Coastal Erosion Management Strategy

Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington

Coastal Erosion Management Studies, Volume 7

WASHINGTON STATE DEPARTMENT OF ECOLOGY

August 1994
94-80

printed on recycled paper

Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington

Coastal Erosion Management Studies, Volume 7

August 1994

Prepared by:

Ronald M. Thom and David K. Shreffler,
Battelle Marine Sciences Laboratory, Sequim, Washington;
and Keith Macdonald, CH2M Hill, Seattle, Washington

Report 94-80

Shorelands and Environmental Assistance 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:

Douglas J. Canning
Shorelands and Environmental Assistance Program
Washington Department of Ecology
P. O. Box 47600
Olympia, WA 98504-7600
Telephone: 360.407.6781
Internet: dcan461@ecy.wa.gov

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

Recommended bibliographic citation:

Thom, Ronald M., David K. Shreffler, and Keith Macdonald. 1994. *Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound, Washington. Coastal Erosion Management Studies Volume 7.* Shorelands and Environmental Assistance Program, Washington Department of Ecology, Olympia.

Coastal Erosion Management Studies

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

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

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 living resources and ecological processes is complemented by a report on the impacts of shoreline armoring on physical coastal processes (task 3; volume 5). 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."

Douglas Canning and Hugh Shipman
Shorelands and Coastal Zone Management Program
Washington Department of Ecology
Post Office Box 47600
Olympia, WA 98504-7600

Acknowledgments

This report has been prepared by Battelle/Marine Sciences Laboratory and CH2M HILL for the Washington State Department of Ecology, Shorelands and Coastal Zone Management Program under Memorandum of Agreement C9300102 for development of a Coastal Erosion Management Strategy. The report documents the results of work done under Scope of Work *Task 5, Shoreline Armoring Effects on Coastal Ecology and Biological Resources in Puget Sound.* We kindly thank Douglas Canning and Hugh Shipman, Program Managers for the Washington Department of Ecology, for their help and guidance during the conduct of this task.

Information, including data, reports, and personal observations, used in this report was generously provided by the following individuals: Douglas Canning; Hugh Shipman; Gretchen McCabe and Katherine Wellman of Battelle's Seattle Research Center; John Armstrong of the Environmental Protection Agency (Region 10); Charles Simenstad of the University of Washington (School of Fisheries); John Downing and Walter Pearson of Battelle's Marine Sciences Laboratory; Steven Martin of the U.S. Army Corps of Engineers (Seattle District); Daniel Pentilla, Kurt Fresh, Neil Rickard, Kenneth Bates, Douglas Thompson, Richard Bumgarner, and Robert Ziegler of Washington State Department of Fish and Wildlife; Douglas Clark of the U.S. Army Corps of Engineers (Waterways Experiment Station); Thomas Fredette of the U.S. Army Corps of Engineers (New England District); Marvin Yoshinaka of U.S. Fish and Wildlife Service (Portland); David Jamison of the Washington State Department of Natural Resources; Colin Levings of Fisheries and Oceans Canada (North Vancouver Laboratory); James Lovoorn of the University of Wyoming (Department of Zoology); Jane Gendron of CH2M HILL; Thomas Terich of Western Washington University (Department of Geography and Regional Planning); Richard Sternberg of the University of Washington (School of Oceanography); Eric Nelson and David Schuldt of the U.S. Army Corps of Engineers (Seattle District); Wolf Bauer; and Jeff Layton of Layton and Sell. Additional acknowledgments are cited in text Section 6.4 for specific contributions related to the ecology of Puget Sound coastal bluffs.

Report graphics were prepared by Dennis Kirby; text word processing was done under the direction of Mary Morris and Beth Paveglio. Editor Jill Irwin smoothed assembly of the final report.

We especially appreciate detailed peer reviews received from Washington Department of Fish and Wildlife staff: Richard Bumgarner (shellfish), Daniel Pentilla (bait fish), Kurt Fresh (salmonids), Robert Zeigler (upland wildlife), and Neil Rickard (overview). We are also particularly indebted to Jeff Ward of Battelle's Marine Sciences Laboratory, Charles Simenstad, Donald Heinle of CH2M HILL, Douglas Canning, and Hugh Shipman for providing their technical peer reviews of the document.

Contents

(Contents, continued)

Fact Sheets

Tables

(Contents, continued)

Figures

1.0 Introduction

1.1 Background

Development along coastal areas of the United States has been extensive. Culliton et al. (1992) estimated that between 1970 and 1989 approximately half of all residential and non-residential construction in the United States occurred in the (federally designated) coastal zone. During this period, approximately 640,000 permits for construction in coastal counties of Washington State were issued. It is not known exactly how many projects were directly located on shorelines. However, waterfront property is prime real estate and substantial development has occurred along Washington's shorelines. Many structures are built dangerously close to the shoreline where natural erosion can threaten coastal property (Canning and Shipman 1993, Macdonald et al., 1993). To protect these properties, erosion control structures such as concrete or rock bulkheads are erected. However, adverse effects of shoreline armoring can occur which, in the worst case, can totally alter the physical structure of the beach and adjacent upland habitats (Downing 1983). Alteration of the physical conditions of the shoreline can cause changes in the structure and functioning of shoreline habitats and alter use of the habitats by fish, shellfish, birds, marine mammals and other organisms.

To minimize harm to the "natural environment" of the shorelines of Puget Sound while still allowing erosion control measures, the Washington State Legislature passed *Engrossed Senate Bill 6128* which requires local governments to develop standards for structures used to protect shoreline properties. The Washington State Department of Ecology (Ecology) Shorelands and Coastal Zone Management Program initiated a three-year strategy to resolve coastal erosion issues (Canning and Shipman 1993). This strategy involves ten tasks that investigate the effects of alternative shoreline armoring technologies on both the physical features of the beach and the ecology of the nearshore zone. The present report deals with Task No. 5 of this strategy: **Assessment of the effects of shoreline armoring on ecological systems.**

The Washington State Department of Fish and Wildlife (WDFW; previously two separate agencies) is now responsible for issuance of Hydraulic Project Approvals (HPAs) which deal with any proposed alterations to the shoreline. An HPA is required for construction of any project or other work taking place at or below the ordinary high water line, including construction of shoreline armoring. In 1991, the then Department of Fisheries (Fisheries) developed rules regarding Hydraulic Permits for Bulkhead or Rockwall Construction (RCW 75.20.160) which was enacted by the State Legislature under *Engrossed Substitute Senate Bill 5642*. These rules are meant to protect the food fish resource that might be impacted by shoreline armoring. A draft of the Hydraulic Code Rules (Chapter 220-110 WAC) dated 1 July 1993 contains significant verbiage pertaining to shoreline armoring (Neil Rickard, Fisheries, pers. comm., 1993). The draft Code specifies that "Single-family residence bulkheads shall not result in permanent loss of critical food fish or shellfish habitat" (New Section WAC 220-110-285).

1.2 Objective

The objective of this report is to define the affects of shoreline armoring on habitat structure, ecological processes and selected biological resources of the nearshore zone of Puget Sound. Effects are addressed as (1) temporary direct effects, (2) permanent direct effects, (3) permanent indirect effects, and (4) cumulative effects. Companion studies to this one (Macdonald et al., 1993; Cox et al., 1993) have described known physical effects caused by various erosion control technologies, and have evaluated the applicability of a wide variety of armoring technologies for use in Puget Sound.

1.3 Approach

The results of prior Study Tasks 2 and 3 (Cox et al., 1993, Macdonald et al., 1993, respectively) were used as a starting point for evaluating ecological effects. The previous studies found that, although general observations regarding physical impacts were extensive, very little quantitative data were available from Puget Sound. The same is true for ecological impacts. Although there is a wealth of observational information available from scientists at Fisheries, the University of Washington and elsewhere, there are almost no quantitative data on shoreline impacts.

