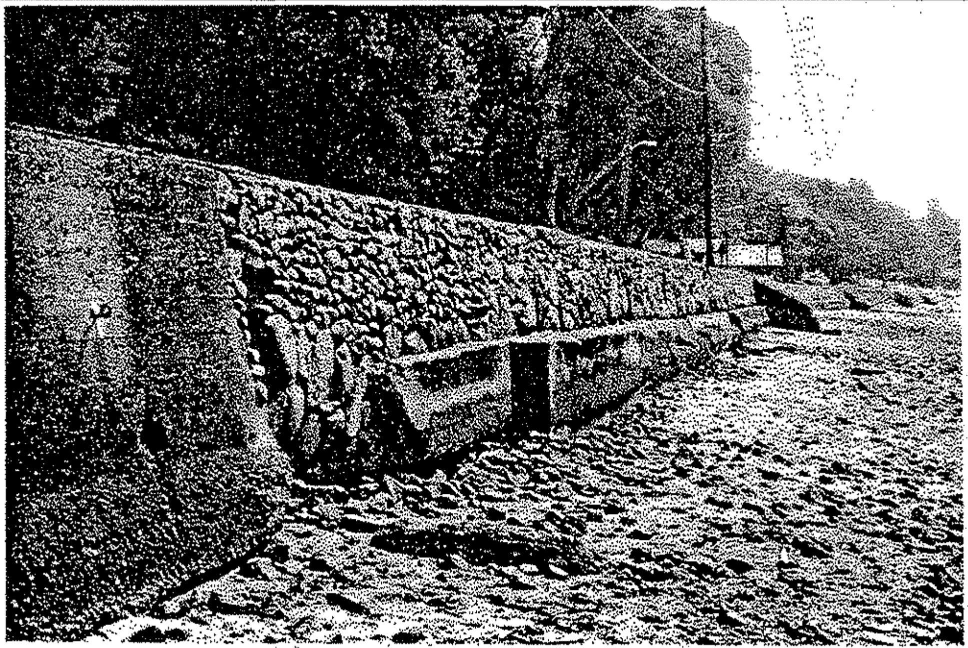
Source: City of Seattle, Dept. Parks and Recreation.

Figure 5-12
Lincoln Park Beach
Seawall Construction, March 1936

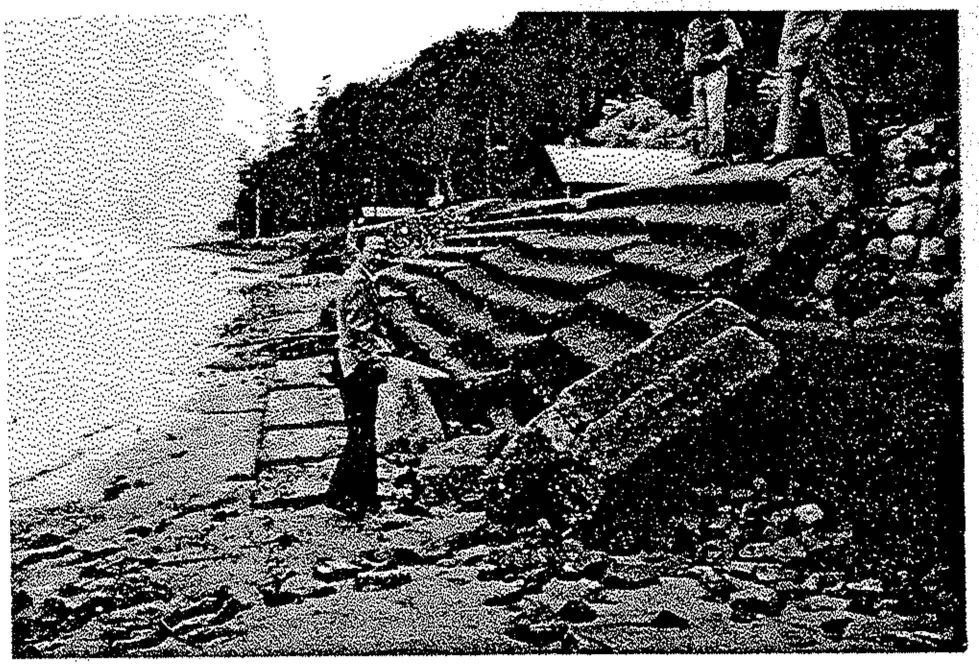


Source: Army Corps of Engineers, 1986.

Figure 5-13
Lincoln Park Aerial View



Southwest beach seawall showing undermining of 1950's toe protection works. Note section of concrete seawall at photo left. Quarry stone on beach surface has washed out from behind seawall.



Southwest beach seawall showing collapsed beach access steps.

Source: Army Corps of Engineers, 1986.

Figure 5-14
Lincoln Park Beach Seawall Damage

Williams Point seawall failure and backfill washout, Winter 1981.

Southwest beach seawall showing quarry stone backfill of voids. Asphalt promenade adjacent to seawall was removed in spring 1985 and voids backfilled with stone and granular material.

Source: Army Corps of Engineers, 1986.

Figure 5-15
Lincoln Park Beach Seawall Damage (Cont.)

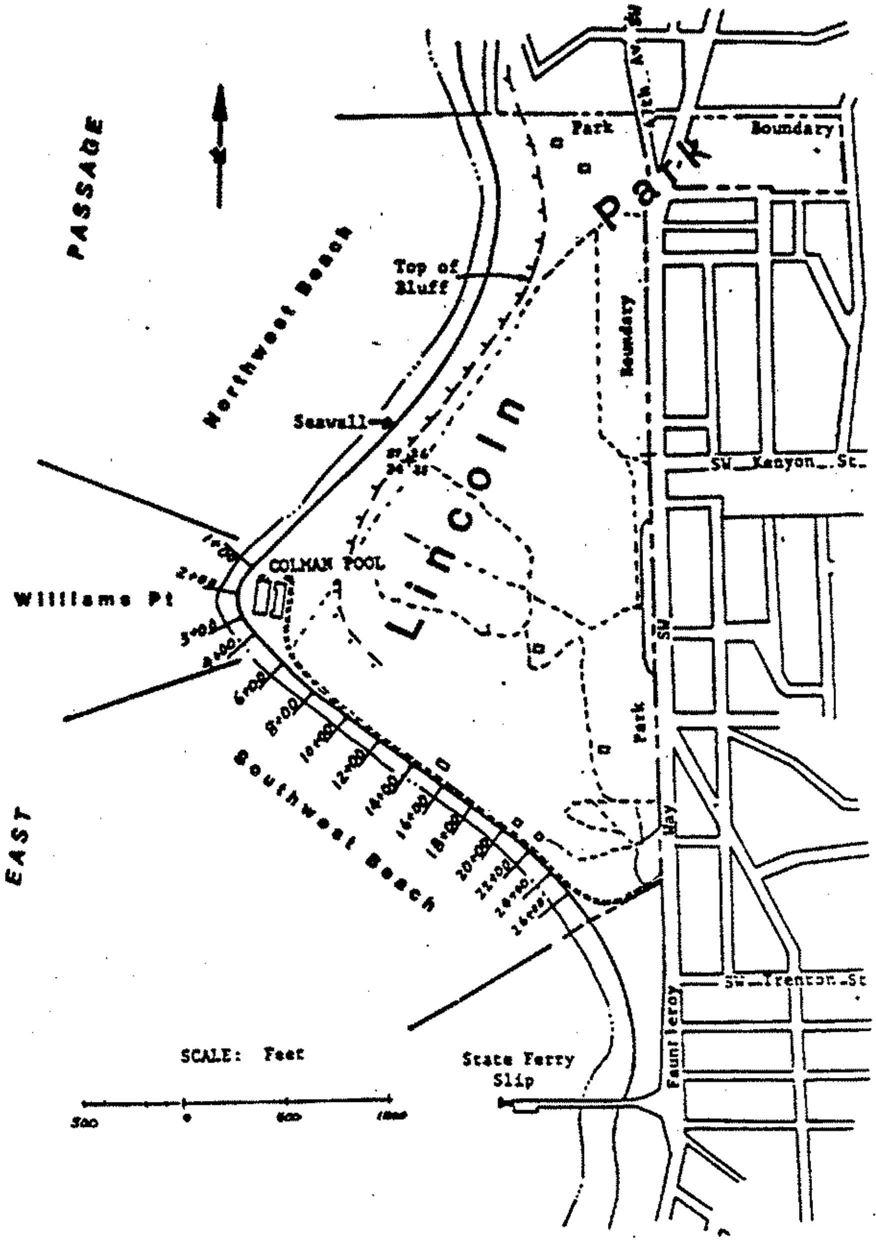
Erosion Study (1984), and Final Detail Project Report and Final Environmental Assessment (1986).

In 1983, the Seattle District Army Corps of Engineers formulated two structural plans for long-term beach erosion protection, one incorporating a concrete and sheet-pile barrier for seawall toe protection, the other placing fill material directly in front of the seawall at both the southwest beach and at Williams Point. The later alternative was selected and beach nourishment was completed in December 1988. Approximately 20,000 yd^3 of sand, gravel, and cobbles were placed in the work. Additionally, 3,900 tons of armor stone was placed along Williams Point to replace the old sections of failed seawall. All of the materials were brought to the site by a barge equipped with a conveyor system. After placement on the beach, the material was distributed and graded with earth-moving equipment at low tide. Key components of the project include periodic renourishment and revetment rehabilitation, as well as benthic recovery studies and biological monitoring to help minimize the loss of intertidal habitat due to the project. The recently completed Detailed Project Report (Army Corps of Engineers, October 1992) provides the basis of design for the renourishment of Lincoln Park Beach, with the work anticipated to be complete by October of 1993.

Historic beach elevations were inferred from as-built drawings during seawall construction and repair (Eric Nelson, Seattle District Army Corps of Engineers, personal communication), since only one beach survey was conducted by the Corps prior to the initial placement of the beach nourishment material in 1988. The beach transect stationing convention used by the Corps is shown in Figure 5-16. Lincoln Park Beach Erosion Study (1984) documents lowering of the beach profiles along selected sections of the southwest beach and Williams Point by comparing the 1981 and 1984 beach profile data to survey profiles from 1974 (Figures 5-17 through 5-20).

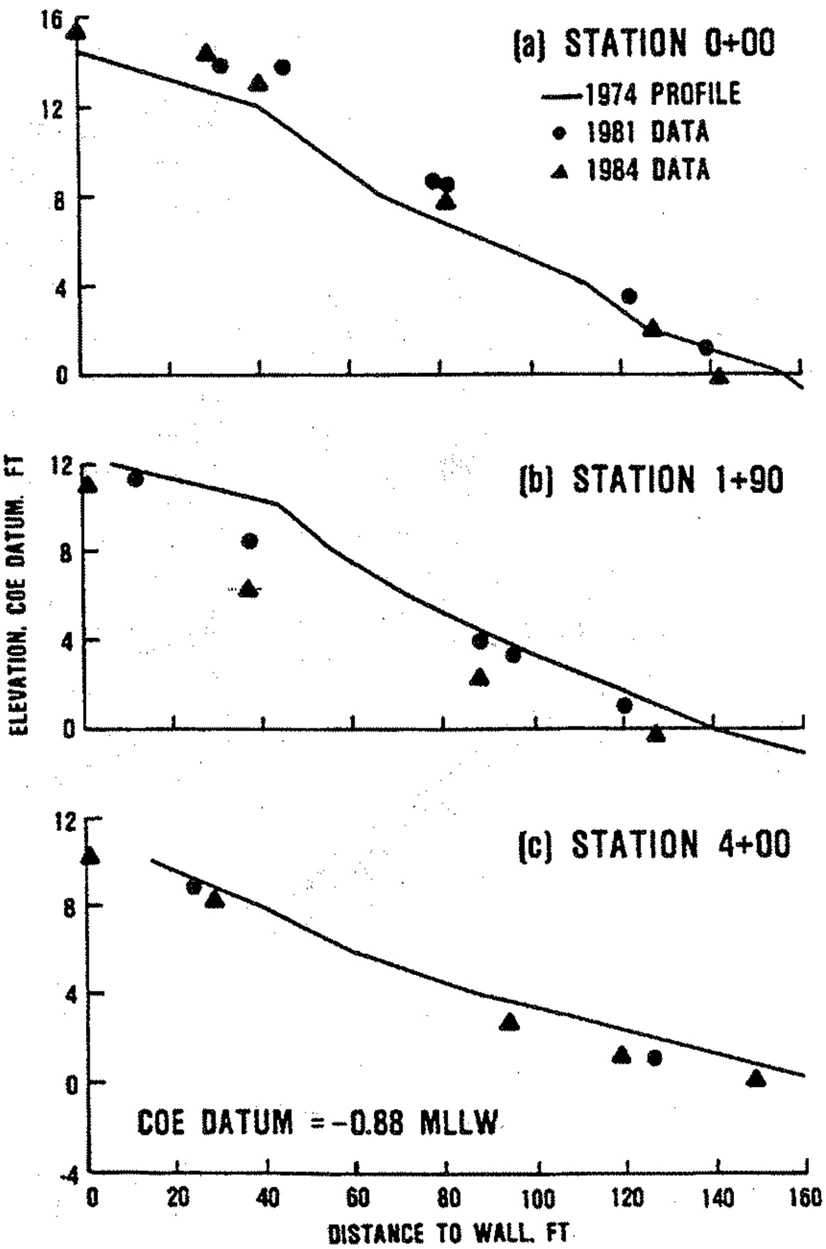
Comparisons of 1981 through 1984 data with 1974 data indicates erosion has slowed at Lincoln Park. In fact, with the exception of the beach in front of Williams Point, Lincoln Park Beach, in general, has suffered only minor erosion during the 1974 to 1984 period. The reports conclude, however, that although the beach appears to be fairly stable in recent years, the shoreline profile along the seawall is shifting toward the north (Army Corps of Engineers, 1984). As is the case with the shoals at Sunnyside Beach, Williams Point is also particularly vulnerable to wave attack because of the way that it protrudes into Puget Sound. In contrast to the constant erosion rate along the southwest beach, the erosion rate at Williams Point was apparently in an accelerating mode (Army Corps of Engineers, 1984). It has been suggested that this was exacerbated by the lack of a natural sediment source updrift (south) to nourish the beach.

From 1932 (4 years prior to the seawall construction) to 1974, the beach profile at Lincoln Park was lowered, on the average, about 3 to 4 feet per year (Army Corps of Engineers, 1984). The area between Williams Point (Station 4+00) south to Station 22+00 appeared to suffer the greatest loss from erosion (Figure 5-21). This figure does not necessarily indicate that the shoreline elevation has lowered solely as a result of the installation of the



Source: Army Corps of Engineers, 1984.

Figure 5-16
Lincoln Park Study Area

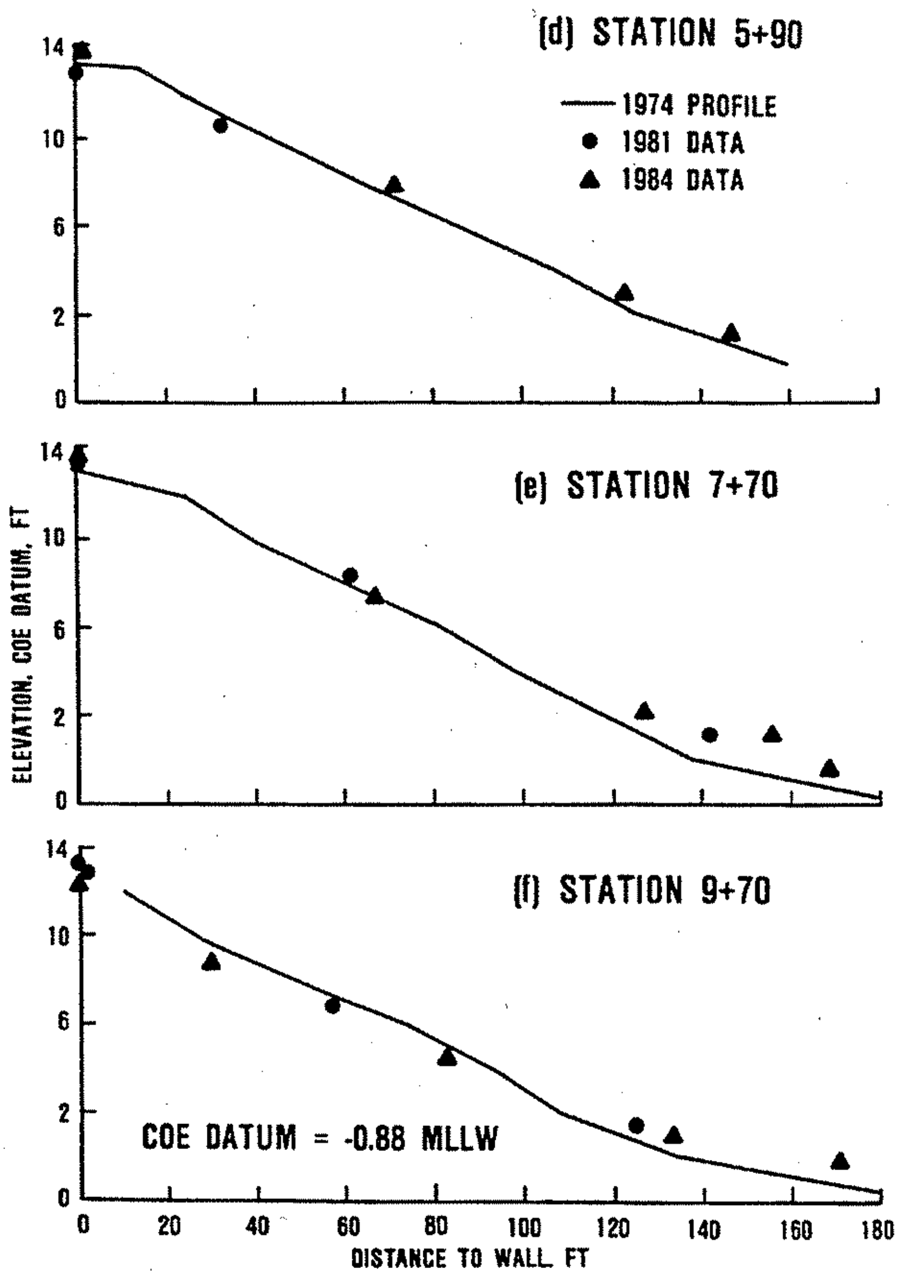


Note: See Figure 5-16 for station locations.

Source: Army Corps of Engineers, 1984.

Figure 5-17

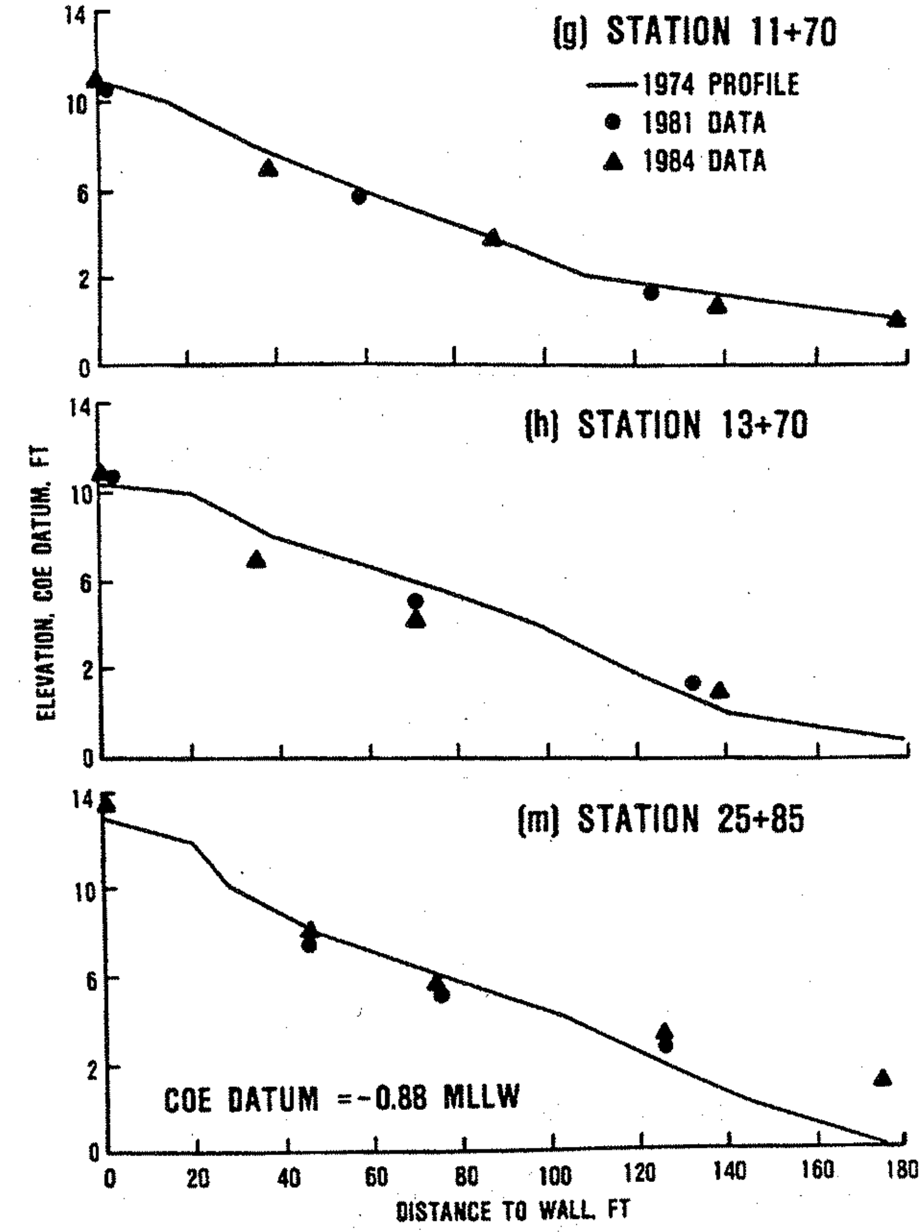
Lincoln Park Beach Profiles, 1974-1984 (Stations 0 to 4)



Note: See Figure 5-16 for station locations.

Source: Army Corps of Engineers, 1984.

Figure 5-18
Lincoln Park Beach Profiles, 1974-1984 (Stations 5 to 9)

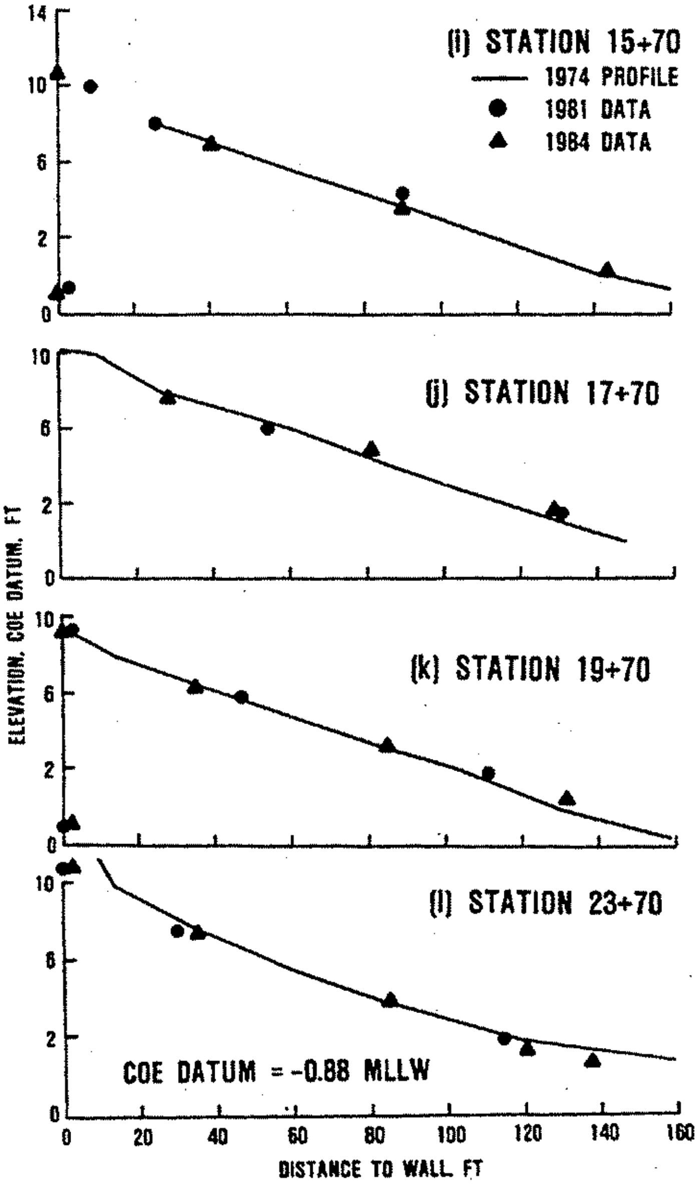


Note: See Figure 5-16 for station locations.

Source: Army Corps of Engineers, 1984.

Figure 5-19

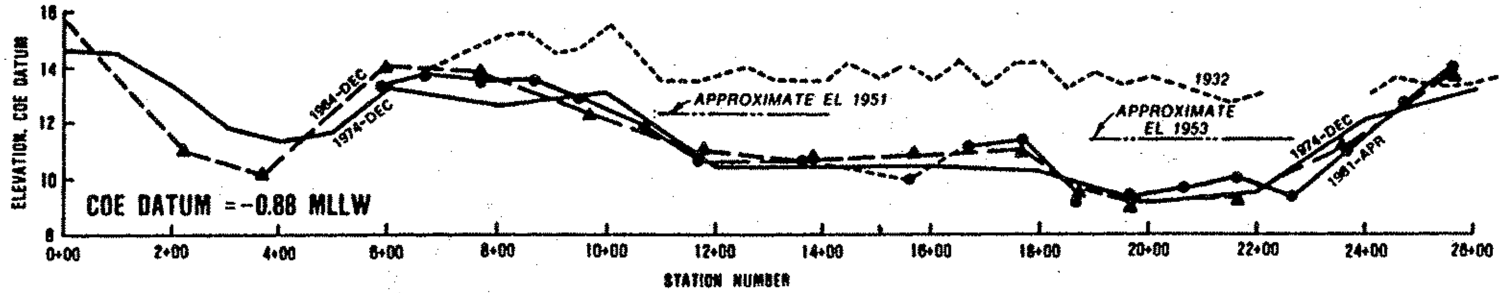
Lincoln Park Beach Profiles, 1974-1984 (Stations 11 to 25)



Note: See Figure 5-16 for station locations.

Source: Army Corps of Engineers, 1984.

Figure 5-20
Lincoln Park Beach Profiles, 1974-1984 (Stations 15 to 23)



Beach elevation at the base of the seawall, 1932-1984.
Note pronounced beach profile lowering.

Note: See Figure 5-16 for station locations.

Source: Army Corps of Engineers, 1984.

Figure 5-21
Lincoln Park Beach Seawall, Shoreline Elevations, 1932-1984 (Stations 0 to 26)

seawall, but rather shows that the area between Stations 6+00 and 22+00 more or less reached a state of equilibrium by the 1974-1984 period, and had gradually lowered since the seawall was built. Using estimated 1951 and 1953 profiles, the Army Corps calculated the erosion rate along this portion of the shoreline to be about 0.1 foot per year (Army Corps of Engineers, 1984). This rate reflects the fact that shoreline processes in Puget Sound occur relatively slowly and, as a result, equilibration times are long.

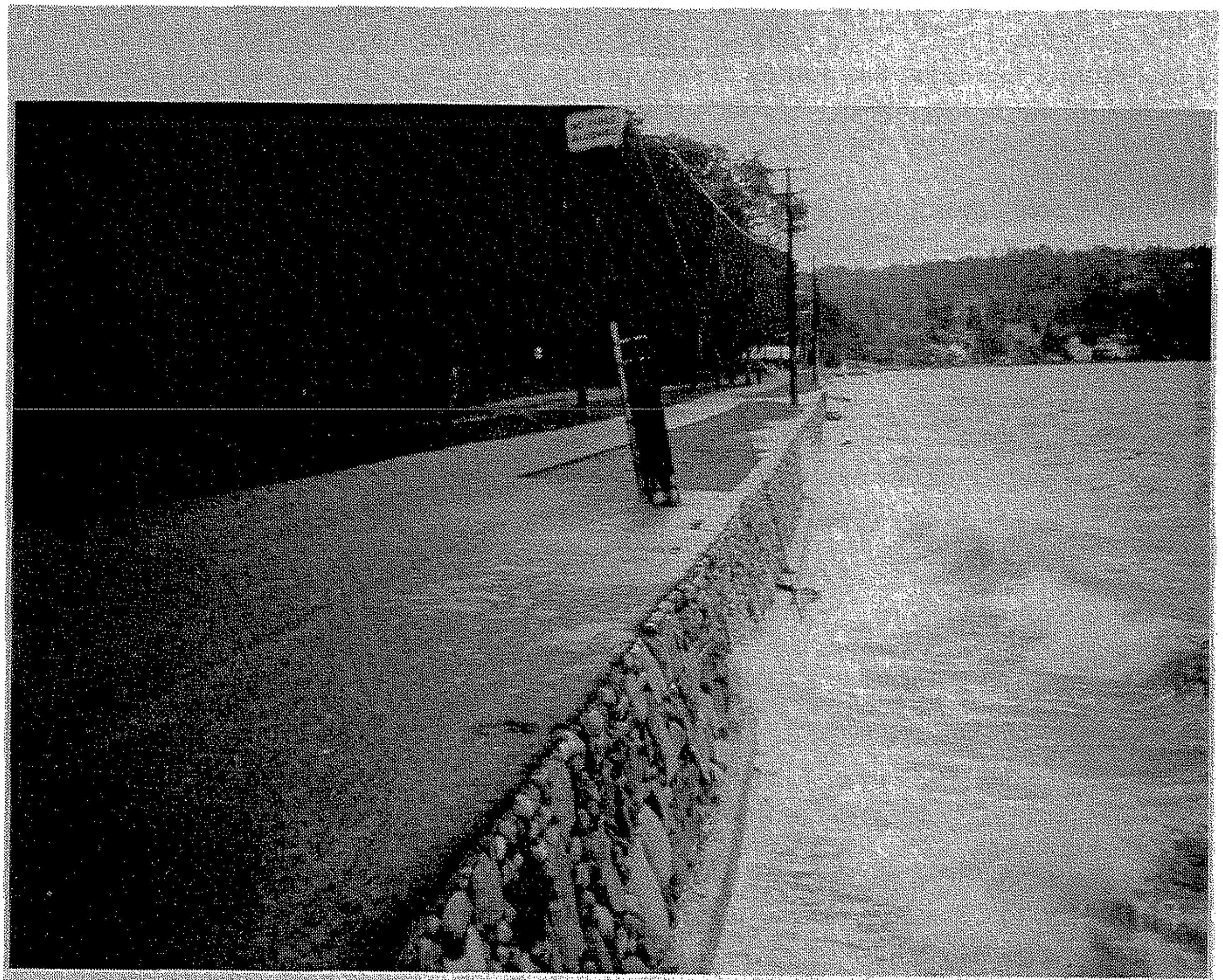
Army Corps reports state that the beach profile at Lincoln Park (especially along the Williams Point beach and southwest beach) has been lowered by wave-induced scour. As in the case at the Sunnyside Beach, however, it would be difficult to conclude that this was solely the result of seawall installation in 1936. The lowering of the profile is generally thought to be due to lack of a sediment source south of the site, which leads to beach starvation and a gradually lowered profile. As the profile continues to lower and water depth in front of the seawall increases, larger and larger waves are capable of reaching and directly attacking the seawall during high tide conditions (Figure 5-22). This, in turn, lowers the beach profile even further.

The 1991 beach profiles indicate a slight lowering along the entire length of the southwest beach and significant lowering in front of the Williams Point revetment (actual data not available for this report). No explicit mention has been made about Lincoln Park beaches narrowing, but if the profiles have been lowering with water levels staying the same, it can be inferred that the beaches are narrowing.

Placing beach nourishment material in front of the existing seawall has effectively "removed" any effects of the wall from the littoral system. To confirm this, photographs before and after beach nourishment were inspected, and preliminary wave runup calculation was made. A significant wave height (H_s) of 6 feet and wave period of 4 seconds were used for the wave runup calculation to determine the probable extent of runup and likelihood of seawall overtopping. The results indicate that the slope and coarseness of material making up the new beach serve to effectively dissipate wave energy before the original seawall location is reached. In essence, the original seawall now has been totally "removed" from the system and no longer affects beach profile dynamics.

Size distribution of native beach material was determined using sieve analysis (Army Corps of Engineers, 1984). In general, an increase in sand content was evident from the surface to increasingly deeper layers. Coarser, more resistant gravel and cobble material was more prevalent in the surface layers. For example, it was observed that the first 6-inch deep layer consisted of poorly sorted gravel (with scattered cobbles) in the lower area of the beach. Sand content in the 1.5-foot depth layer was observed to vary from 30 to 70 percent by weight. No alongshore variability in sediment size was noted in any of the Corps reports.

The change in substrate size at this one point in time (i.e., 1984 study) merely indicates that winnowing of fine (silt and clay) particles has occurred, leaving behind only coarse material. Samples *deeper* than 1.5 feet below the surface, representing the native beach



Southwest beach; seawall prior to beach nourishment installation. Same location as Figures 5-23 and 24.

Source: Eric Nelson, US ACOE, Seattle District, 1986.

Figure 5-22
Lincoln Park Seawall Under Wave Attack

material at the time the seawall was installed, would be required to make a general statement about the relationship between a change in substrate size and construction of the seawall. The large proportion of coarse material at the beach is likely the result of the loss of silt and clay particles through winnowing, combined with the lack of an updrift sediment source. Additional information of this type would be valuable for providing information about the shoreline that existed prior to intervention by man.