A complicating factor is the ephemeral use of the shoreline by many important biological resources such as salmon, surf smelt, shorebirds, waterfowl and Dungeness crab. Many of these resources spend only a short part of their life history in these habitats, yet the habitats are critical to the survival of the population. For example, Pacific herring deposit eggs on benthic vegetation (primarily eelgrass) during winter. The eggs hatch approximately 2 to 4 weeks after deposition, whereafter the juvenile herring take up a pelagic existence. Reduction in spawning habitat may negatively affect spawning success of the population. Because many species have a short-lived period of use of nearshore habitats, quantitative data such as species abundances and residence times are difficult to obtain. For this reason, knowledge of fundamental aspects of shoreline use is lacking for most species over the vast majority of Puget Sound. Hence, in only a few cases can we quantitatively describe the effects of shoreline armoring on biological resources of Puget Sound.

The physical aspects of a beach—including grain size, sediment and water chemistry, frequency and dynamics of disturbances due to wave action, tides, and currents, degree of human disturbance, and adjacent upland (riparian) conditions—strongly influence the biological assemblages on the beach. Based on an extensive review of information from Puget Sound, Simenstad et al. (1991b) showed that somewhat distinct groups of species ("assemblage species") occur in association with eight different habitat types. These physically and biologically defined habitats were: emergent marsh, mudflat, sandflat, gravel-cobble, eelgrass, nearshore subtidal soft bottom, nearshore subtidal hard substrate and water column.

Based on the fact that "...a limited set of physical parameters—substratum types, wave or current energy, salinity, and depth or elevation—strongly constrain the distributions and interactions of marine plants and animals," Dethier (1990) designed a marine and estuarine habitat classification system. This hierarchical system separates marine from estuarine areas based on salinity; then uses substrata type, followed by exposure to waves and currents, to further classify the habitats. Finally, the species that are diagnostic and characteristic of each habitat are provided. The work of Simenstad et al. (1991) and Dethier (1990) provides a comprehensive framework for linking habit types and species distributions to shore-zone physical conditions.

The approach to analysis of ecological effects of shoreline armoring used here involves the following components:

1. Review of relevant information including:

   - Published and unpublished reports from Puget Sound and elsewhere, that describe habitat/species changes

   - Observations by knowledgeable individuals of Puget Sound shoreline habitats

   - Information on habitat requirements of selected biological resources

   - Understanding of physical effects based upon previous Study Task reports

2. Development of a simple conceptual model of potential effects, based upon understanding of the close connection between physical conditions and biological communities provided by Simenstad et al. (1991) and Dethier (1990).

In-hand references were assembled and key-word dialog literature searches were conducted on the National Technical Information Service (NTIS) and Aquatic Sciences and Fisheries Abstracts (ASFA) databases. NTIS covers federal government reports and conference proceedings; ASFA includes a broad range of materials—journal articles, books, monographs, conference proceedings, and technical reports—focusing on science, technology, and management of marine and freshwater environments. The literature search was comprehensive, but not exhaustive.

Conceptual modeling represents the only viable option for predicting effects in lieu of direct evidence. Limited available studies, as well as general observations from Puget Sound, provide verification of the model. The conceptual model provides a framework for describing the ecological effects of shoreline armoring in general terms. Quantification of such effects clearly requires further investigation.

1.4 Organization of the Report

The remainder of this report is divided into eight sections including a brief description of the general ecology of Puget Sound's coastline, a summary of armoring effects upon physical processes, an analysis of shoreline armoring effects on habitat structure, ecological processes and biological resources, cumulative ecological effects, and finally, conclusions and research needs.

sea100285C5.wp5

2.0 General Ecology of Puget Sound Coastline

2.1 Geomorphology

Puget Sound proper is a fjordal estuary, which displays most of the coastal features found worldwide in temperate latitudes. Major and minor rivers form deltas at their junction with Puget Sound. Formed relatively recently by glaciation, most of the sediments along the shorelines are glacial tills. Because of its narrow profile and deep central basin (i.e., 600 ft), the shoreline is relatively steeply sloping in many areas. Beaches are nourished primarily by erosion of shoreline bluffs and secondarily by sediment from rivers and streams. Compared with open ocean coast locations, long-term erosion rates are modest, but can increase in the short-term under the high tidal amplitudes and winter storm conditions experienced in Puget Sound. Substratum types and temporal changes in both beach sediments and profiles are dictated by adjacent sediment sources and local erosional/depositional processes (Downing, 1983).

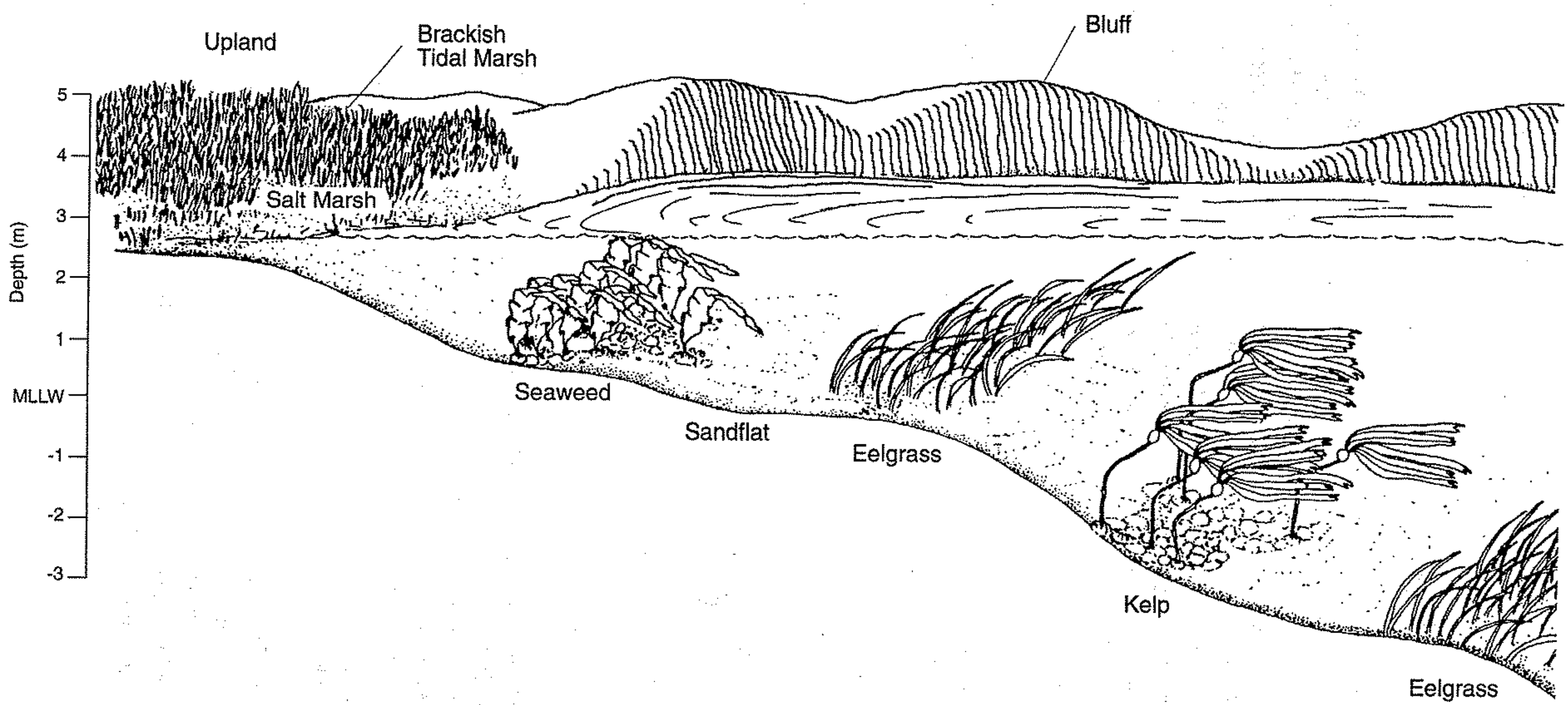
Puget Sound shoreline consists of an intertidal zone and a shallow subtidal zone (between -1m and -15m mean lower low water (MLLW)). Together, the intertidal and shallow subtidal zones can be referred to as the *nearshore zone* of Puget Sound. This is probably the zone most directly affected by alterations in physical conditions of the shoreline, including armoring. It contains all major vegetated habitats from high intertidal marshes to subtidal kelp forests. The mean tidal range within Puget Sound is on the order of 2 to 3 m.

High bluffs fronted by coarse sand and gravel beaches are the most common shoreline landforms around Puget Sound. Fine sand and mud occurs primarily at the mouths of larger rivers entering Puget Sound and in quiet bays. Shoreline boulder fields and rock benches are both relatively rare (Downing, 1983).

2.2 Habitat Types

Nearshore habitats consist of vegetated and unvegetated areas that are distributed along elevational, salinity and exposure gradients. A highly stylized diagram of major Puget Sound habitats is shown in Figure 2-1. This diagram shows the relative locations of different habitat types, but in reality they would not all occur together at a single site as shown. Within Puget Sound the most common intertidal habitat type is a gravelly sand-to-muddy sand substrate, often with an "armor layer" of large gravel-to-cobbles and only sparse macroalgae.

Habitat types within the intertidal and shallow subtidal Estuarine System as defined by Dethier (1990) are given in Table 2-1. The Estuarine System generally consists of semi-enclosed water bodies that have an open, partly obstructed, or sporadic connection to the ocean, and in which seawater is measurably diluted by freshwater runoff from the land. The salinity range within this system is 0.5 to 30 ppt. As such, the Estuarine System includes Puget Sound and the Strait of Georgia. In total, Dethier includes over



After Thom and Hallum (1990)

Figure 2-1
Nearshore Habitats in Puget Sound

Table 2-1
Puget Sound Intertidal and Shallow Subtidal Estuarine Systems: Habitats, Diagnostic and Common Taxa

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

Table 2-1 (continued)

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

HABITATS	DIAGNOSTIC OR COMMON PLANT TAXA (EXAMPLES)	DIAGNOSTIC OR COMMON ANIMAL TAXA (EXAMPLES)	SITE EXAMPLE	FINFISH SPAWNING	JUV. FINFISH FORAGING	JUV. FINFISH REARING	JUV. SALMON MIGRATION	HARDSHELL CLAM HABITAT	CRAB,CUCUMBER, URCHIN, ETC. HABITAT
INTERTIDAL:									
MUD	*Zostera*	*Macoma nasuta*	Dockton (Vashon Island)	X	X	X	X		X
PARTLY ENCLOSED		*Macoma balthica*							
AND ENCLOSED									
ORGANIC	*Deschampsia caespitosa*	none listed	Nisqually River Delta		X		X		
PARTLY ENCLOSED	*Distichlis spicata*								
BACKSHORE	*Salicornia virginica*								
POLYHALINE (MARSH)	*Potentilla pacifica*								
	Grindelia integrifolia								
	Juncus gerardii								
ORGANIC	*Deschampsia caespitosa*	none listed	Nisqually River Delta		X		X		
PARTLY ENCLOSED	*Juncus balthicus*								
BACKSHORE	*Potentilla pacifica*								
MESOHALINE (MARSH)	*Carex lyngbyei*								
	Festuca rubra								
	Agrostis alba								
ORGANIC, SAND,	*Juncus balthicus*	none listed	Hamma Hamma River Delta		X		X		
MIXED-FINE OR MUD	*Potentilla pacifica*								
PARTLY ENCLOSED	*Calamagrostis nutkaensis*								
BACKSHORE	*Picea sitchensis*								
OLIGOHALINE (MARSH)	*Typha latifolia*								
MIXED-FINES	*Zostera marina*	chironomid larvae	Skagit Flats	X	X	X	X		
AND MUD		*Corophium salmonis*							
CHANNEL/SLOUGH		juvenile salmonids							
SHALLOW (<15M) SUBTIDAL:									
ROCK	*Nereocystis luetkeana*	*Metridium*	Restoration Point	X	X	X	X		X
OPEN	*Agarum*								
COBBLE	*Laminaria saccharina*	*Saxidomus giganteus*	Fox Island	X	X	X	X	X	X
OPEN									
SAND	*Zostera marina*	*Dendraster excentricus*	Windy Point	X	X	X	X		X
OPEN									
MIXED-FINES	*Zostera marina*	*Clinocardium*	Lummi Island	X	X	X	X		X
OPEN	*Laminaria saccharina*	*Psephidia lordi*							
MUD	*Zostera marina*	*Psephidia lordi*	Samish Bay	X	X	X	X		
OPEN		*Macoma nasuta*							
MUD	none listed	*Macoma nasuta*	Commencement Bay		X	X	X		X
PARTLY-ENCLOSED		*Mysella tumida*							
		Armandia brevis							
SAND AND MUD	none listed	*Magelona*	none listed			X	X	X	
CHANNELS		*Corophium salmonis*							
		Macoma balthica							

Source: Dethier (1990)

220 diagnostic and common taxa within the estuarine habitats listed in Table 2-1. Diagnostic taxa and examples of common taxa listed next to each habitat type in Table 2-1 indicate the predominant taxon one would expect to find in the habitat.

In some cases, the diagnostic or common taxon may only occur sporadically within the habitat. For example, *Intertidal Open Sand* may have patches of eelgrass (*Zostera marina*) interspersed with expanses of sand with little or no vegetation. Some habitat types may include several distinct communities that occur adjacent to one another. For example, *Intertidal Mixed-Fines Partly Enclosed* includes five communities, some with co-dominants: (1) *Carex lyngbyei-Distichlis spicata*, (2) *Distichlis spicata-Salicornia virginica-Triglochin maritimum*, (3) *Jaumea carnosa-Salicornia virginica-Triglochin maritimum*, (4) *Salicornia virginica-Triglochin maritimum*, and (5) *Zostera marina*. These communities, as ordered here, are distributed from the higher elevations of the marsh down to the lower intertidal zone. The communities overlap; the deepest eelgrass community (e.g., No. 5) may exist in channels in close proximity to higher marsh communities (e.g., No. 2), or be separated by a substantial distance from the marshes by an unvegetated sand/mud flat.

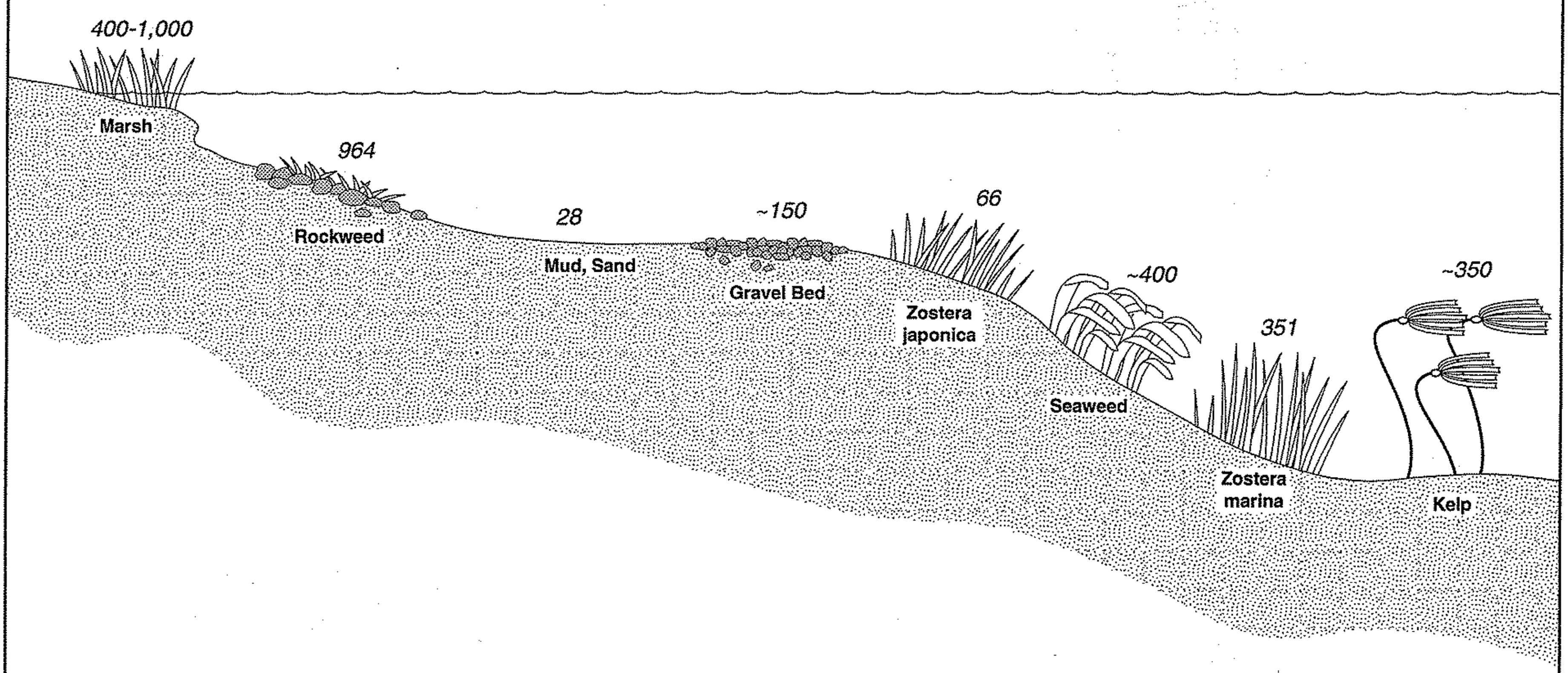
Many important species in terms of food web support are neither listed as diagnostic nor common in the matrix. Although not indicated, virtually all of these habitats contain diverse and productive microflora assemblages. These assemblages, which consist of diatoms, macroalgal spores and germlings, and other types of small algae, may be a major source of organic matter to the food web in some habitats (Thom, 1989). Very small animals, such as microcrustacea (e.g., harpacticoid copepods), occupy many of these habitats also. Some of these animals are known to be very important in the diet of juvenile finfish (e.g., Simenstad and Salo, 1980).