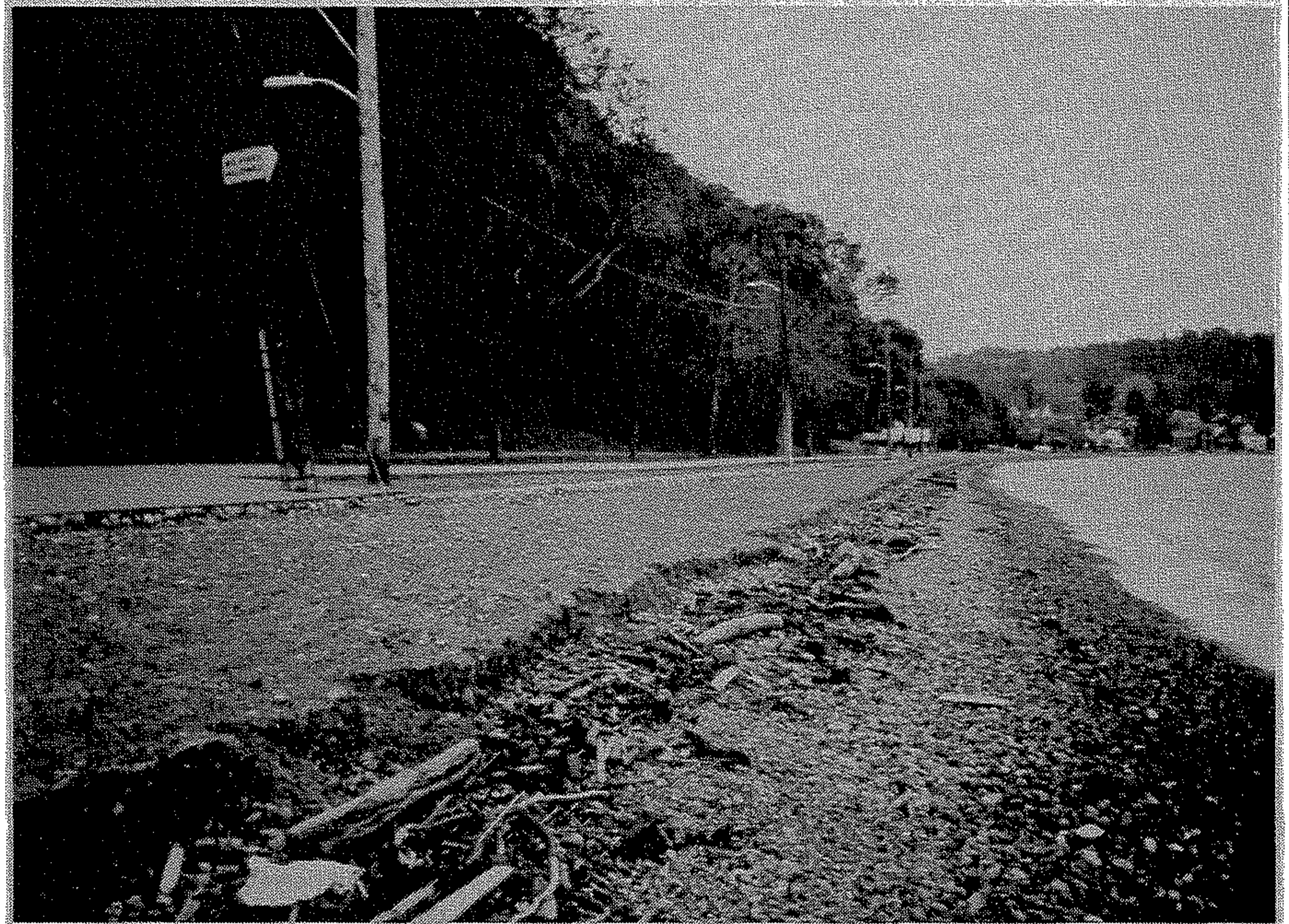
Since placement of the beach nourishment material in 1988, drift logs and other detritus have accumulated on the first 8 to 10 feet of the beach directly seaward of the seawall. By January 1989, the waves had cut into the beach profile to produce an erosional beach scarp in the foreshore (Figure 5-23); by April 1989 (Figure 5-24), the beach had reached an equilibrium profile. [Note that Figures 5-22 through 5-24 were taken from the same location to provide a perspective on the shoreline change from a single point]. In addition to helping dissipate wave energy during high tide conditions, drift-logs also serve to trap organic debris and fine sediment between them and the seawall. However, during storm conditions (large waves combined with high tides), drift-logs can act very effectively as scouring devices high up on the beach profile as they are forced against the banks by incoming waves. Prior to nourishment of the beach, wave energy in front of the old seawall was too strong to allow accumulation of drift-logs and organic debris.

The Detailed Project Report (Army Corps of Engineers, 1992) states that the Lincoln Park Beach Shoreline Erosion Control Project is not expected to have any significant adverse effects on adjacent shorelines because beach nourishment does not materially alter the transport processes of the area. Since 1988, some private beaches south of Lincoln Park have experienced some accumulation of coarse fill material as a result of some recent winter storms from the north (Eric Nelson, Seattle District Army Corps of Engineers, personal communication). However, because the predominant littoral transport direction is to the north, some downdrift (primarily) and updrift beaches have experienced minor accretion of fill material from Lincoln Park. As shown in Figures 5-23 and 5-24, the shoreline is adjusting to a new equilibrium profile, and in the process, beach fill material is being mobilized. The observed transport of beach fill at Lincoln Park, both north and south of the site, provides an excellent opportunity to measure potential effects on biological communities in these areas.

Summary

1. Lincoln Park Beach studies provide quantitative data on the physical impacts of both historic seawall armoring and more recent beach nourishment. The most recent beach nourishment project, completed in December 1988 is being actively monitored.

2. There is good evidence, including some quantitative measurements of both beach narrowing and lowering in front of the historic seawall.



Southwest beach following beach nourishment. Beach scarp marks erosion as beach seeks new equilibrium profile. Same location as Figure 5-22 and 5-24.

Source: Eric Nelson, US ACOE, Seattle District, 1989.

Figure 5-23
Lincoln Park Beach, January 1989

Southwest beach; beach nourishment has achieved eqilibrium profile. Same location as Figures 5-22 and 23.

Source: Eric Nelson, US ACOE, Seattle District, 1989.

Figure 5-24
Lincoln Park Beach, April 1989

3. Minor adjustments to beach profiles following placement of nourishment materials suggest that new equilibrium profiles have been established and prior impacts from the seawall have been "removed."

4. There is some evidence that winnowing of the beach nourishment material has created a natural armor layer of coarser sediment on the new beach surface.

Other Sites

The remaining site descriptions are based largely on qualitative rather than quantitative information. Although qualitative information can be valuable, it is difficult to defend any conclusions about shoreline armoring effects without quantitative data to support them. Nevertheless, a brief site history and the sequence of events leading up to the present shoreline configuration may reveal some clues as to whether the armoring of a particular site has directly impacted the width and/or profile of the beach, substrate size, accumulation of organic debris, or had any downdrift effects.

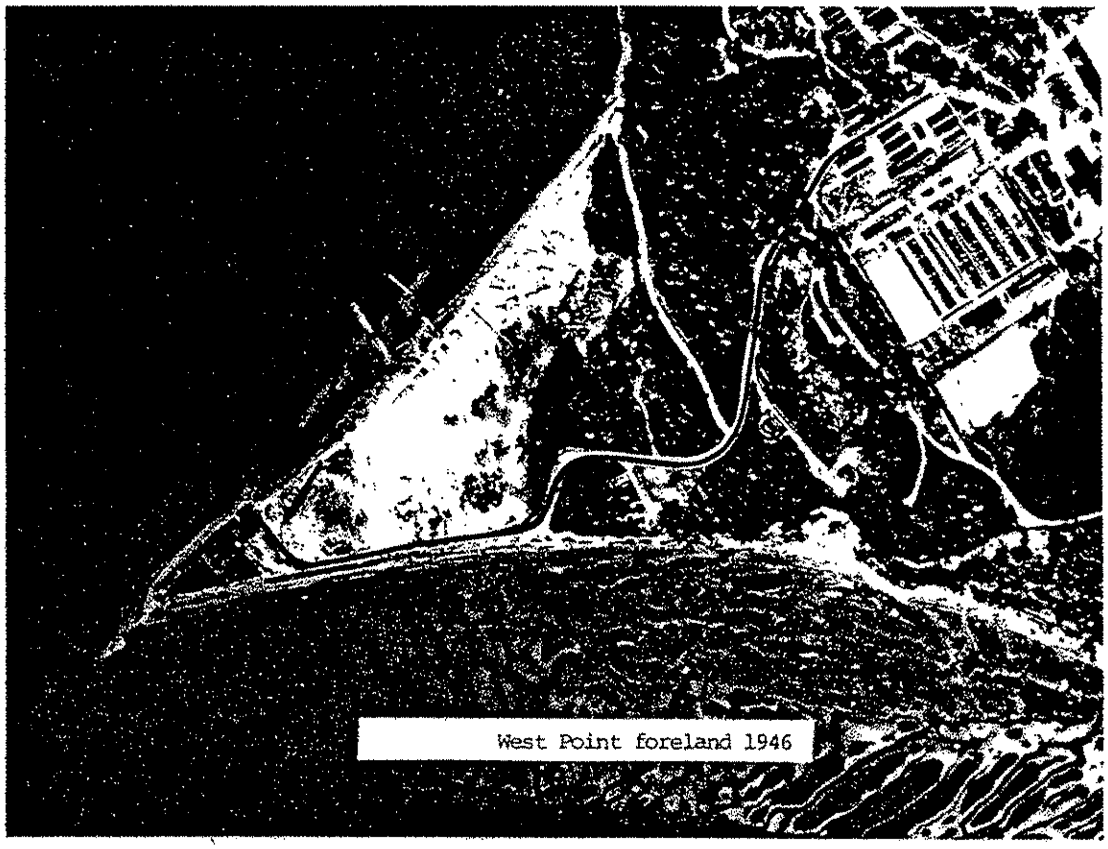
West Point South Beach (Discovery Park)

Data

- Beach profiles (1962)
- Historic and/or aerial photographs (1936, 1946, 1961, 1966, 1967, 1970, 1977, 1981, and 1986)

Chronological history of this site is discussed by Domenowske (1987). The West Point peninsula (Figure 5-11), classified as a triangular cuspate foreland, was created by material from eroding feeder bluffs (Magnolia Bluff) carried by local longshore transport and nearshore currents. This site has had a long history of shoreline manipulation and modification dating back to the 1930s. Presently, the West Point property is shared by Fort Lawton (U.S. Army) and the Municipality of Metropolitan Seattle (Metro), and Discovery Park, created in 1972 by the City of Seattle. In the late 1800s, the U.S. Army acquired most of the upland property for the creation of Fort Lawton. The North Trunk Sewer was constructed in 1912 by the City of Seattle, which would later become the site for the Seattle Regional Wastewater Treatment Plant.

By the 1930s, the U.S. Army had filled the low-lying saltmarsh areas of West Point for use in training exercises during World War II. The configuration of the West Point peninsula at this time is shown in a 1946 aerial photograph (Figure 5-25). Note the extensive system of sand bars in the sub-tidal region that serve as the source for seasonal onshore-offshore exchange of sand. Earlier aerial photographs (1936) also show this sand reservoir to be well established. This material was important as a buffer for protection of the beach, as it caused waves to break offshore, and dissipating energy on the sand bars



Source: Domenowske, 1987.

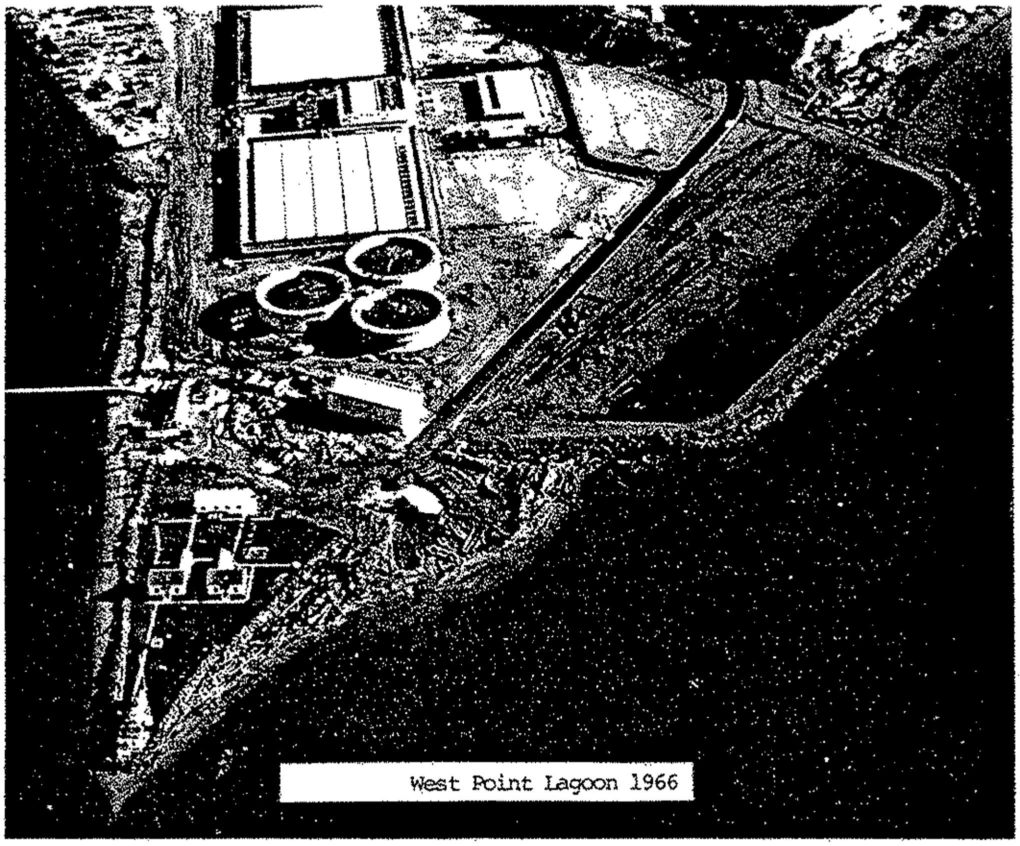
Figure 5-25
West Point Foreland, 1946

rather than the beach face itself. In 1962, Metro began construction for the wastewater treatment plant expansion project on 15 acres at West Point. In addition to nearly 3,200 feet of seawall construction and about 25 acres of backfilled intertidal area on the north side of West Point (for plant expansion), a six acre sludge lagoon, enclosed by a rock revetment, was constructed on the south side (Figure 5-26). Prior to the construction of the lagoon, beach profiles were measured along three transects (Figure 5-27). These are the only known beach profile data available prior to construction of an artificial gravel beach in 1981. The south side of West Point is exposed to a long fetch to the south, and during the winter months wind-induced waves drive the littoral transport from southeast to northwest (Figure 5-28). The littoral drift direction is responsible for patterns of erosion and deposition observed north and south of the lagoon, respectively.

Much of the existing information about West Point is summarized in a 1979 report to Metro Engineers prepared by Professors Richey and Sternberg at the University of Washington and John Downing at Battelle. They were asked by Metro to investigate the probable impacts to the shoreline of removal of the sludge lagoon. They also addressed various alternatives for restoration of the shoreline to its original (pre-1962) configuration. Their study is based on analysis of an 1883 Coast Guard survey, aerial photographs dating back to 1936, and site visits.

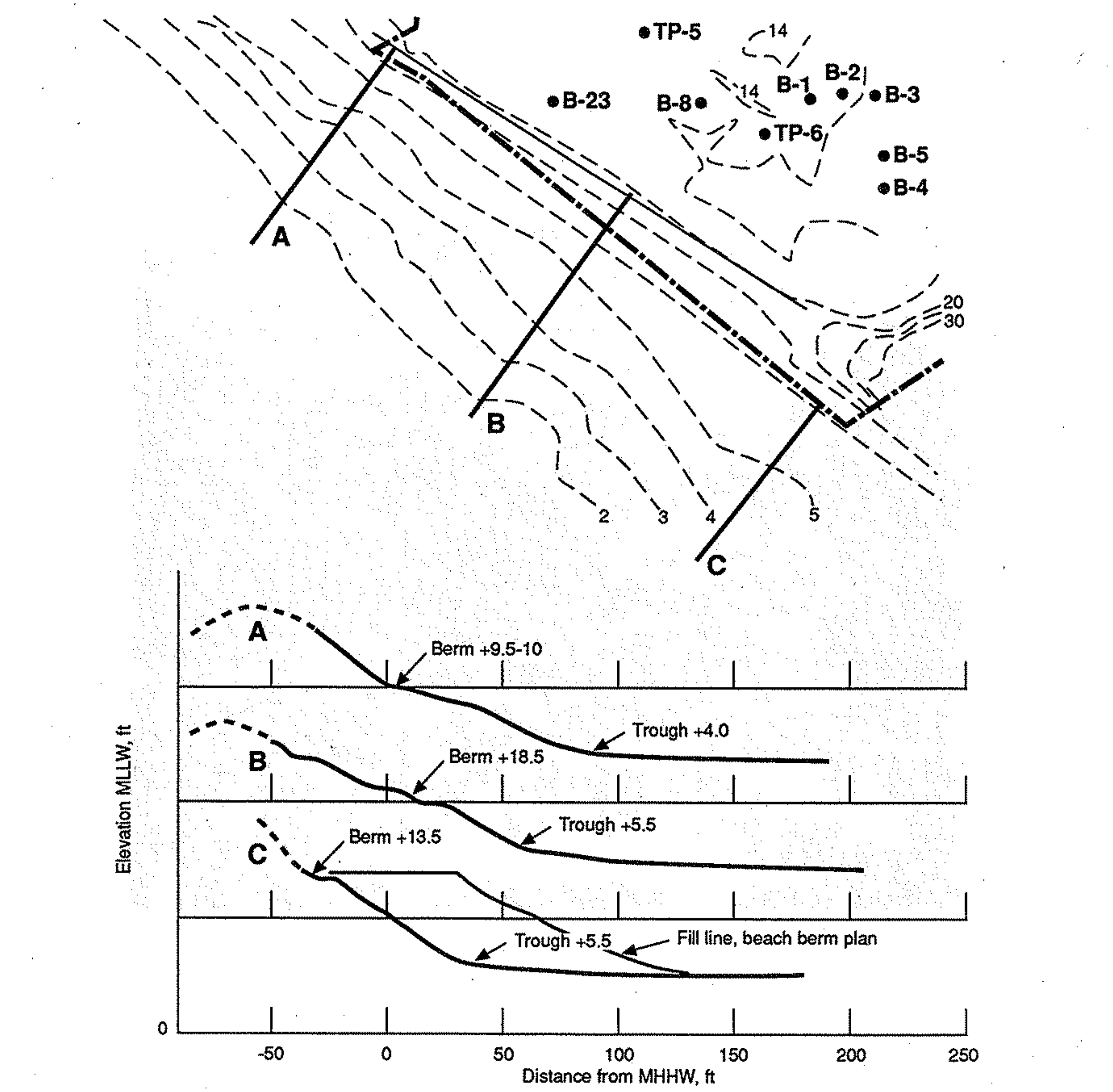
Comparing distance and area measurements from aerial photographs taken between 1936 and 1977, Richey, et al., drew several conclusions about temporal variations in the shoreline configuration. They concluded the shoreline was relatively stable following the 1883 survey, and changed less than 40 feet between 1936 and 1961.

Construction of the sludge lagoon, protruding into Puget Sound, interrupted littoral drift and caused rapid modification to the shoreline both up and downdrift. This was clearly evident from erosion and accretion areas that developed at the north and south ends of the lagoon (Figure 5-28 and 5-29). The effects of accretion south of the lagoon were felt as far as 750 feet updrift (south), at which point a natural, undisturbed shoreline was observed. This distance might be used to as a check to McDougal's (1987) theory that the effects from bulkheads are "felt" by adjacent unprotected shorelines for a downdrift distance that corresponds to 70 percent of the length of the bulkhead (refer to *Section 2—Shoreline Processes*). Based on the observation of a shallow longshore trough (having a bottom elevation no deeper than any other natural feature up or downdrift of the lagoon) that developed soon after construction of the lagoon revetment, Richey, et al., concluded that the installation of the revetment did not appear to have caused erosion below the grade of the pre-existing beach (prior to 1962). In summary, they concluded that after removal of the lagoon from the south side of West Point, the shoreline would very likely return to its pre-1962 configuration.



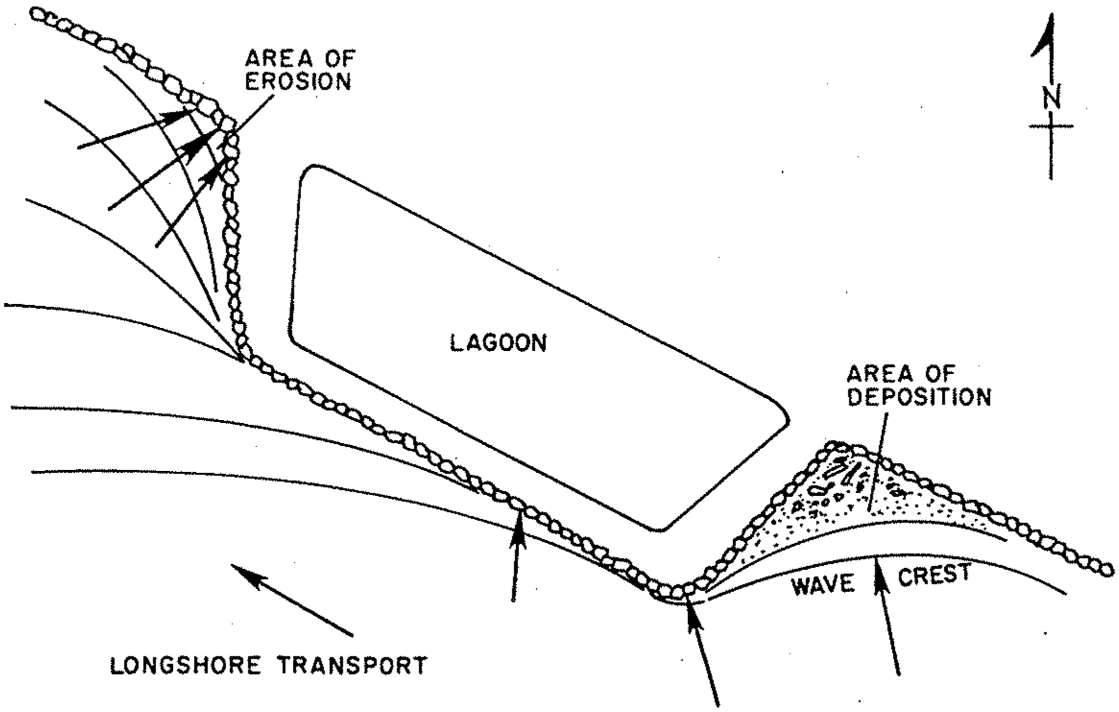
Source: Domenowske, 1987.

Figure 5-26
West Point Foreland and Treatment Lagoon, 1946



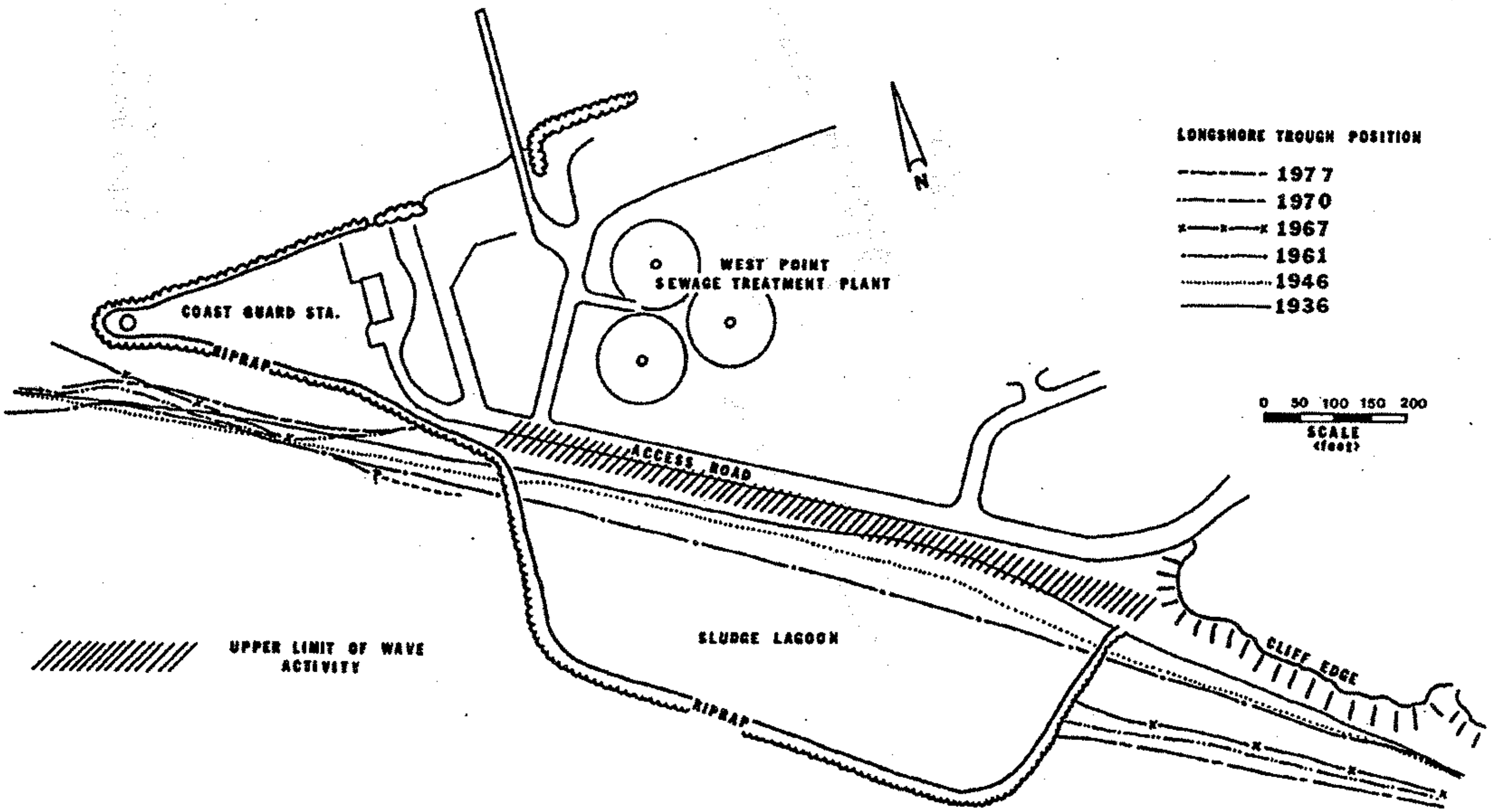
Note: Profiles cross location of treatment lagoon.

Figure 5-27
West Point Foreland Beach Profiles, 1962



Source: Domenowske, 1987.

Figure 5-28
West Point Treatment Lagoon:
Wave Diffraction, Deposition, and Erosion



Source: Richey at al, 1979.

Figure 5-29
West Point Foreland:
Shoreline Response to Treatment Lagoon

The sludge lagoon was removed by Metro in 1980 and replaced by an artificial gravel beach designed by Wolf Bauer[1]. The final gravel beach design reflected a consensus among all concerned property owners: Metro, U.S. Coast Guard, Department of Defense, and the Washington State Department of Natural Resources. The gravel beach design required the removal of 20,000 yd^3 of sludge and sand from the old lagoon; burial of about 12,000 yd^3 of riprap in the backshore region; and construction of 3,000 feet of new gravel beach, which included 58,000 yd^3 sand and gravel, in the backshore area (Domenowske, 1987; Figure 5-30).

The first year after construction, an estimated 3,000 yd^3 (approximately 14 percent of the total fill material) moved around the point to the north side of West Point (Domenowske, 1987). The maximum drop in beach elevation observed on the south tip was about 6 feet, which represents about one-half of the gravel originally placed. Approximately 60,000 yd^2 of beach grass was planted in the sand fill to aid stabilization of the backshore region. Since completion of the gravel beach in 1981, the shoreline has successfully endured over 10 years of winter storms combined with high tides. Plans are presently underway for renourishment of the gravel beach and possible construction of sediment retention structures (a groin or anchor sill) to help slow the littoral transport of material around the point to the north.

West Point is different from other sites described in that a "hard" shore protection structure was only in place temporarily—less than 20 years. Also, the previous two case studies each involve vertical bulkheads rather than riprap revetments, which certainly interact differently in coastal environments. Had the revetment simply been removed (i.e., no gravel beach constructed), this may have provided a unique opportunity to observe the potential re-equilibration of the shoreline back to its original configuration. Had the re-equilibration not occurred, this fact may have provided useful information about the effect from updrift (bulkheaded) sections of shoreline adjacent to West Point.

Whidbey Island (western shore)

Professors Thomas Terich and Maurice Schwartz at Western Washington University are conducting an ongoing beach monitoring study at three sites located at Bush and Lagoon Points along the southwest shoreline of Whidbey Island (Figure 5-31). This is the first study in Puget Sound to investigate shoreline conditions before and after construction of bulkheads and quantify impacts to adjacent, natural, unprotected shorelines (Terich and Schwartz, 1993). The study began in spring 1991; two additional surveys remain (spring and summer 1993) before the final report will be prepared in fall 1993 (T. Terich, personal communication, April 1993).

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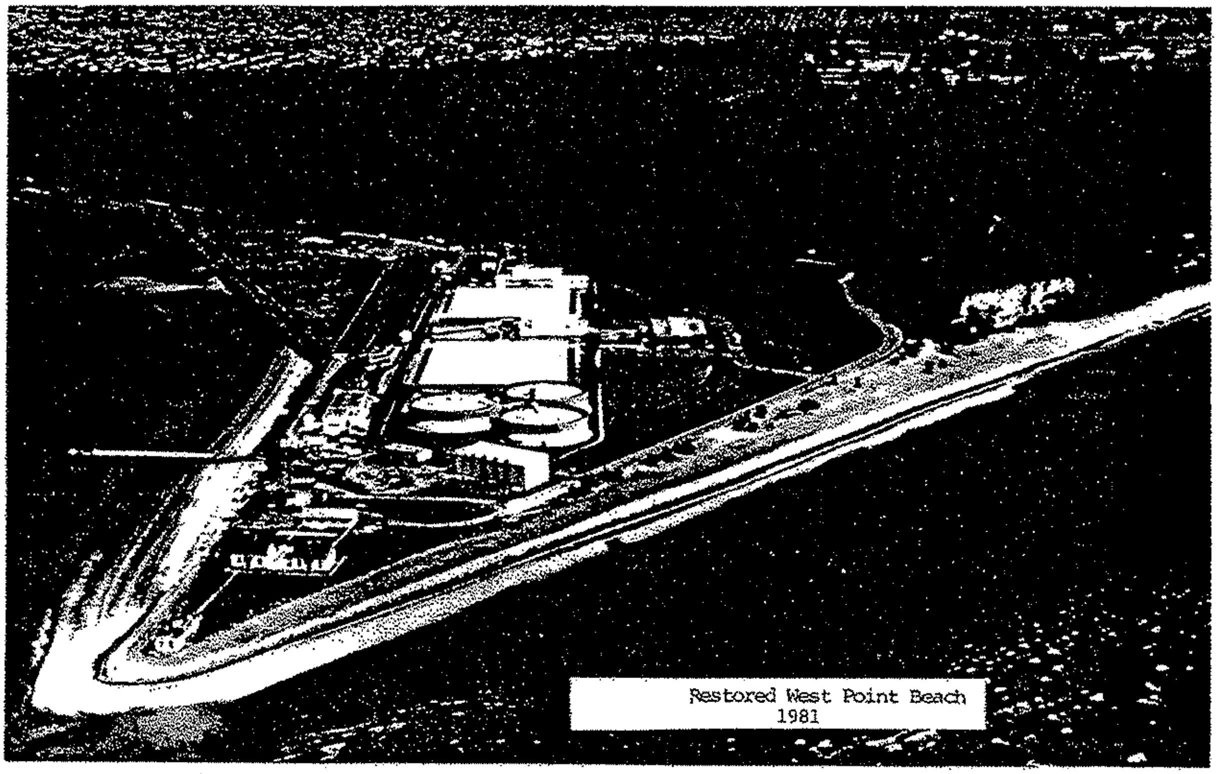
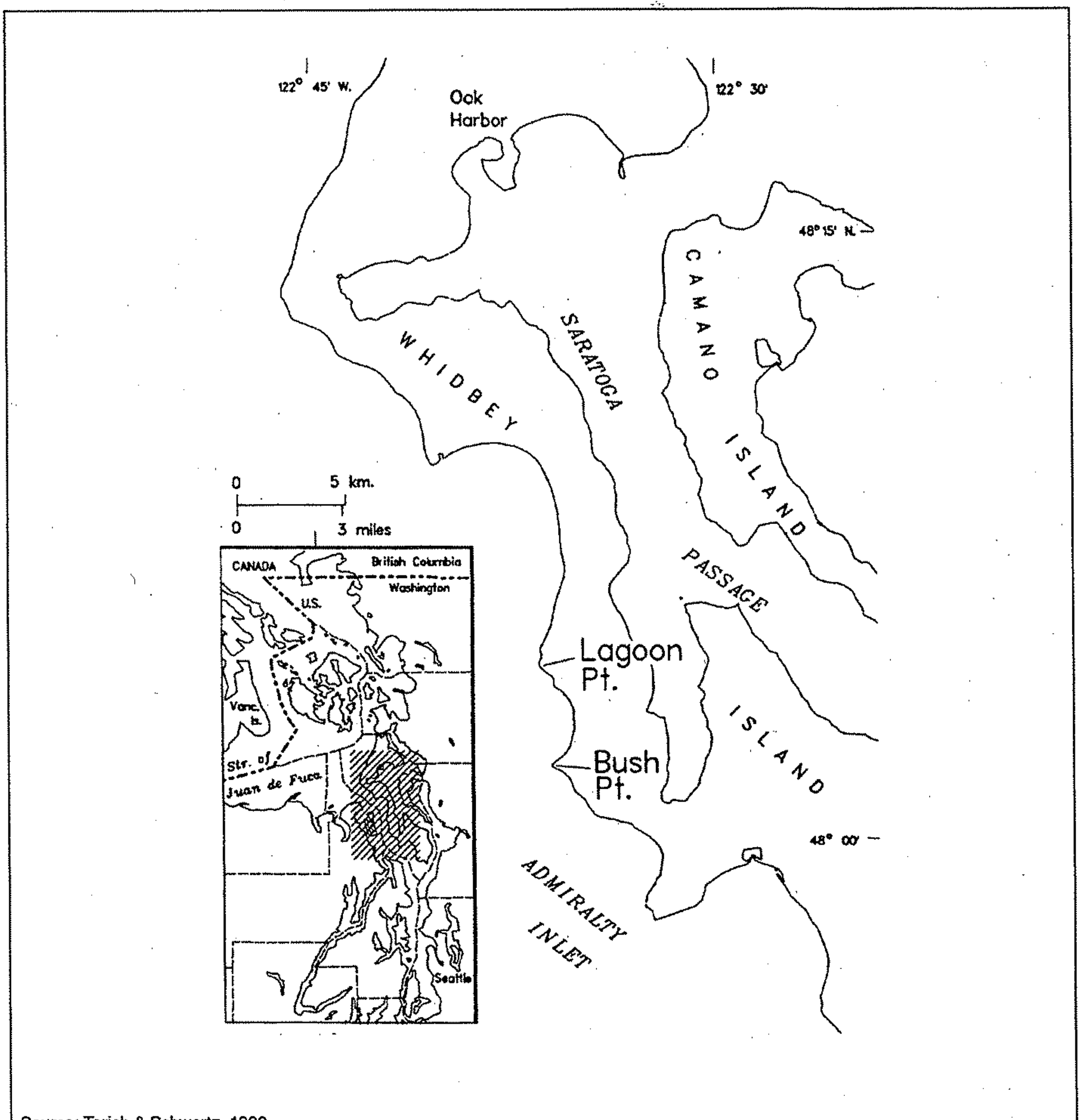
[1]**Wolf Bauer**, with over 60 years' experience of Puget Sound shorelines, is an ardent supporter of beach restoration around Puget Sound. He has designed and installed gravel berm beaches at Lion's Park (Bremerton), North Beach (Orcas Island), Seward Park, Brace Point, Tolmie State Park, and Birch Bay, among others. He has extensive photographic documentation of sites before and after beach restoration. To date, however, no systematic quantitative monitoring of these artificial beach restorations, or their physical and biological impacts, has been conducted.