2.3 Ecological Processes

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

Only limited data are available on these processes in Puget Sound. Studies on primary production, the fundamental process that fixes inorganic carbon into organic matter, in Puget Sound have been conducted in a limited number of habitats and communities (Figure 2-2). These data can be used to characterize productivity for various habitat types and communities in Puget Sound. One data set exists on remineralization rates from four

NPW35072.T5 Ecology/Biology 4/11/94 DK



All measurements as grams carbon/m^2/year

Sources: Thom 1983, 1987, 1989, 1990, Thom and Albright 1990

Figure 2-2
Puget Sound: Annual Net Primary Productivity by Habitat

near-shore habitats. This study was conducted to evaluate the effects of placement of gravel on mudflats for the purpose of enhancing hardshell clam production (Thom et al., 1994). There are anecdotal observations on transport, with one notable study on the movement of organic matter and epibenthic organisms over the tideflat in Padilla Bay (Simenstad et al. 1988), and a short-term investigation of organic matter and nutrient flux rates from a constructed tidal wetland in Commencement Bay (Thom et al., 1990).

Observations by many individuals prove that animals move among habitats. In particular, birds utilize both aquatic and upland habitats (Figure 2-3; see accompanying **Fact Sheet**). Simenstad et al. (1988) showed that as the tidal front moved over the broad flat in Padilla Bay, epibenthic crustacea were moved from the site of production to higher elevations. Wracks of floating organic debris (seaweed, seagrasses) are common in Puget Sound especially during periods following heavy storms coupled with extreme high tides. This material can be transported long distances from the site of production. These drift lines often have large concentrations of small fish and zooplankton associated with them, probably due to the cover and structure provided, but also because there is abundant organic matter that is a source of food to the zooplankton.

Logs, tree roots, and branches are collectively referred to as large organic debris (LOD). It is estimated that over 2 billion board feet of wood is transported annually to the North Pacific from coastal stream and rivers (unpublished data from Sedell and Hansen, cited in Gonor et al., 1988). LOD is typically deposited high on beaches where it collects on berms throughout the Northwest, and where it may passively stabilize the shoreline. Eilers (1975) showed that logs can disturb salt marshes by killing marsh plants and forming pits or holes in the marsh surface. LOD is considered an important habitat feature for birds such as herons, gulls and cormorants that utilize the LOD for perching while fishing and for avoidance of predators (Gonor et al., 1988). In addition, the organic matter breaks down and enters the nearshore food web. Fish congregate around floating logs, and herring are known to spawn on branches of stranded trees (Pentilla, 1986).

2.4 Biological Resources Using the Habitats

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

In 1991, the agencies that manage aquatic and terrestrial resources met to summarize ecological data on the species they manage (Armstrong and Copping, 1990). The purpose of the meeting was to examine temporal trends in population sizes, catch statistics, and other

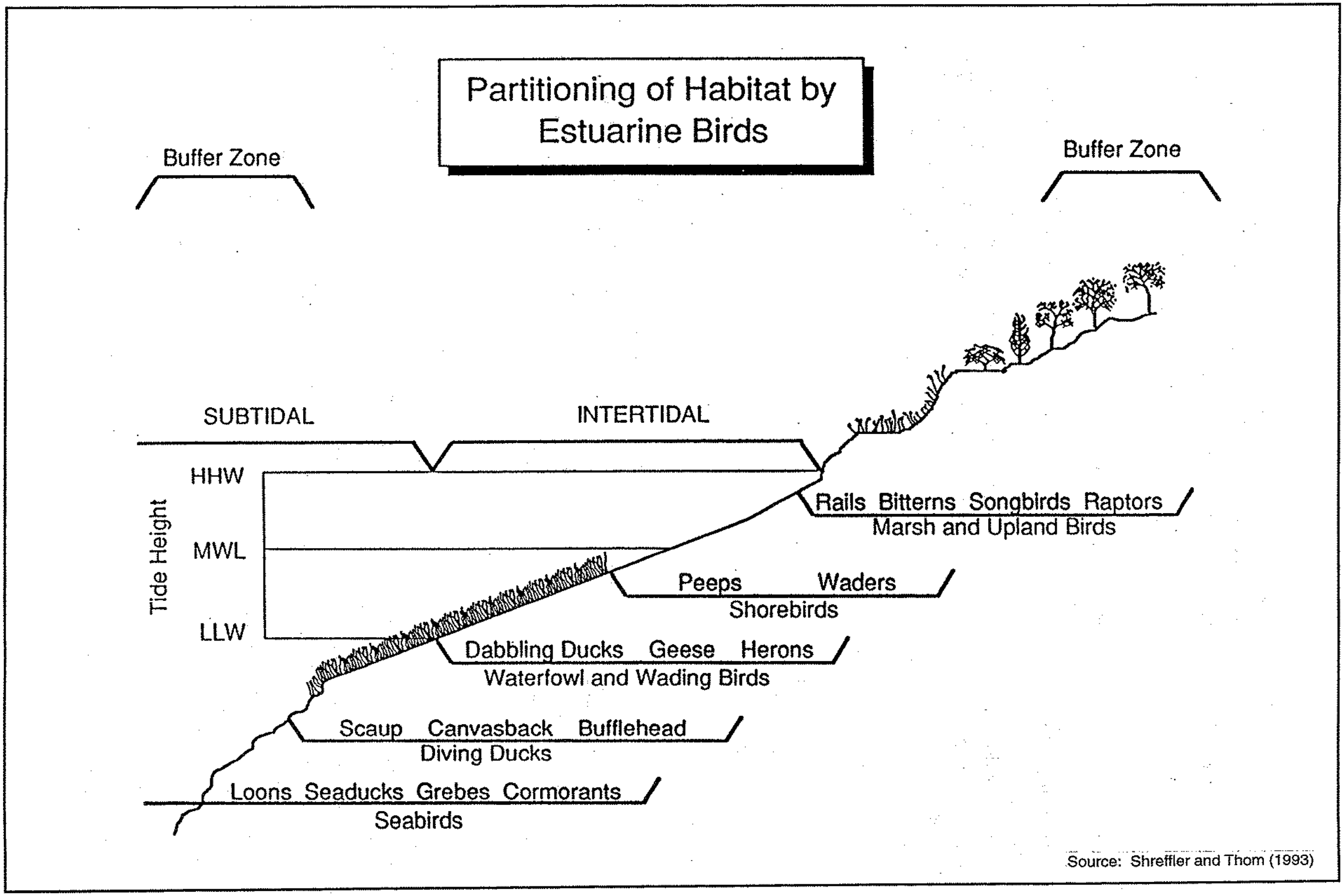


Figure 2-3
Habitat Partitioning by Group-Specific Feeding Requirements

Dependence of Birds on Puget Sound Estuaries



In the Puget Sound basin, greatest use of estuaries by birds occurs during migration and winter, with the influx of ducks, geese, shorebirds, loons, and grebes that breed elsewhere (see Butler et al. 1989). Herons, bitterns, rails, cormorants, and bald eagles breed locally and feed in estuaries throughout the year, but their numbers are substantially augmented during the non-breeding season. Although northern harriers feed mostly on small mammals in marshes, eagles and other raptors such as peregrine falcons feed mainly on ducks and shorebirds. Songbirds use riparian areas and marshes for breeding as well as migration and wintering. This discussion will focus on waterbirds dependent on intertidal and shallow subtidal habitats primarily during winter and migration.

Most waterbirds are extremely mobile during the non-breeding period. For example, ducks frequently move 15-110 km between the Fraser River Delta and a number of bays and estuaries in northern Puget Sound. Such movements are often related to severe weather with ice cover or storm waves, and small areas that usually support few birds can become important at such critical times. Thus, in the Puget Sound area, waterbirds need a variety of alternative sites in the regional habitat system.

From a landscape perspective, many waterbirds require both upland and aquatic habitats. Shorebirds and waterfowl that feed intertidally often roost in nearby fields at high tide or during storms (e.g., Brennan et al. 1985). Dabbling ducks in the Fraser River Delta, which feed almost entirely in intertidal habitats in autumn, switch in early winter to feeding in farmland at night and roosting on the bay by day (Baldwin and Lovvorn 1992). In the Puget Sound region, areas with extensive intertidal habitat but lacking adjacent farmland tend to support fewer ducks, and do not provide complete wintering habitat. The early-winter shift to feeding in uplands apparently corresponds to seasonal disappearance of the eelgrass *Zostera japonica*, which is an important forage item (widgeon eat almost nothing else in autumn) and supports diverse invertebrate prey species. Although persisting throughout winter at lower elevations, *Zostera marina* does not replace *Z. japonica* in the diet, probably because of its shorter daily period of accessibility to surface-feeding ducks. Elevation (duration of exposure), salinity, and sediment characteristics (grain size, organic matter content) are major determinants of the habitat zones of intertidal food organisms, and thus of feeding guilds of water-birds. Nearshore seabirds feed mainly on fish; diving ducks on benthic plants and invertebrates (Vermeer and Levings 1977); dabbling ducks on seeds, leaves, and rhizomes of eelgrass and emergent plants, and on invertebrates such as amphipods and bivalves (Baldwin and Lovvorn 1992); and snow geese mainly on bulrush rhizomes (Burton 1977). Herons feed on fish (Butler 1991); shorebirds on invertebrates, especially amphipods such as *Corophium spp.* (Couch 1966); and rails and bitterns on a wide variety of fish, invertebrates, and insects. Foraging in modes (probing, wading, dabbling, diving) further associates these foraging guilds with particular foods in different habitat zones.

Humans place high value on approaching and viewing birds, but most birds are very susceptible to human disturbance. In urban areas, street and car lights, traffic noise, boaters, and people may determine levels of bird use more than the biological suitability of the habitat. Disturbance buffers on both landward and seaward sides of intertidal habitat are critical. Required buffer width will vary within and among species, depending partly on the experience of birds at that site. Birds that have been shot at during migration or in local hunting areas, or chased by dogs or people, are more susceptible to disturbance. Waterfowl sensitized to boating disturbance will often flush when a boat motor approaches within a kilometer or more (Kahl 1991).

The predicted biological effects of shoreline armoring on birds include habitat fragmentation and reduced access to intertidal feeding areas, reduced disturbance buffers on both the landward and seaward sides of intertidal habitat, and potential changes in the types and quantities of food available.

Dr. James Lovvorn
University of Wyoming

factors. An important finding was that virtually all of the resources that are managed or of concern spend part or all of their life history on, in, or otherwise associated with beaches. The list of managed species and species of concern includes (but is not limited to) hardshell clams, crabs, shrimp, sea urchins, oysters, geoduck, sea cucumber, rock sole, sand sole, english sole, herring, salmon, smelt, sandlance, waterfowl, and marine mammals.

These animals use beaches as a place to feed, rear, reproduce, and rest. In addition, certain vegetated habitats (e.g., eelgrass) provide important corridors of migration for fish species such as juvenile salmon. Hardshell clams such as the butter clam *Saxidomus giganteus* generally settle as larvae on beaches and occupy gravel and cobble habitats for the remainder of their life. Dungeness crab spawn in deep water, and the larvae move into shallow water where they settle and develop. Survivorship of the newly settled crabs appears to be enhanced in habitats such as eelgrass and shell hash (e.g., Dumbauld et al., 1993). Following a period of up to 1 year in the nearshore zone, these crabs migrate out to deeper waters. Adult crabs often feed in shallow water, however. Surf smelt and sandlance deposit eggs in sandy areas of the intertidal zone. Daniel Pentilla of Fisheries, who has been conducting spawning surveys on beaches for almost two decades, has documented spawning of rock sole, sand lance, and smelt on 20, 50, and 130 miles of Puget Sound beaches, respectively.

2.5 Historical Habitat Losses

The shoreline habitats of Puget Sound have suffered significant losses over the past 125 years. Bortelson et al. (1980) estimated that approximately 32 percent of intertidal wetland and 73 percent of subaerial wetland bordering Puget Sound has been lost. Much of this loss is due to diking and filling of these areas (see also Nesbit, 1885; Boulé et al., 1983; Blomberg et al., 1988). By the late 1800s, much of the tidal marshes in the Skagit River delta had been enclosed by dikes. Most losses in Puget Sound took place between 1910 and 1950, during a period of rapid port development (Thom and Hallum, 1990). Kelp beds appear to have increased between surveys early in this century and surveys done in the mid-1970s (Thom and Hallum, 1990). A partial explanation for this increase may be the increase in hard substrata in the shallow subtidal zone which is required by kelp for attachment.

Eelgrass changes are difficult to assess due to lack of comprehensive baseline information. In Padilla Bay, eelgrass appears to have increased its distribution dramatically, possible due to the rerouting of the main flow of the Skagit River from Padilla Bay to Skagit Bay. This change increased salinity in Padilla Bay and decreased fine sediment input. Bellingham Bay and the Snohomish River delta have seen declines in eelgrass due, in part, to port development activities. Habitats continue to be stressed by water born pollutants, harvesting of resources (e.g., removal of kelp), bulkhead construction, dock and pier construction, diking, aquaculture, and a variety of other factors. Global changes in sea level and climate may also have more widespread ramifications on the habitats and the Puget Sound ecosystem as a whole (Klarin et al., 1990; Thom, 1992).

These quantitatively important habitat changes must have had significant effects on the biological resources that utilize them. However, we presently lack any data that directly correlates habitat destruction with quantifiable loss of fisheries resources.

sea100285C8.wp5

3.0 Armoring Effects on Physical Processes

Macdonald et al. (1993) identify six categories of potential physical response of a natural, undisturbed, shoreline system to placement of different forms of shore protection. These categories are:

- Sediment impoundment
- Modification of groundwater regime
- Narrowing of beach
- Lowering of beach profile
- Modification of beach substrates
- Loss of beached organic debris

The relative degree of response varies according to the type of shore protection, wave energy regime, and site geology. The types of structures can be divided into "hard" and "soft," with hard structures including bulkheads, sea walls, and revetments. Soft structures may include vegetation (e.g., dune grasses) and beach nourishment fills. Armoring affects can occur directly under, immediately seaward, and horizontally along the beach ("updrift" or "downdrift" based upon the direction of the prevailing longshore current) from the structure.