Source: Domenowske, 1987.

Figure 5-30
West Point Foreland Restored, 1981



Source: Terich & Schwartz, 1992.

Figure 5-31
Whidbey Island
West Shore Study Sites

Preliminary conclusions presented in Terich and Schwartz (1993) include:

- Puget Sound beaches definitely respond to seawall construction.

- Quantitative impacts of seawalls to the shoreline depend upon two main factors: (1) the availability, or lack of, a sediment source to nourish the beach, and (2) the specific location and orientation of the seawall within the beach profile.

- Preliminary results indicate that when a structure such as a bulkhead is built well back on the upper beach berm, the response of the shoreline is small.

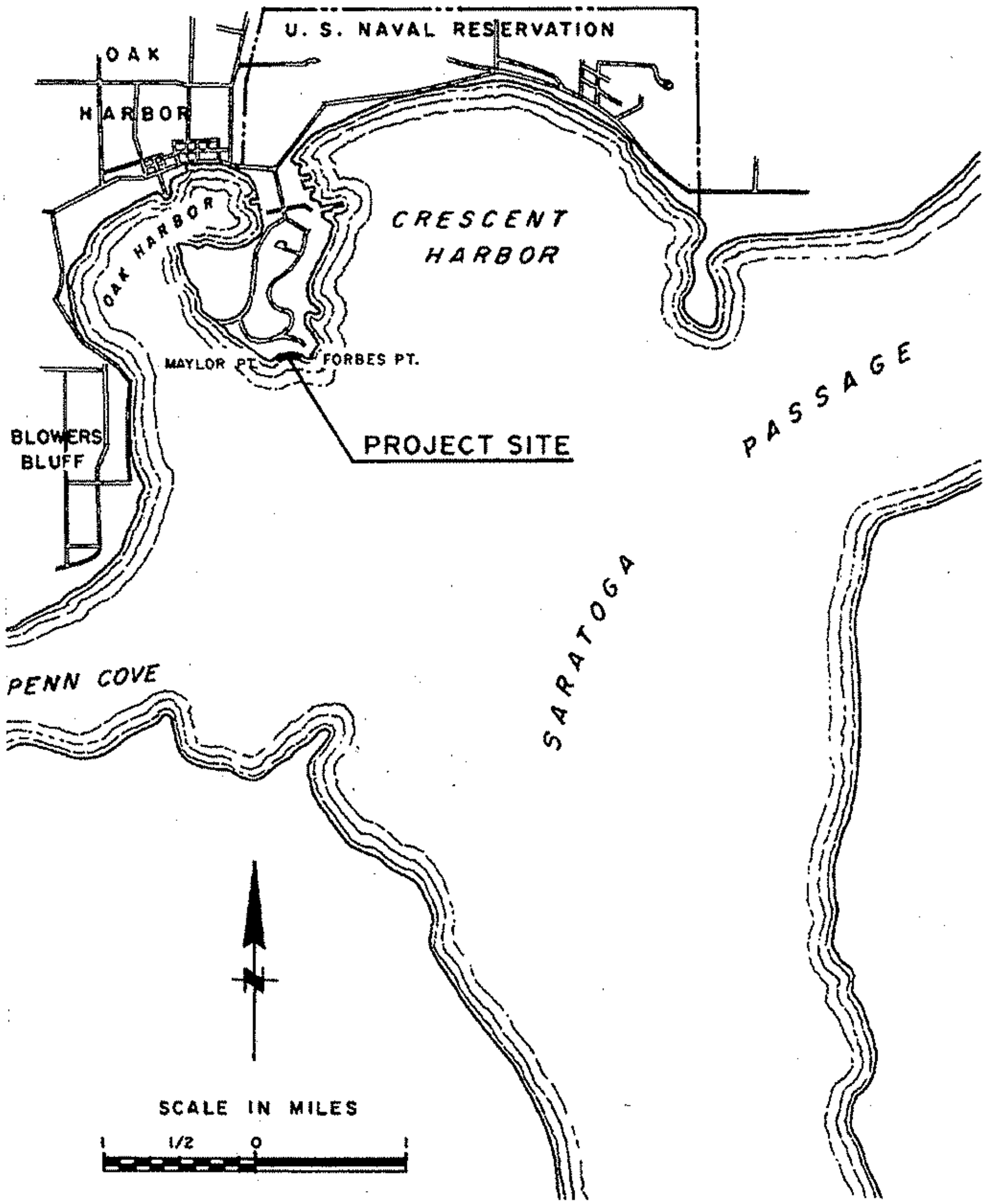
- Natural, unprotected beaches adjacent to armored shorelines become increasingly susceptible to erosion following bulkhead installation.

Other than lowering of the beach profiles and downdrift impacts on adjacent unprotected shorelines, no mention was made of the remaining primary physical impacts addressed in this report, such as an observed change in beach width, coarsening of substrate size, or the accumulation/loss of organic debris from the beachface.

This study represents the type of research that is so sorely needed for Puget Sound shorelines. Its value will be greatly increased if quantitative monitoring can be continued over a longer timeframe, primarily because shoreline processes in Puget Sound operate slowly (e.g., at least longer than over a 2- to 3-year period). Importantly, care is also being taken to document bulkhead-related impacts as opposed to those that are occurring as a result of natural processes (T. Terich, personal communication, May 1993).

Whidbey Island (Oak Harbor)

The Army Corps of Engineers conducted a 1979 demonstration project at Forbes Point on Whidbey Island (Figure 5-32) to assess the protective capabilities of different types of shore protection (Army Corps of Engineers, 1981; Downing, 1983). The focus of the project was to evaluate the structural integrity of different bulkhead designs, i.e., timber pile seawall, gabion mat revetment, sand-cement bag revetment, etc. In general, the project investigated bulkheading more from an engineering and "stormworthiness" perspective than an analysis of physical or biological impacts of armoring on the adjacent beach viewpoint. The applicability of the demonstration project to this study is thus limited, as it does not really address the direct or cumulative impacts that may result as a consequence of bulkheading.



Source: Army Corps of Engineers, 1981.

Figure 5-32
Whidbey Island
Forbes Point Study Site

Days Island

Ecology, Shorelands and Coastal Zone Management Program, recently prepared a brief preliminary report (Shipman, 1993) on shoreline erosion at Days Island, Pierce County. The report summarizes erosion problems (bulkhead undermining) along the eastern shore of Tacoma Narrows and where a groin field has been constructed to intercept littoral drift. Available sources of information include aerial photographs, the Coastal Zone Atlas, and the report on net shore-drift for Pierce County (Harp, 1983). Detailed site-specific information is very limited but this may prove an excellent location for future studies.

There is not enough information to draw conclusions about direct impacts from bulkheading. An observation by Harp (1983), however, regarding vertical offsets of 0.5 to 0.75 meter in the beach profile is very interesting and ties into the Sunnyside Beach example. These vertical offsets are caused by accumulations of sand on one side of a groin and cause a vertical difference in profile elevation between the updrift and downdrift sides of the groin. This observation leaves little doubt as to whether updrift sites (as at Sunnyside Beach, for example) are nourishing this section of shoreline. This site would be a particularly interesting case study because it contains one of the few groin fields in Puget Sound and definitely deserves further investigation.

Rich Passage

In 1990, a study was conducted along the Rich Passage shoreline to determine the extent of impacts resulting from operation of the Seattle-to-Bremerton high speed passenger-only ferry (Hartman Associates, 1990). The study area is shown in Figure 5-33. Complaints from local landowners ranged from an increase in observed erosion rates to damage of intertidal biological resources. Overall conclusions drawn from the study were as follows:

- High-speed ferries operating during the study period (April 23 to June 7, 1990) did not erode sand and gravel along the shoreline under consideration.

- At two out of the three sites studied, physical damage to bulkheads was not a result from ferry operations.

- High-speed ferries operating during the study period did not damage or destroy kelp beds at the study site.

Relative to the scope of this study, Hartman Associates (1990) conclude that the presence of shoreline protection structures prevents the natural shoreline from adapting to ferry wakes and from establishing a sediment equilibrium condition similar to past conditions. They further concluded that bulkhead designs within the study area are not adequate to prevent long-term damage to the shoreline from bulkhead overtopping and toe erosion.

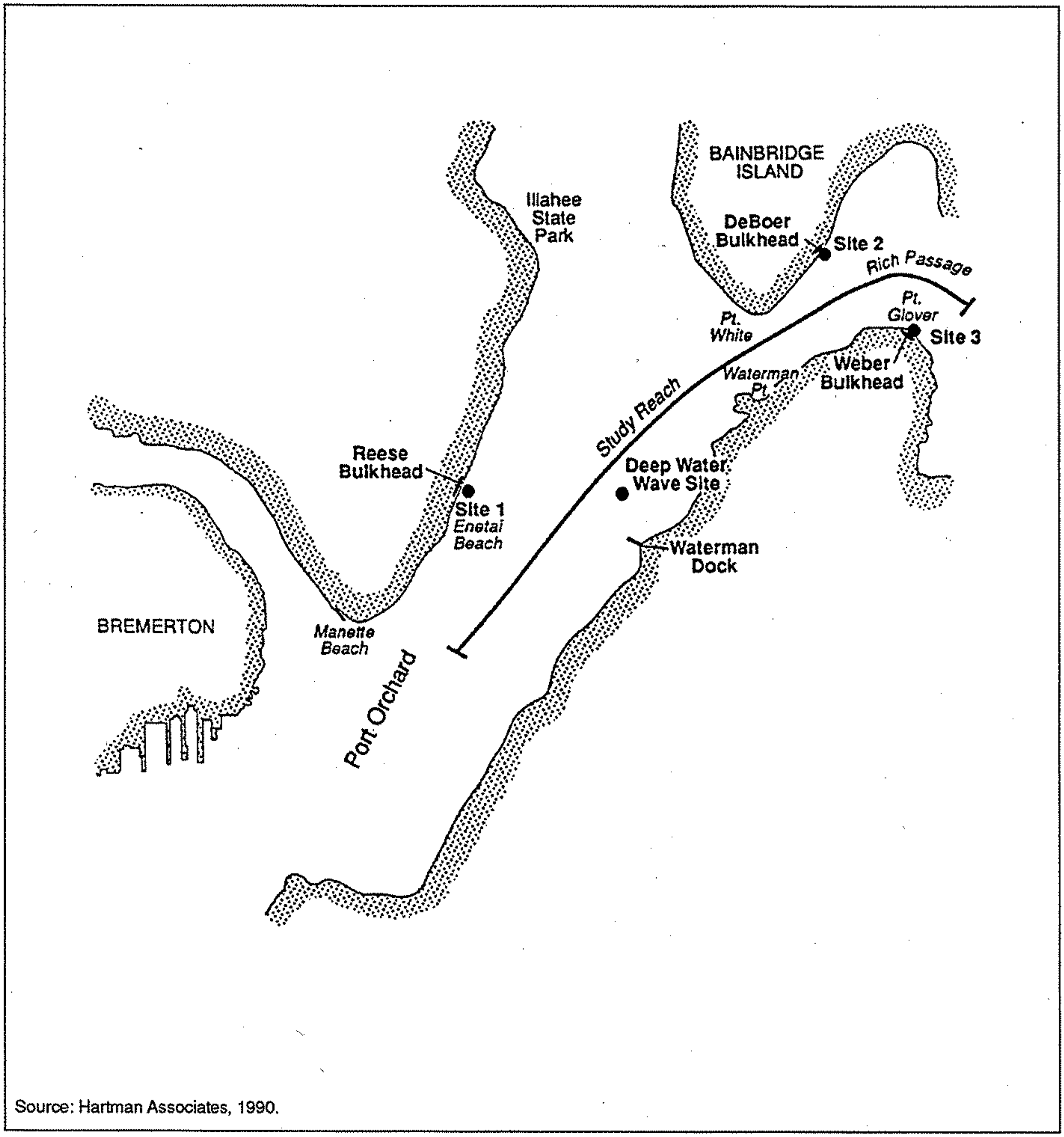


Figure 5-33
Rich Passage Study Sites

South Puget Sound

Bulkheading characteristics along portions of shoreline on Eld and Totten Islands, Thurston County, are summarized in a memorandum by Douglas Canning at Ecology (October 1992). The memorandum describes bulkhead projects constructed by Japhet Construction. The bulkheads constructed by Japhet consist of two basic designs (Figure 5-34), a conventional gravity bulkhead and a zero clearance at dog-leg bulkhead.

Japhet's bulkhead designs have evolved over the years as his direct field experience with their construction and maintenance increased.

Most observations in the memorandum are engineering-related (i.e., materials used, design specifics, typical bulkhead longevity) and not specifically applicable to this impact analysis. However, this type of information may be very useful in the future in helping to evaluate direct impacts from bulkheading in south Puget Sound.