Direct and indirect effects of shoreline armoring to physical processes identified by Macdonald et al. (1993) are given in Table 3-1. The accompanying **photo-folio** illustrates some of the natural habitat complexity associated with undisturbed Puget Sound shorelines. Direct permanent impacts include excavation and burial effects from placement of structures and the loss of sediment sources from bluffs. Noise, vibration, increased turbidity, work barge impacts, and accidental spills constitute temporary direct impacts associated with construction. Indirect permanent impacts as listed in Table 3-1 are the result of reduced sediment supply to the beach and interruption of groundwater input to the beach. These effects occur adjacent to the structure and generally take place over an extended period of time. For example, beach profile lowering may begin immediately after the structure is in place but will take place gradually. At Lincoln Park Beach in West Seattle, armoring of the shoreline lowered the beach on the order of 0.1 foot per year between 1932 and 1974, although most of the erosion took place prior to the 1950s (Macdonald et al., 1993). Erosion usually occurs gradually in areas like this but can occur rapidly as a result of severe storms coupled with extreme high tides and storm surge. These major events often result in undermining and failure of shoreline protection structures.

Modification of the groundwater regime is not often thought of when assessing impacts of shoreline armoring. Changes in groundwater dynamics can affect nearshore habitats by, for example, robbing wetlands at the base of cliffs of their water resource. In addition, groundwater may be a significant source of inorganic nutrients to the Puget Sound system

Table 3-1
Shoreline Armoring Effects on Physical Processes

Direct Effects

a. Temporary Construction Effects
b. Permanent Effects
   - Placement of Structures/Loss of Beach Fill
   - Impoundment (Loss) of Sediment Source Behind Structures

Indirect Permanent Effects

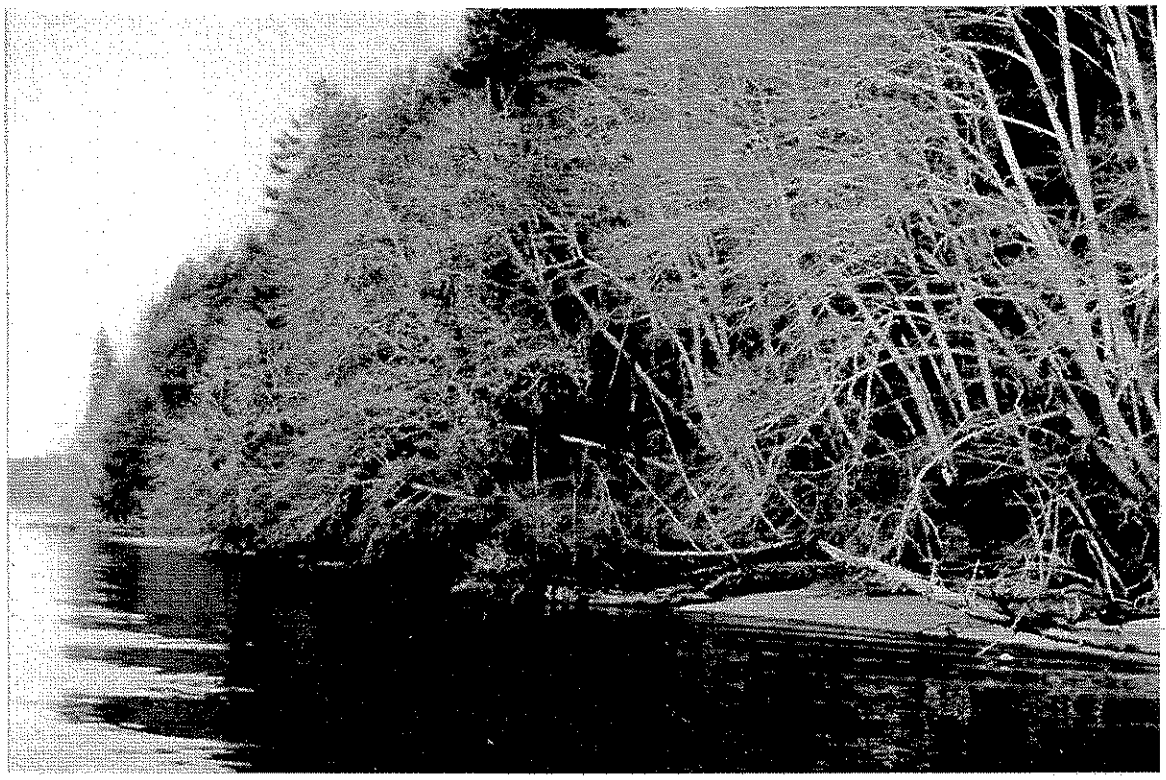
a. Downdrift Permanent Effects from Sediment Impoundment
b. Modifications of Groundwater Regime
c. Hydraulic Effects from Armoring
   - Increased Energy Seaward of Armoring
   - Reflected Wave Energy from Other Structures
   - Dry Beach Narrowing/End Wall Effects
   - Substrate Winnowing/Coarsening
   - Beach Profile Lowering/Steepening
   - Potential "During Storm" Effects
   - Sediment Storage Capacity Changes
   - Loss of Organic Debris (including LOD)
   - Downdrift Effects of the Above

Cumulative Effects

a. Incremental Increases in All Effects
b. Effects to Single Drift Sectors
   - Downdrift Sediment Starvation
c. Potential Threshold Effects

Source: Macdonald et al. (1993).

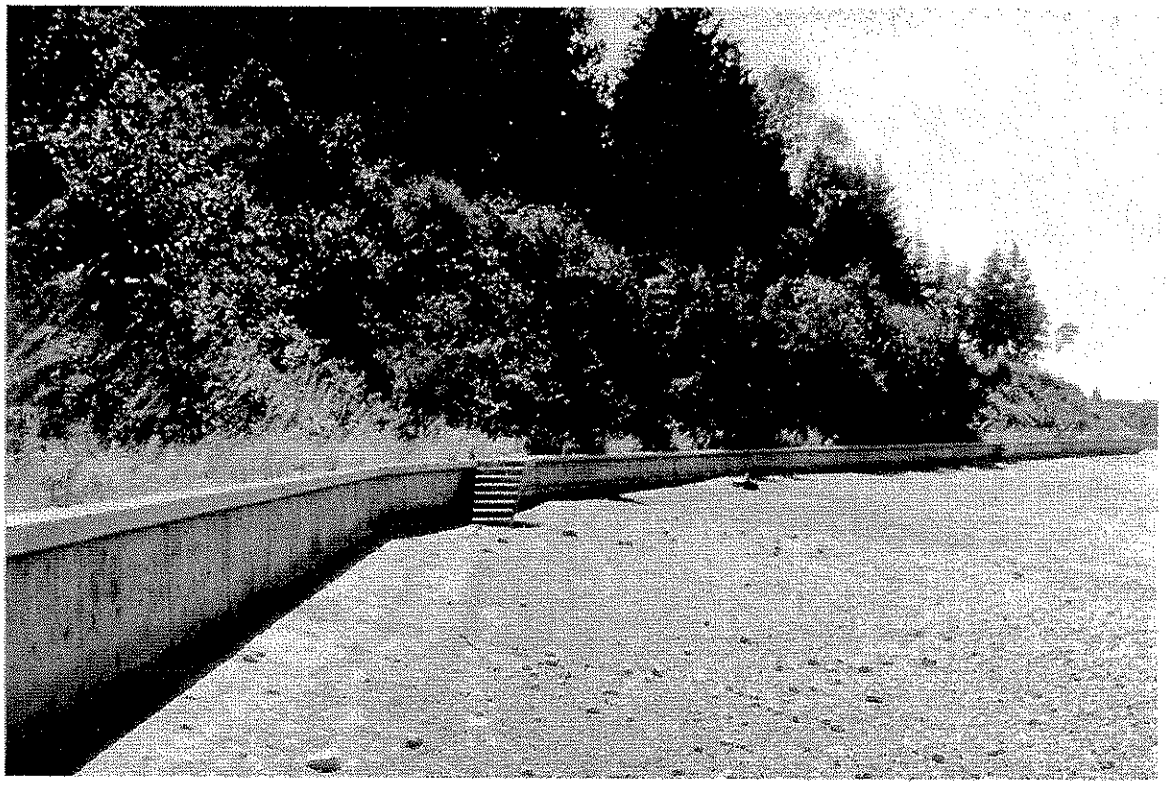
sea10028638.wp5



Totten Inlet, Thurston County (Winter): Unmodified bluff with diverse overhanging vegetation and complex shaded upper foreshore.