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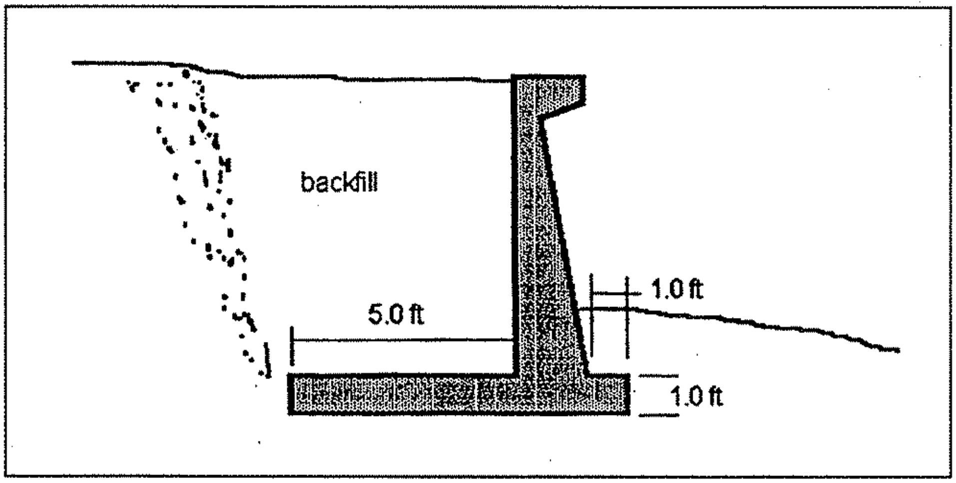
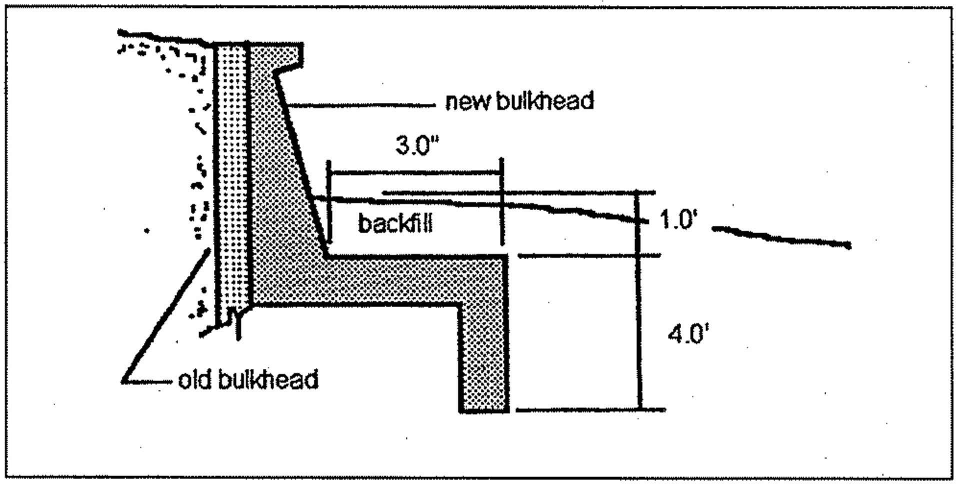


Conventional gravity bulkhead



Zero-clearance bulkhead

Source: Douglas Canning, Ecology, October 1992.

Figure 5-34
Thurston County, Typical Shoreline Bulkheads

Section 6
Cumulative Effects On Physical Coastal Processes

Cumulative impacts are codified in guidelines for the National Environmental Policy Act (40 CFR§1508.7) and similar state legislation. Cumulative impact refers to environmental effects that stem from more than one action. Considered alone the impact of each action might be minor, but seen together as a group, the impacts become significant. They may occur onsite or offsite, may be spatially or temporally displaced from the original disturbance and may be produced by additive or synergistic interactions, "the distinguishing characteristic is that at some point the cumulative effect of the incremental actions become significant (Tuttle and Dickert, 1987)."

Problems of assessing cumulative impacts are the choice of boundaries within which to evaluate cumulative impacts and system thresholds. Threshold is important because it is the point where combined effects become significant. "In some systems thresholds are technically difficult to identify, particularly if masked by natural variation and system noise. In others, an intrinsic threshold may not exist, if the impact responds linearly to increasing stress."

Despite a relatively long regulatory history, meaningful examples of cumulative impact studies remain scarce—and even fewer of them concern the impacts of shoreline armoring.

An excellent introduction to the whole concept of cumulative impacts is provided by Leopold (1980) in an assessment of forest management effects on California watersheds. Several excellent papers on the cumulative impacts of small hydropower developments on watershed fisheries production are included in the proceedings of a symposium on Small Hydropower and Fisheries (American Fisheries Society, 1985). Bain, et. al. (1988) present a methodology for assessing cumulative impacts to fish and wildlife; while Tuttle and Dickert (1988) and Nestler (1992) outline methods for assessing cumulative impacts to wetlands. Virginia Coastal Resources Management Program also recently published a report on Management of Cumulative Impacts in Virginia (University of Virginia, 1991). Shipman and Canning (1993) provide a framework for reviewing cumulative impacts of shoreline stabilization in Puget Sound.

Thurston County Bulkhead Inventory

How much of Puget Sound's shoreline has been altered by some form of shore protection or armoring? Lots—but we do not know how much. What forms of shore protection or armoring are most commonly used in Puget Sound, and in what situations? Again, we do not know. Despite the obvious potential environmental significance of shoreline armoring, no systematic quantitative database summarizing these most fundamental features of Puget Sound presently exists.

To begin filling this gap, Task 1 of the Coastal Erosion Management Strategy study addresses the question: *What are the extent, rate, and character of recent shoreline armoring*? Using Thurston County shorelines as the model, Thurston Regional Planning Council (1993) is quantifying the extent and nature of shoreline armoring over the past 15 years and examining how shore protection is correlated with land use types and development densities. Some interesting preliminary results[1] are presented in Figure 6-1 and Table 6-1.

Table 6-1
Thurston County Inventory of Shore Protection Types, 1993[a]

Armoring Type	No. Parcels	Length/Feet
Concrete	956	105,120
Concrete + Log	21	2,776
Concrete + Riprap	27	2,515
Concrete + Wood Plank	1	111
Log	180	20,480
Other	51	5,024
Riprap	95	11,207
Riprap + Log	6	1,101
Riprap + Wood Plank	4	516
Wood Plank	97	9,375
Wood Plank + Log	5	1,001

[a]J. Kettman, Thurston County (pers. comm., April 1993).

Thurston County shoreline, outside Olympia City limits (excluded from the study area), extends approximately 117 miles along the southernmost portion of Puget Sound (Figure 6-1). An analysis of 1992 aerial photographs and field ground-truthing indicates that nearly 35 miles, or almost 30 percent, of this shoreline is presently armored. The nature of the armoring, by cumulative shore length, is shown in Table 6-1.

Preliminary analysis of a 1977 aerial photo-set (subject to greater error since it cannot be field checked) indicates approximately 16 miles of shore had been armored at that time. If verified, these numbers indicate an increase in total shoreline armoring between 1977 and 1992 of about 18.5 miles or 114 percent (Figure 6-1).

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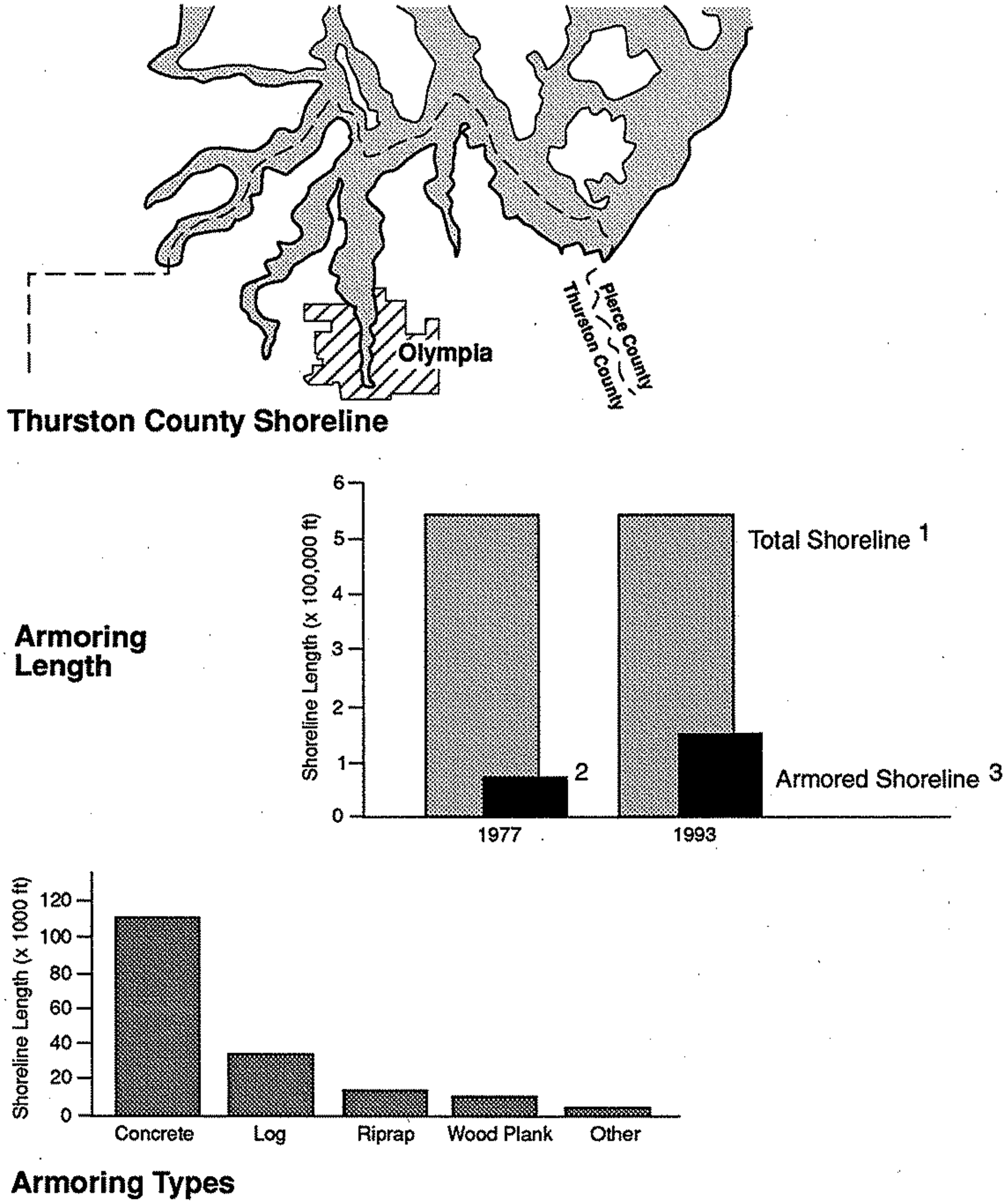
[1]These preliminary results were kindly provided by Jackie Kettman, Thurston Regional Planning Council (personal communication, April 1993) and may be subject to revisions as the Task 1 Report is finalized.



1) Exclusive of City of Olympia.
2) Data for 1977 subject to revision.
3) Armoring doubled in 17 years.

Figure 6-1
Thurston County Shoreline Armoring

Similar surveys from other counties bordering Puget Sound would be extremely useful but are not available. Armoring inventories would be expected to differ among counties reflecting different regional industries, county standards, and the work of local bulkheading contractors.

Other Examples

The best regional example of documented cumulative physical impacts, from both hard and soft shoreline protection methods, comes from Ediz Hook, Clallam County, and has already been described in Section 5.

Good (1992) presents another interesting data set on the cumulative impacts of shore protection structures (SPSs, typically riprap revetments or low seawalls) built along the oceanfront dunes and seacliffs on the Siletz littoral cell (drift sector) on the central Oregon Coast. This shoreline is the most intensively developed along the Oregon Coast with 70 percent of some 900 buildable oceanfront lots developed. It is also one of the most erosion-prone areas of the coast.

From 1967 through 1992, the cumulative length of shore protection structures increased from 2.0 miles to 6.8 miles, or 49 percent of the 14-mile-long beachfront in the littoral cell. Incremental bulkheading increased in years following El Niño events, typically marked by major storms and severe erosion episodes.

Study results suggest that long-term cumulative impacts are potentially among the most serious concerns for a littoral cell like the Siletz, for cliff-supplied sand is a major contributor to the sand budget. As SPSs cut off the cliff-supplied sand, the beaches are narrowing and episodic erosion is increasing. Between 1967 and 1992, bulkheading "locked up" 39 percent of the annual sand supply previously available to the beach from the cliffs. By the year 2050, Good estimates that further SPS's will have "locked up" 56 percent of the sand supply and the threat of coastal erosion will be increasing.

Another study of shoreline cumulative impacts involves bank erosion on Sauvie Island, between miles 99 and 100, on the Columbia River (U.S. Army Corps 1986). Cumulative increases in pile dike construction (1915 to 1940), followed by riprap bank protection (1960 to 1985), along with annual river dredging led to increasing sediment starvation and severe bank erosion on Sauvie Island.

McDonald and Patterson (1985) reported results of comprehensive beach profile surveys carried out over 20 years along the city of Gold Coast, Australia. Comparisons show the cumulative effects of seawalls, groins, training walls, and beach nourishment projects. Steepness of profiles in front of a seawall tended to increase with time. They concluded that seawalls' impact on beaches "is largely dependent on their location on the beach profile. The further seaward they are constructed, the greater their influence and the less likely will a usable beach be maintained in front." This is consistent with Weggel's (1988) concept of interaction of the structure and beach. It justifies the regulatory preference for keeping shore armoring high in the profile. They also concluded that on the persistently eroding shores they studied, "the receding beach line has effectively placed the seawall progressively further and further seaward on the beach profile until no beach exists at all in front of the wall." This is consistent with Dean's (1986) observation that, "the behavior of a beach in nature is dependent primarily on the amount of sand in the nearshore system as compared to that for the equilibrium profile."

Tracking cumulative growth in bulkhead and seawall construction and monitoring resulting impacts is rarely done. Some information on the California coast reported by Griggs (1987) will be useful to future studies of cumulative impacts. In 1971 the Corps of Engineers documented 1,476 km of eroding coastline, with 124 km critically eroding. A total of 43 km of shoreline were protected by structures. In 1977 the Department of Navigation and Ocean Development reported that 170 km of shoreline were eroding critically enough to threaten present development. An additional 506 km of shoreline were eroding fast enough to threaten future development. At that time, 186 km of shoreline were protected by structures. If the information could be reduced with similar criteria regarding critical erosion and erosion that is not critical, the extent of erosion and of protection structures could be known at two points in time. Sediment budget and site specific information would be needed in future assessments, but the escalation of shore erosion and shore protection could be tied together. It is realized that quantitative relationships developed on open coast sandy shores could not be applied directly in Puget Sound, but they could guide investigators in making inferences.

Cumulative effects of shore protection structures may be interpreted from the sequence of structural responses reported by Reynolds (1987) at the northern end of Marco Island, on the south Florida Gulf Coast. It is a mesotidal environment, with a net longshore transport rate of 26,400 cubic yards per year from north to south with a strong seasonal variation. From aerial photographic interpretation of five intervals between 1926 and 1981, it was determined that the shoreline in the study area was accreting in the period 1926-1962, and retreating after 1962. The first condominiums were constructed there in 1966, along with the first shore structure. It was a landscape wall approximately 2 feet high and set about 50 feet landward from the MHW contour position. Adjacent condominiums were built in 1968, 1970, and 1972. The sequence of shore structure installation shows the escalation of engineering efforts to protect the condominiums. In 1970, the first landscape wall was replaced with a retaining wall. In 1972, it was replaced with a seawall and at the adjacent two sites the retaining wall was moved back 50 feet. In 1973, the first seawall was destroyed and rebuilt. In 1974 the adjacent seawalls were repaired. In 1975 rock revetment was added to the first location, and in 1976, the seawall was moved back 40 feet and riprap was added. In 1980 and 1983 adjacent seawalls were repaired and heightened. At the present, a 7-foot seawall, protected by rip-rap, fronts the five condominiums and there is no beach.

Regional factors enter into the analysis of this sequence of events. It is unknown if construction began with unlucky timing just at the start of an erosional cycle, or if dynamics of an updrift ebb tidal shoal was the dominant influence at this site, or if indeed the presence of the structures did cause the need for escalating protection. Reynolds drew two conclusions from the study, however, that are worthy of consideration in Puget Sound. Structural response to beach erosion is generally an escalation of engineered structures, with an inevitable loss of the beach. Mistakes of improper placement of structures can be avoided by careful study of historical shoreline change and geomorphological processes.

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Section 7

Conclusions and Research Needs

Summary of Study Conclusions

This section brings together some of the principal conclusions reached during the course of this study. The reader's attention is also directed to the conclusions that follow each impact subsection in Section 4 and the summaries that follow some of the major case studies in Section 5.

1. Traditional studies of waves and beaches have focused on academic interests in general shore zone erosion and sediment transport mechanisms and on engineering concerns about the success or failure of coastal structures. Studies of shore protection impacts on physical and biological beach processes are much more limited. A recent comprehensive annotated bibliography of shore protection physical impact studies (Kraus, 1988) cited only about 40 studies worldwide.

2. In developing a general understanding of shore protection impacts on beaches, it is important to distinguish between naturally sediment-starved coastlines experiencing regional erosion and retreat versus stable equilibrium coastlines with an abundance of beach sediments. The impacts of shoreline armoring are likely to be very different between the two cases.

3. There is broad-based general agreement that the physical impacts of "hard" solutions to coastal erosion concerns—i.e., shoreline armoring—include sediment impoundment (which has the potential for significant downdrift impacts), beach narrowing, and shore profile lowering. All three impacts have been described from numerous widely distributed field sites as well as from theoretical and modeling studies. Very few of these studies have been conducted in Puget Sound, however.

4. Other major physical impacts discussed here—i.e., sediment coarsening, groundwater impacts, and loss of large organic debris (LOD)—have not been studied systematically and generally receive only limited attention. In fact, these impacts may have very significant physical and ecological implications, especially for Puget Sound.