South King County (Winter): Toe of unmodified bluff, showing habitat complexity, large organic debris, and overhanging vegetation.

Nisqually Reach, Thurston County (Summer): Unmodified bluff with diverse overhanging vegetation shading upper foreshore.



Totten Inlet, Thurston County (Summer): Recently bulkheaded shoreline showing "simplification" of upper foreshore.

(cf. Sapik et al., 1988). Although not studied at all in this region, data from east coast marsh systems show that groundwater is a major source of nitrogen to the system (Valiela et al., 1978; Giblin and Gaines, 1990).

Cumulative effects are more difficult to define but can be viewed, for example, as incremental impacts associated with ever increasing armoring of a shoreline within an embayment. As the direct and indirect impacts of shoreline armoring increase, habitats are lost or altered dramatically, and resources that use the habitats decrease in abundance in the system. The point at which available habitat significantly constrains population size is unknown for the Puget Sound region. As an example of cumulative loss of habitat, Gonor et al. (1988) state that suitable intertidal spawning substrate is limited in Oregon estuaries, and herring spawn becomes heavily overlain and crowded on existing habitat. Eggs are easily dislodged and die as drift on beaches. In addition, gull predation on eggs can be significant in these areas (Bayer, 1980). Synergistic effects can take place as physical alterations become extreme. For example, as the beach profile lowers to an extreme point, the beach loses its frictional effect on waves, and wave energy is reflected off the armoring structure, thus enhancing erosion in front of the structure.

The following sections of this report describe the direct, indirect and cumulative effects of physical changes, as summarized above, on habitat structure, ecological processes, and biological resources. Quantitative data and qualitative observations directly available from Puget Sound are used as much as possible. Inferences from other regions are made where appropriate.

sea100285CB.wp5

4.0 Armoring Effects on Habitat Structure

Habitat structure is defined here as substrate type or types, along with the associated communities of organisms. The habitats defined by Dethier (1990) in Table 2-1 include substrate, as well as diagnostic and common taxa, and thus constitute habitat structure. Habitat structure can also refer to the density and abundance of organisms, species, sizes, etc.

Shoreline armoring affects habitat structure directly and indirectly by altering physical conditions. Habitats do not cease to exist, but shift from one type to another. In fact, the armoring material itself becomes a habitat type. The factors that must be considered in order to predict the *habitat shift* include: (1) the initial condition of substrata and exposure to waves and current, (2) the degree of alteration of sediment supply to the system, (3) the geological characteristics of the subsurface materials, (4) the time frame for the shift, and (5) the predicted habitat that will form under new physical conditions. It is assumed that under natural conditions, most "soft" habitats such as marshes will tend to be depositional and accrete sediments. "Hard" habitats such as bedrock or hardpan indicate erosional conditions with no net accretion. Altering sediment supply, as would happen with armoring, would result in reduced accretion rates in deposition systems. If sediment supply is very much reduced, soft habitats would tend to erode at a rate that is dependent upon the degree of exposure to waves and currents.

4.1 Geological Considerations

A limited data set on geological characteristics of subsurface materials on beaches of Puget Sound comes from core samples collected for stratigraphic analysis by Beale (1990), Atwater and Moore (1992), and Bucknam et al. (1992). These data are not complete for all Puget Sound nearshore habitats but do provide an indication of the types of materials that would be exposed by erosion at selected sites. For example, cores in the high and low marsh at Fishermans Cove in Quilcene Bay (Figure 4-1) show alternating peat and thin clay layers down to about 0.5 m below the surface (Figure 4-2). Thereafter, clay predominates to a depth of 1.5 m where it meets a homogeneous layer of gravel. Erosion of peat/sand can proceed rapidly. Erosion rates would be relatively slower in the clay layers, and would be very slow at the gravel layer. The gravel layer is located at approximately MLLW (Beale, 1990). At Padilla Bay marsh, 0.5-m-thick layers of peat, silty-peat, and clay alternate from the surface to at least 3 m below the surface (Beale, 1990). Hence, erosion would proceed relatively rapidly to well below MLLW under a severe shoreline armoring scenario. Erosion of more exposed substrata such as cobble-gravel substrata that occurs on many of Puget Sound's beaches follows a different pattern of change. In general, the substrata coarsens to large cobble and rock, and finally to hardpan. Rates of erosion are not precisely known. However, information at some sites (see below) indicates that erosion from cobble-gravel to hardpan can occur in a matter of 10 to 20 years under severe shoreline armoring conditions.

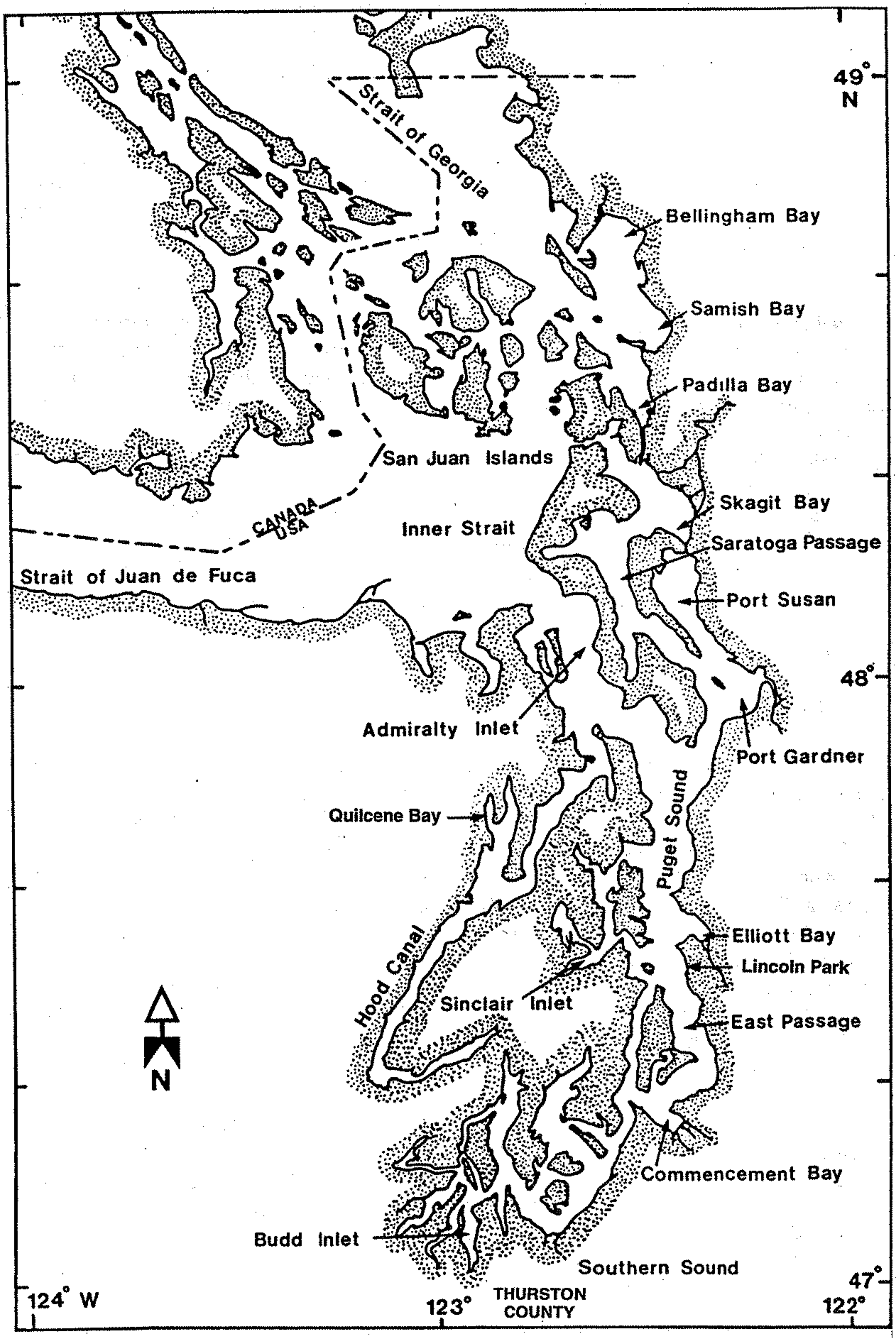
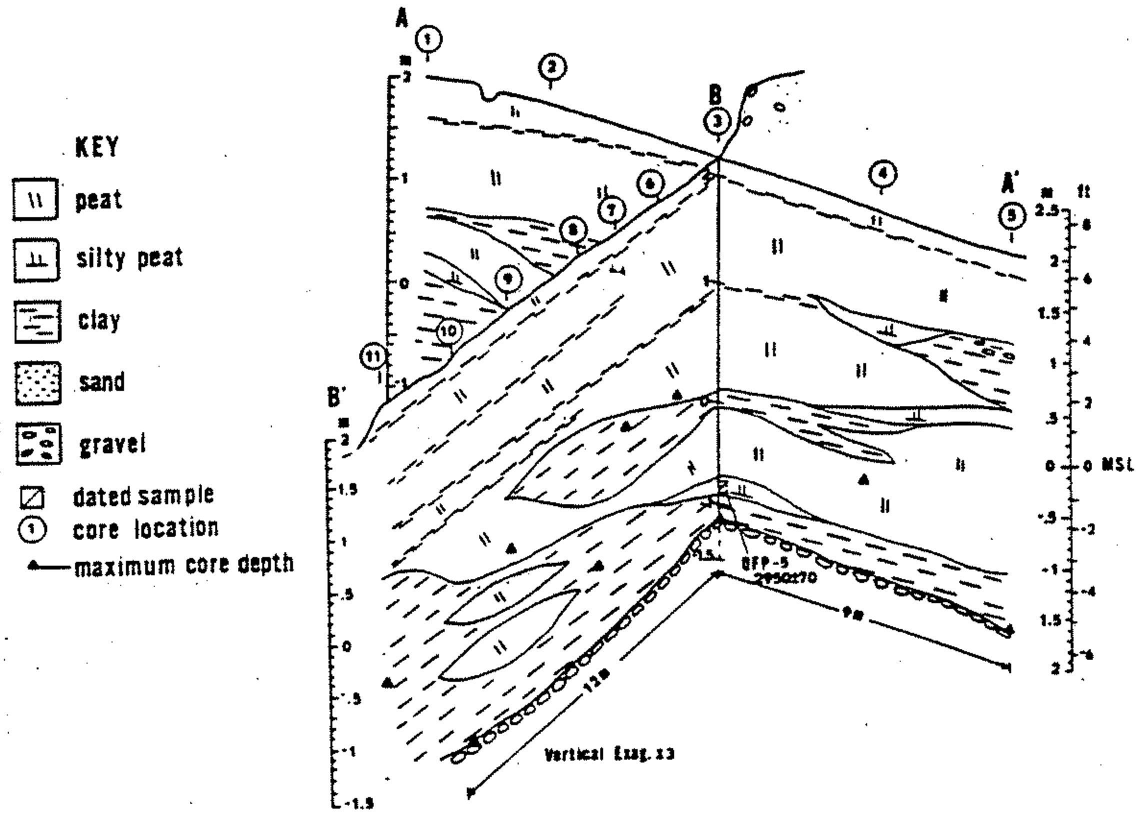