5. A significant conclusion of many shore armoring/beach impact studies is that the level of physical impacts increases significantly as armoring is placed successively waterward of OHWM. Structures located landward of OHWM generally cause minimal impacts to the beach. Maximum **net** erosion impacts are noted when armoring structures are placed on the beach about three-fifths of the distance from wave breakpoint to the still waterline (Kraus, 1987).

6. Dimensional relationships describing shore protection impacts—e.g., the length, breadth, depth, or volume of beach erosion versus wall length, wave height, or sediment type—remain poorly documented, and broad-based quantitative generalities have yet to emerge.

7. There is a fundamental difference in the physical impacts likely to result from "hard" and "soft" solutions to shore protection. Hard solutions—seawalls, bulkheads, and revetments, for example—protect the land behind them, but not the beach that fronts them. In addition to impoundment impacts, hydraulic impacts resulting from increased turbulence in front of the "hard" armoring can cause beach narrowing, profile lowering, and sediment coarsening. Soft solutions—beach nourishment, for example—can also result in impoundment of back-shore sediment sources and may involve direct burial of a portion of the fronting beach with the nourishment fill. On the other hand, soft solutions generally avoid the hydraulic impacts typical of hard solutions.

8. To date, most field studies of shoreline armoring impacts on beaches have been conducted at open coast sites characterized by well-sorted sandy sediments. Further, most studies have examined the impacts of major storm events on coastal structures. While this provides important data on the potential failure and redesign of coastal structures, it does not inform us about armoring impacts on beaches under more normal, less vigorous wave conditions. These studies do confirm that single storm events can produce major (episodic) impacts not otherwise seen during many years of more normal wave action.

9. Nordstrom (1992) makes an excellent case that protected estuarine systems, including Puget Sound, have their own unique beach characteristics and do not necessarily respond simply as "scaled-down ocean systems." This implies that open coast shore protection impacts can be translated to Puget Sound only with care and insight.

10. The search for documented case examples of shore protection impacts on beaches in Puget Sound identified only a handful of sites for which some historical background and quantitative data are available. The best documented of these, to date, include Ediz Hook (Port Angeles), Lincoln Park Beach (Seattle), Sunnyside Beach (Steilacoom), and West Point South Beach (Seattle).

11. Ongoing monitoring at Lincoln Park Beach (USACOE, Seattle District) and on Whidbey Island's west shore (Terich and Schwartz, Western Washington University) will yield valuable additional data quantifying shoreline protection impacts within Puget Sound.

12. Data concerning cumulative impacts of shore protection remain extremely scarce. Results from Ediz Hook, Oregon's Siletz littoral cell, and Gold Coast, Australia, all confirm that increased bulkheading results in cumulative impoundment of sediment sources that eventually leads to beach "starvation" and severe beach loss. By

analogy, significant cumulative impacts can be expected as Puget Sound drift sector "source areas" are increasingly cut off (impounded) by cumulative bulkheading.

13. To echo Tait and Griggs (1991), an important conclusion of this study is to re-emphasize the wide variety of interdependent factors that can influence specific impacts of shore protection on the beach at a particular site. Beach response must be regarded as a site-specific impact.

Future Research Needs

Much remains to be learned about shore protection alternatives in Puget Sound. General impacts are reasonably well understood, but quantitative studies to assess their rates, magnitudes, and significance remain very scarce. While valuable insights can be gained from coastal erosion/protection studies conducted elsewhere (see Tait and Griggs, 1991; Good and Ridlington, 1992; and Nordstrom, 1993, for example), Puget Sound has enough unique characteristics that local data are needed to verify applicability of such studies to the Sound.

It would be convenient and encouraging to say that completion of Ecology's **Coastal Erosion Management Strategy** study will answer the questions about shore protection impact and spell out clear policy options to deal with such impacts. Unfortunately, such won't be the case! Our understanding will have been advanced and many of the arguments will be more clearly framed—but there still remains a critical need for objective, quantitative data to assess the potential shoreline processes and impacts discussed herein.

The following list identifies some of the most obvious and critical data needs concerning shoreline armoring impacts in Puget Sound.

1. The lack of relevant shore protection impact data for Puget Sound needs to be more clearly and more widely understood.

2. Thurston Regional Planning Council's inventory of shoreline bulkheading needs to be expanded to other Puget Sound Counties so we know how shorelines are being changed, what's being lost, and how fast its happening.

3. Quantitative measurements of short- and long-term shoreline and bluff erosion rates, and rates of net shore-drift around Puget Sound are needed to expand the presently limited database of such measurements.

4. Terich and Schwartz's ongoing beach monitoring studies on the southwest shore of Whidbey Island (Section 5), in which they are quantifying "before and after" impacts of shore armoring, need to be expanded to other Puget Sound locations.

5. Quantitative monitoring of interactions between shore protection hydraulic impacts, habitat characteristics,and biological community processes, need to be conducted at appropriate carefully selected sites (see Section 5).

6. Innovative approaches to shore protection—particularly "soft" solutions (beach nourishment) and hard/soft combination solutions—need to be installed and monitored as pilot projects around Puget Sound.

7. More field monitoring needs to be conducted following installation of "hard" and "soft" shore protection solutions to provide comparative impact data.

The following paragraphs offer an additional perspective on future research needs—with a broader, rather different focus.

Population trends lead to the prediction of increased human impacts in coastal counties. Increasing value of waterfront property is usually accompanied by increasing requests to armor the shore. The Ad Hoc Committee on Coastal Engineering Research Needs, a committee of ASCE Coastal Engineering Research Council, stated (Dean, et al., 1991) "At present there is a dearth of data relative to the coastal design needs. Therefore, there is a great need for data collection, analysis, and presentation of results to describe quantitatively the physical phenomena driving coastal processes, as well as improve our understanding of coastal processes and the effects of anthropogenic impacts on these processes."

This committee pointed out that the largest population growth will be in California, Florida, and Texas, so it can be fairly concluded that whatever future increase in data collection and analysis there might be on a national scale will probably be slanted toward the sand beach/outer coast environment. The points made by the committee are still valid, but there is little hope that activities prompted by the committee will benefit management activities of erosion in Puget Sound. Yet, as clearly noted by Nordstrom (1993), estuarine beaches such as those of Puget Sound require and deserve their own separate research agenda.

Wiegel (1992) stated "Coastal engineers and scientists have put too much of their research effort into studies of small scale hydraulic models and numerical models, rather than making full-scale studies. Field studies show the complexity of wave action that can occur at revetments. Complete field experiments are needed, not the partial experiments that so many of them have been."

Referring to the Griggs and Tait (1991) studies in Monterey Bay, Weigel states, "It is important for this type of field research to be expanded." Studies of the scale of those in Monterey Bay should be adapted to Puget Sound shorelines.

Detailed investigation of turbulence and sediment movement in the vicinity of armoring would clarify understanding of local processes, and should be carried out at a site the history of which is well documented. Efficiency could be best achieved by remotely measuring surf characteristics and beach responses. A video image processing technique developed by Holman for coastal applications (Lippmann and Holman, 1989) has been shown to be a reliable method to remotely measure nearshore morphology. This method and other instrumentation should be investigated for application to the problem of wave interaction with armoring at Puget Sound beaches.

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Section 8
Works Cited

American Fisheries Society. *Small Hydropower and Fisheries*. Proceedings of Symposium, Aurora, Colorado, May 1985.

Angell, T., and K. C. Balcomb, III. *Marine Birds and Mammals of Puget Sound*. Puget Sound Books, a Washington Sea Grant Publication. University of Washington Press. 1982.

Bain, M. B., J. S. Irving, and G. W. Witmer. *An Approach to Assessing Cumulative Impacts on Fish and Wildlife*. 21 pp. Argonne National Laboratory, Argonne, Illinois. 1988.

Bainbridge Marine Services and Jones and Stokes Associates. Marine Bulkheads Construction Methods and Effects. VHS video recording. May 1992.

Basco, David R. Boundary Conditions and Long-Term Shoreline Change Rates for the Southern Virginia Ocean Coastline. *Shore and Beach*, Vol. 60, No. 4, pp. 8-13. 1992. [October issue]

Bascom, W. *Waves and Beaches*. Anchor Books, Doubleday, New York. Revised Edition. 1980.

Bauer, W. *Erosion-Protective Beach Design for the West Point South Beach Rehabilitation*. Position paper prepared for the Municipality of Metropolitan Seattle (Metro). 1979.

Bird, Eric C. F. Changes on Artificial Beaches in Port Phillip Bay, Australia. *Shore and Beach*, Vol. 59, No. 2, pp. 19-27. 1991. [April issue]

Bodge, Kevin, and Robert Dean. *Short-Term Impoundment of Longshore Sediment Transport*. Miscellaneous paper CERC-87-7. U. S. Army Waterways Experiment Station. Vicksburg, MS. 1987.

Canning, D. Technical memorandum to Keith Macdonald/CH2M HILL regarding field inspections with Floyd Japhet. October 27, 1992.

Da Costa, Steven L., J. Scott, and D. Simpson. Gravel Equilibrium Beach Design for Arresting Shore Erosion at Flathead Lake, Montana. *Proceedings, Coastal Engineering Practice 92,* Am Soc Civil Engineers. 1992. Pp. 154-169.

Dean, Robert G. Heuristic Models of Sand Transport in the Surf Zone. *Proceedings of the Conference on Engineering Dynamics in the Surf Zone*. 1973. Pp. 208-214.

―――――――. *Equilibrium Profiles: U. S. Atlantic and Gulf Coasts.* Technical Report No. 12, Department of Civil Engineer, University of Delaware, Newark, DL. 1977.

―――――――. Coastal Armoring: Effects, Principles and Mitigation. *Proceedings, Twentieth Coastal Engineering Conference*, Am. Soc. Civil Engineers. 1986. Pp. 1843-1857.

―――――――. Equilibrium Beach Profiles: Characteristics and Applications. *Journal of Coastal Research.* Vol. 7, No. 1. 1991. Pp. 53-84.

Dean, Robert G. et. al. Coastal Engineering Research Needs. *Shore and Beach* Vol. 59, No. 4, pp. 4-7. 1991.

Dean Robert G., H. Pilkey, Jr., and R. Houston. Eroding Shoreline Impose Costly Choices. *Geotimes*, May 1988. Pp. 9-14.

Domenowske, R. W. Municipality of Metropolitan Seattle, West Point Beach Restoration. *Coastal Zone 87: Proceedings of the Fifth Symposium of Coastal and Ocean Management,* Seattle, Washington, May 26-29, 1987. Vol. 2. 1987. Pp. 2141-2152.

Downing, John. *The Coast of Puget Sound, Its Processes and Development.* Washington Sea Grant Publication, University of Washington Press, Seattle. 1983. 126 pp.

Everts, C.H. Effects of Small Protective Devices on Beaches. California's Battered Coast: Proceedings of Conference on Coast Erosion, California Coastal Commission. 1985. Pp. 127-137.

FitzGerald, D. M. Effects of Intense Storm at Winthrop Beach, Massachusetts. *Shore and Beach.* Vol. 48, No. 3. 1980. Pp. 6-19.

Fulton-Bennett, Kim, and Gary Griggs. *Coastal Protection Structures and their Effectiveness.* Department of Boating and Waterways and Marine Sciences Institute of University of California. 1986.

Galster, Richard W. and L. Schwartz. Ediz Hook—A Case History of Coastal Erosion and Rehabilitation. *Journal of Coastal Research.* Special Issue No. 6. 1990. Pp. 103-113.

Good, J. W. Ocean Shore Protection Policy and Practices in Oregon, pp. 145-162, In Good, J. W. and S. S. Ridlington (eds.) *Coastal National Hazards: Science, Engineering, and Public Policy.* Oregon Sea Grant, ORESU-B-92-001. 1992.

Griggs, Gary. The Production, Transport, and Delivery of Coarse-Grained Sediment by California's Coastal Stream. *Proceedings, Coastal Sediments 87,* Am Soc Civil Engineers. 1987a. Pp. 1825-1838.

————. California's Retreating Shoreline: The State of the Problem. *Proceedings, Coastal Zone 87.* Am. Soc. Civil Engineers. 1987b. Pp. 1370-1383.

Hansen, Hans, and Nicholas, Kraus. *GENESIS: Generalized Model for Simulating Shoreline Change.* Technical Reference, Technical Report CERC-89-19, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 1989.

Harp, B. D. *Net Shore-Drift of Pierce County Washington.* M.S. thesis. Western Washington University, Bellingham, Washington. 1983. 177 pp.

Hartman Associates. *Impacts of Passenger-Only Ferry Wake Rich Passage to Bremerton.* Prepared for the Washington State Ferry System. Seattle, Washington. 1990.

Hsu, John, R. Silvester, and Yi-Min Xia. Static Equilibrium Bays: New Relationships, *Journal of the Waterway, Port Coastal, and Ocean Engineering Division*, Am Soc Civil Engineers. Vol. 115, No. 3. 1989. Pp. 194-197.

Jones, D. F. *The Effect of Vertical Seawalls on Longshore Currents.* Ph.D. thesis, Department of Coastal and Oceanographic Engineering, University of Florida, Gainesville, Florida.

Kamphuis, J. W. Recession Rate of Glacial Till Bluffs. Am Soc Civil Engineers, *Journal of Waterway, Port, Coastal, and Ocean Engineering*. Vol. 113, No. 1. 1987. Pp. 60-73.

Keuler, R. F. *Coastal Zone Processes and Geomorphology of Skagit County, Washington.* M.S. thesis, Western Washington University. 1979. 127 pp.

————. Map showing coastal erosion, sediment supply, and longshore transport in the Port Townsend 30- by 60-Minute Quadrangle, Puget Sound Region, Washington, Map 1199-E, Miscellaneous Investigation Series, U.S. Geological Survey. 1988.

Kozloff, E. N. *Seashore Life of Puget Sound, the Strait of Georgia, and the San Juan Archipelago.* University of Washington Press. Seattle. 1974.

Kraus, Nicholas C. The Effect of Seawalls on the Beach: A Literature Review. *Proceedings, Coastal Sediments 87,* Am Soc Civil Engineers, New York. 1987. Pp. 945-960. Also Journal of Coastal Research, Special Issue 4, 1988. Pp. 1-28.

————. Personal communication with David Simpson, Newport, Oregon. June 10, 1992.

Kraus, Nicholas, M. Gravens, and D. Mark. *Coastal Processes at Sea Bright to Ocean Township, New Jersey*. Volume II, Appendixes B-B, miscellaneous paper CERC-88-12, U. S. Army Waterways Experiment Station, Vicksburg, MS. 1988.

Larson, Magnus. *Quantification of Beach Profile Change*. Department of Water Resources Engineering Lund University, Report No. 1008, Lund, Sweden. 1988.

Leopold, Luna B. The Topology of Impacts, p. 1-21, In Standiford, R. B. and S. I. Ramacher (eds.) *Cumulative Effects of Forest Management on California Watersheds: An Assessment of Status and Need for Information*. Department of Forestry/Resource Management, University of California, Berkeley. June, 1980.

Lippmann, T. C., and R. A. Holman. Quantification of Sand Bar Morphology: A Video Technique Based on Wave Dissipation. *Journal of Geophysical Research*. Vol. 94, No. C1. 1989. Pp. 995-1011.

Maser, C., R. F. Tarrant, J. M. Trappe, and J. F. Franklin (tech. eds.). *From the Forest to the Sea: A Story of Fallen Trees*. Pacific Northwest Research Station, U. S. Department of Agriculture, Forest Service, Portland, Oregon. General Technical Report. PNW-ETR-229. 1988. 153 pp.

McDonald, H. V., and D. C. Patterson. Beach Response to Coastal Works, Gold Coast, Australia. *Proceedings of Nineteenth Coastal Engineering Conference*. Am Soc Civil Engineers. 1985. Pp. 1522-1538.

McDougal, William, M. Sturtevant, and P. Komar. Laboratory and Field Investigations of the Impact of Shoreline Stabilization Structures on Adjacent Properties. *Proceedings, Coastal Sediments '87*, Am Soc Civil Engineers. 1987. Pp. 961-973.

Mossa, Joann, P. Meisburger, and A. Morang. *Geomorphic Variability in the Coastal Zone*. Technical Report CERC-92-4, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 1992.

Myers Biodynamics, Inc. *Slope Stabilization and Erosion Control Using Vegetation: A Manual of Practice for Coastal Property Owners*. Washington Department of Ecology. Olympia, Washington. 1993. 43 pp.

Naiman, R. J., and J. R. Sibert. Detritus and Juvenile Salmon Production in the Nanaimo Estuary: III. Importance of Detrital Carbon to the Estuarine Ecosystem. *J. Fish. Res.Board Can.* 36:504-520. 1979.

Nestler, John. Cumulative Impact Assessment in Wetlands. *Wetlands Research Program Bulletin,* Vol. 2(1), p. 1-4, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. April, 1992.

Pentilla, D. *Studies of the Surf Smelt (Hypomesus pretiosus) in Puget Sound.* Washington Department of Fisheries. Technical Report No. 42. 1978.

Phillips, R. C. *Ecology of Eelgrass Meadows in the Pacific Northwest: A Community Profile.* Prepared for U. S. Fish and Wildlife Service and Corps of Engineers. FWS/PBC-84/24. 1984.

Pilkey, Orrin, and William Neal. Coastal Geologic Hazards, The Geology of North America. In R. E. Sheridan and J. A. Grow, eds. Vol. I-2, *The Atlantic Continental Margin,* Chapter 28, The Geological Society of America. 1988.

Pollock, C.B. Nearshore Berm Testing of SUPERTANK. *Dredging Research,* U.S. Army Corps of Engineers, Waterways Experiment Station. Vol. DRP-93-1:1-4. February 1993.

Posey, Frank, and Jeffrey Dick. Case Study on Fifth Years of Seawall and Groin Construction, Tybee Island, Georgia. *Proceedings, Coastal Zone 87,* Am Soc civil Engineers. 1987. Pp. 3221-3232.

Reynolds, William. Coastal Structures and Long-Term Shore Migration. *Proceedings, Coastal Zone 87,* Am Soc Civil Engineers, 1987. Pp. 414-426.

Richey, E. P., R. W. Sternberg, and J. P. Downing. *West Point Treatment Plant-Removal of Experimental Sludge Lagoon Shoreline Restoration Study.* Report prepared for Metro Engineers. 1979.

Sato, Michio. Underground Water Table and Beach Face Erosion. *Proceedings, Twenty-Second Coastal Engineering Conference,* Am. Soc. Civil Engineers, New York. 1990. Pp. 2644-2657.

Sato, S., Tanaka, N., and Irie, I. Study of Scouring at the Foot of Coastal Structures. Proceedings of Eleventh Coastal Engineering Conference, Am. Soc. Civil Engineers. 1969. Pp. 579-598.

Schou, A. Direction Determining Influence of the Wind on Shoreline Simplification and Coastal Dunes. *17th Conference of International Geographical Union, Proceedings,* Washington, D.C. 1952. Pp. 370-373.

Schwartz, Maurice L., R. Wallace, and E. Jacobsen. Net Short-Drift in Puget Sound. *Engineering Geology in Washington,* Volume II, Washington Division of Geology and Earth Resources Bulletin 78. 1989. Pp. 1137-1146.

Shipman, H. Potential Application of the Coastal Barrier Resources Act to Washington State. *Proceedings, Coastal Zone 93, Eight Symposium on Coastal and Ocean Management,* July 19-23, 1993, New Orleans, Louisiana, American Society of Civil Engineers. New York. Preprint. 1993. 9 pp.

————————. *Preliminary Report on Shoreline of Days Island, Pierce County,* March 18, 1993. Washington State Department of Ecology, Shorelands and Coastal Zone Management Program, Olympia, Washington. 1993.

————————. Shoreline Erosion Rates. *Coastal Erosion Bulletin.* Washington Department of Ecology, Shorelands and Coastal Zone Management Program. Olympia, Washington. No. 2, p. 3. March 1993.

Shipman, Hugh, and Douglas Canning. Cumulative Environmental Impacts of Shoreline Stabilization of Puget Sound. *Proceedings, Coastal Zone 93 Eighth Symposium on Coastal and Ocean Management, July 19-23,* Am Soc Civil Engineers, New York. 1993.

Silvester, Richard, and John R. C. Hsu. *Coastal Stabilization—Innovative Concepts*, PTR Prentice Hall, Inc., Englewood Cliff, New Jersey. 1993. 578 pp.

Smith, A.W., and D.M. Chapman. The Behavior of Prototype Boulder Revetment Walls. Coastal Engineering. Vp. 1914-1929. 1982.

Tait, James F., and Gary B. Griggs. *Beach Response to the Presence of a Seawall, Comparison of Field Observations.* Contract Report CERC-91-1, U. S. Army Waterways Experiment Station, Vicksburg, Mississippi. 1991.

Terich, T. A. *Living with the Shore of Puget Sound and the Georgia Strait.* Sponsored by the National Audubon Society. Duke University Press, Durham. 1987.

Terich, T. A., and M. L. Schwartz. The Effects of Seawalls upon the Beaches of Puget Sound, Washington, USA. To be presented at the Canadian Coastal Conference, Vancouver, B.C., Canada, May 4-7, 1993.

Thieler, E. Robert, S. Young, and H. Pilkey, Jr. Discussion of Boundary Conditions and Long-Term Shoreline Change Rates for the Southern Virginia Ocean Coastline. *Shore and Beach.* Vol. 60, No. 4. 1992. Pp. 29-30.

Toue, Tako, and Hsiang Wang. Three Dimensional Effects of Seawall on the Adjacent Beach. *Proceedings, Twenty-Second Coastal Engineering Conference,* Am Soc Civil Engineers. 1990. Pp. 2782-2795.

Toyoshima, O. Effectiveness of Seadikes With Rough Slope. Proceedings of Sixteenth Coastal Engineering Conference, Am. Soc. Civil Engineers. 1979. Pp. 2528-2539.

Tubbs, D.W. *Causes, Mechanisms and Prediction of Landsliding in Seattle*. Unpublished dissertation, University of Washington, November 1975.

Tuttle, Andrea, and Thomas Dickert. Assessing Cumulative Impacts on Wetland Watersheds. *Proceedings, Coastal Zone 87 Fifth Symposium on Coastal and Ocean Management,* Am Soc Civil Engineers, New York. 1987. Pp 1760-1774.

U. S. Corps of Engineers. *Bulkheads—Their Applications and Limitations.* Technical Note CETN-III-7, Waterways Experiment Station, Vicksburg, MS. 1981. 8 pp.

————————. *Seawalls—Their Applications and Limitations.* Technical Note CETN-III-8, Waterways Experiment Station, Vicksburg, Mississippi. 1981. 7 pp.

————————. *Revetments—Their Applications and Limitations.* Technical Note CETN-III-9, Waterways Experiment Station, Vicksburg, Mississippi. 1981. 9 pp.

————————. *Low Cost Shore Protection—Final Report on the Shoreline Erosion Control Demonstration Program (Section 54).* Contract No. DACW72-79-R-0009. 1981.

————————. *Shore Protection Manual (SPM; 4th Edition).* Coastal Engineering Research Center, Waterways Experiment Station, Vicksburg, Mississippi. Two Volumes. 1984.

————————. *Final Report, Lincoln Park Beach Erosion Study.* Waterways Experiment Station, Coastal Engineering Research Center. Report to Seattle District Corps of Engineers. 1984b.

————————. *Final Detailed Project Report and Final Environmental Assessment, Lincoln Park Beach, Shoreline Erosion Control, Seattle, Washington.* September 1986.

————————. *Investigation of Bank Erosion at Sauvie Island, Oregon.* Portland District, Planning Division Technical Report. September, 1986.

————————. Detailed Project Report (Supplement No. 1), *Lincoln Park Beach, Shoreline Erosion Control,* Seattle, Washington. 1992.

University of Virginia. *Management of Cumulative Impacts in Virginia: Identifying the Issues and Assessing the Opportunities.* Prepared for Virginia Council on the Environment, Coastal Resources Management Program. Richmond, Virginia. December, 1991.

Wallace, R. Scott, and M. C. Schwartz. Quantification of Net Shore Drift Rates in Puget Sound and Strait of Juan de Fuca. *Proceedings, Coastal Zone 87 Fifth Symposium on Coastal and Ocean Management*, Am Soc Civil Engineers, New York. 1987. Pp. 1075-1081.

Washington State Department of Ecology. *Coastal Zone Atlas of Washington,* Volume 7, Pierce County. Publication No. DOE 77-21-7. 1979.

____________. Creosote-Treated Wood in the Aquatic Environment. Focus Sheet F-TC-93-122. Olympia, Washington. April 1993. 2 pp.

Weggel, J. Richard. Seawalls: The Need for Research, Dimensional Considerations and a Suggested Classification. *Journal of Coastal Research.* Special Issue No. 4. 1988. Pp. 29-39.

Wiegel, Robert, 1992. Some Complexities of Coastal Waves, Currents, Sand, and Structures. *Shore and Beach*, Vol. 60, No. 1, p. 21-33.

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Appendix A
Glossary

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Glossary

Accretion. May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of water- or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

Alongshore. Parallel to and near the shoreline; **Longshore.**

Artificial Nourishment. The process of replenishing a beach with material (usually sand) obtained from another location.

Backrush. The seaward return of the water following the uprush of the waves.

Backshore. That zone of the shore or beach lying between the foreshore and the coastline comprising the **berm** or **berms** and acted upon by waves only during severe storms, especially when combined with exceptionally high water.

Bar. A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents.

Beach. The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach—unless otherwise specified—is the mean low water line. A beach includes **Foreshore** and **Backshore.** See also **Shore.**

Beach Berm. A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

Beach Planform. The general shape of the beach as seen from above; horizontal plan of beach.

Beach Profile. A vertical cross section of a beach measured perpendicular to the shoreline.

Beach Strand. Beach strands are long, uninterrupted stretches of natural or artificially created beach. They act as dynamic wave energy absorbers, deforming in both plan and section to accommodate the wave conditions. Beach strands typically have wide, dry beaches.

Bluff Toe. The face of a bluff where it meets the beach.

Breakwater. A structure protecting a shore area, harbor, anchorage, or basin from waves.

Bulkhead. A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action.

Diffraction. Bending of the direction of propagation of a wave when it meets an obstacle.

Downdrift. The direction of predominant movement of littoral materials.

Drift Sector (also known as a Drift Cell or Littoral Cell). A segment of shoreline along which littoral, or longshore, sediment movement occurs at noticeable rates. It allows for an uninterrupted movement, or drift, of beach materials. Each drift sector includes: a feed source that supplied the sediment, a driftway along which the sediment can move, an accretion terminal where the drift material is deposited, and boundaries that delineate the ends of the drift sector.

Extreme Low Water. The lowest elevation reached by the tide as recorded by a tide gauge during a designated period, ideally a 19-year record. In Puget Sound areas, generally, this point has been determined to be 4.50 feet below the datum plane of mean lower low water (0.0 tide level).

Feeder Bluff. An eroding shoreline bluff that supplies sedimentary material to downdrift shorelines.

Fetch. The horizontal distance (area) in which waves (seas) are generated by a wind having a fairly constant direction and speed. Sometimes used synonymously with **Fetch Length.**

Foreshore. The part of the shore that (1) lies between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low-water mark, and (2) is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall.

Gabion. A wire mesh box filled with smaller sized stones but constrained by the mesh to act as a monolithic unit.

Groin. A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore. **Groin field.** A series of groins acting together to protect a section of beach.

High Water Line. The intersection of the plane of mean high water with the shore. The shoreline delineated on the nautical charts of the National Ocean Service is an approximation of the high water line. For specific occurrences, the highest elevation on the shore reached during a storm or rising tide, including meteorological effects.

Higher High Water (HHW). The higher of the two high waters of any tidal day. The single high water occurring daily during periods when the tide is diurnal is considered to be a higher high water.

Higher Low Water (HLW). The higher of two low waters of any tidal day.

Hindcasting, Wave. The use of historic synoptic wind charts to calculate characteristics of waves that probably occurred at some past time.

Jetty. A structure extending into a body of water designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help deepen and stabilize a channel.

Leeward. The direction *toward* which the wind is blowing; the direction toward which the waves are traveling.

Littoral. Of or pertaining to a shore, especially of the sea.

Littoral Cell. See Drift Sector.

Littoral Current. Any current in the littoral zone caused primarily by wave action, e.g., **Longshore Current, Rip Current.**

Littoral Drift. The sedimentary *material* moved in the littoral zone under the influence of waves and currents.

Littoral Transport. The *movement* of littoral drift in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (on-offshore transport) to the shore.

Load. The quantity of sediment transported by a current. It includes the suspended load of small particles and the bedload of large particles that move along the bottom.

Longshore. Parallel to and near the shoreline; **Alongshore.**

Longshore Current. The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline.

Lower High Water (LHW). The lower of the two high waters of any tidal day.

Lower Low Water (LLW). The lower of the two low waters of any tidal day. The single low water occurring daily during periods when the tide is diurnal is considered to be a lower low water.

Mean Lower Low Water (MLLW). The average of the lower low water elevation of each pair of low waters of a tidal day, ideally measured over a 19-year period. 0.0 tide level has been determined by U.S. Coast & Geodetic Survey to be mean lower low water. All other tidal elevations are based on this datum.

Mean Sea Level. The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings.

National Geodetic Vertical Datum (NGVD 1929). For marine applications a base elevation used as a reference from which to reckon heights or depths.

Nearshore Current System. The current system caused primarily by wave action in and near the breaker zone, and which consists of four parts: the shoreward mass transport of water; longshore currents; seaward return flow, including rip currents; and the longshore movement of the expanding heads of rip currents.

Nourishment. The process of replenishing a beach. It might be brought about naturally by longshore transport, or artificially by the deposition of dredged materials.

Ordinary High Tide. Same as mean high tide or the average of the upper line of tide water flow. In Puget Sound, the mean high tide line varies from 10 to 13 feet above the datum plane of mean lower low water 0.0.

Ordinary High Water Mark (OHWM). A Washington State legal term used in the Shoreline Management Act and Fisheries Hydraulic Code:

> "[T]hat mark that will be found by examining and ascertaining where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from the abutting upland, in respect to vegetation as that condition exists on June 1, 1971, as it may naturally change thereafter, or as it may change thereafter in accordance with permits issued by a local government or the department [of ecology]: provided, that in any area where the ordinary high water mark cannot be found, the ordinarily high water mark adjoining salt water shall be the line of mean higher high tide... RCW 90.58.030(2)(b)."

Perched Beach. A beach or fillet of sand retained above the otherwise normal shore profile level by a submerged dike.

Percolation. The process by which water flows through the interstices of a sediment. Specifically, in wave phenomena, the process by which wave action forces water through the interstices of the bottom sediment and which tends to reduce wave heights.

Pile. A long, heavy timber or section of concrete or metal to be driven or jetted into the earth or seabed to serve as a support or protection.

Profile Deflation. Lowering of the beach profile (elevation) due to erosion.

Quarrystone. Any stone processed from a quarry.

Reflected Wave. That part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface.

Reflection Coefficient. Percentage of wave energy (expressed in terms of wave height) that is reflected back to sea.

Refraction (of water waves). (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed: the part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents.

Return Walls. Walls built at the terminal ends of bulkheads, perpendicular to the bulkhead face, that securely anchor the bulkhead to the native shoreline and prevent end erosion.

Revetment. A facing of stone, concrete, or other material built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.

Riprap. A protective layer or facing of quarrystone, usually well graded within wide size limit, randomly placed to prevent erosion, scour, or sloughing of an embankment or bluff; also the stone so used.

Rubble-Mound Structure. A mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially shaped concrete armor units. (Armor units in a primary cover layer may be placed in an orderly manner or dumped at random.)

Run-up. The rush of water up a structure or beach on the breaking of a wave. Also **Uprush, Swash.** The amount of run-up is the vertical height above still-water level to which the rush of water reaches.

Scarp, Beach. An almost vertical slope along the beach caused by erosion by wave action. It may vary in height from a few centimeters to a meter or so, depending on wave action and the nature and composition of the beach.

Scour. Removal of underwater material by waves and currents, especially at the base or toe of a shore structure.

Seawall. A structure separating land and water areas, primarily designed to prevent erosion and other damage as a result of major wave action, and usually incorporating special geometric shapes for redirecting wave energy. See also **Bulkhead.**

Sheet Pile. A pile with a generally slender flat cross section to be driven into the ground or seabed and meshed or interlocked with like members to form a diaphragm, wall, or bulkhead.

Shingle. (1) Any beach material coarser than ordinary gravel, especially any having flat or flattish pebbles. (2) Beach material of smooth, well-rounded pebbles that are roughly the same size. The spaces between pebbles are not filled with finer materials. Shingle often gives out a musical sound when stepped on.

Shoreface. The narrow zone seaward from the low tide **shoreline,** covered by water, over which the beach sands and gravels actively oscillate with changing wave conditions.

Shoreline. The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach). The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line.

Storm Surge. A rise above normal water level on the open coast due to the action of wind stress on the water surface.

Tidal Flats. Marshy or muddy land areas that are covered and uncovered by the rise and fall of the tide.

Toe. Lowest part of bluff, bank, or shoreline structure, where a steeply sloping surface meets the beach.

Training Wall. A wall or jetty to direct current flow.

Undercutting. The removal of material at the base of a steep slope or cliff by erosive action of waves or running water.

Updrift. The direction opposite that of the predominant movement of littoral materials.

Wave Energy Flux. Transfer of energy from wave motion to sediment movement.

Wave Period. The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.

Wetlands (Biological). Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.

Wetlands (Federal Jurisdictional). Land forms that support, under normal conditions, a predominance of hydrophytic (wetland) vegetation, hydric (wetland) soil types, and wetland hydrology. Typically, they are jurisdictionally defined as: "Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (Federal Interagency for Wetland Delineation, 1989)."

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