Figure 4-1
Puget Sound Location Map



Source: Beale (1990)

Figure 4-2
Vertical Cross-Sections of Marsh Sediments at Fisherman's Point

4.2 Marshes and Protected Habitats

Because marshes are generally confined to either partly enclosed or fully enclosed (i.e., lagoon) situations, deposition exceeds erosion. Hence, it is rare to find a situation where armoring has been placed on a high marsh in Puget Sound in order to protect the adjacent uplands. In some past instances armoring has taken place merely as an amenity for landscape purposes, shoreline access, and to increase property values. As a result, some high saltmarsh areas of Puget Sound have been needlessly armored. Such armoring results in direct and indirect permanent effects to physical as well as biological and ecological processes (Neil Rickard, WDFW, pers. comm.).

Predictably, alterations in sediment supply or increased erosional forces due to armoring at key places *adjacent* to the marsh could have effects on the marsh. The rate of erosion of marshes and underlying layers depends on the erosional forces as well as the degree of depletion of sediment input to these naturally depositional habitats. The anecdotal data available from marshes at Padilla Bay, Elk River in Grays Harbor, and Spencer Island on the Snohomish River estuary, where dikes have enclosed all or part of a marsh, can be used to establish the general process and rate of erosion (Thom, personal observations). Typically, diked marshes subside due to lack of sediment input and concurrent oxidation of peat. Subsidence results in shifts of habitat from natural marsh to lower intertidal marsh-mudflat and eventually to bare mud. No examples of erosion were found in marshes that were not diked but where sediment supply has been cut off. Based upon data from situations where this has occurred, such as the Mississippi River delta, marsh loss can be very rapid. It is estimated that the Mississippi River deltaic marshes are eroding at a rates of 60 km^2 yr^{-1} (Britsch and Kemp, 1990).

4.3 Semiprotected and Exposed Habitats

The prevalent Puget Sound shoreline sediment type is coarse sand and gravel (Downing, 1983). This substrate equates with Dethier's (1990) habitat types of *mixed coarse-open* and *gravel-open habitats* (Table 2-1). It is appropriate to focus attention on these habitats because they are the most likely to be subjected to enhanced erosion as a result of local shoreline armoring.

The events following seawall construction on the southwest side of Point Williams, at Lincoln Park beach in West Seattle, provide an excellent indication of what changes can be expected in habitat structure. The vertical seawall was placed at the upper elevations of the beach in the mid-1930s. By the 1950s, the beach had eroded dramatically and changed from what was probably a coarse sand mixed with gravel and cobble, to a beach consisting of hardpacked clay with scattered cobbles. The lower portion of the beach was probably eroded also, as was the subtidal zone immediately seaward of the beach. The substrate changed from mixed coarse sand through hardpan and the elevation of the beach dropped on the order of several feet in some areas (Macdonald et al., 1993). Because of lower erosional forces on the northwest side of Point Williams, seawall construction there resulted in much less change to the morphology of the beach.

The change in elevation and substrata affected the types of plants and animals that lived on the beach (Figure 4-3). Although preconstruction biological data are not available for the intertidal portion of Lincoln Park, information from data on fill placed at the site can be used to speculate on preconstruction conditions. In addition, the kelp bed located on the south side of Point Williams—which is directly seaward of the seawall—was studied early in the century by George Rigg (1917). It has been subsequently observed almost annually since 1974 (Thom and Hallum, 1990). Rigg showed that the bed never exceeded 180 to 215 m in length during the period of 1914 to 1917, well before sewall construction. Observations made since 1974 indicate that the bed is always at least 600 m long. Because kelp requires rocks for attachment, one can speculate that higher erosion rates removed sediment from subtidal rocks, thus opening space for attachment of kelp (Thom and Hallum, 1990).

Data on Lincoln Park intertidal communities are available from a variety of studies conducted to evaluate the ecology of beach communities (Armstrong et al., 1976; Thom et al., 1976) and to quantify the impacts of beach nourishment (Thom and Hampel, 1985; Thom, 1988; Thom and Hallum, 1989; Hiss et al., 1990; Thom and Hamilton, 1991; Antrim et al., 1993; PENTEC, 1993). The fill placed at Lincoln Park consisted of pit-run gravel and extended from the seawall down to approximately +4 ft MLLW. Pit-run gravel consists of unsorted materials as would be expected to accumulate on Puget Sound beaches. Extensive investigations in 1974 to 1976 and immediately prior to the fill in 1988 showed that the shoreline hardpan contained a typical community that included seaweeds (*Fucus gardneri*, *Ulva* spp.), barnacles (*Balanus* spp.), and a large number of small crustacea, including isopods and amphipods. Post-construction monitoring showed that the beach community did not contain macroalgae or attached macrofauna, but did support bivalves at the lower elevations, as well as harpacticoid copepods and amphipods. PENTEC (1993) concluded that epibenthic crustacean densities were limited on the fill by a lack of detrital material. Erosion of fine sand and associated organic matter was evident within 4 years of fill placement (Antrim et al., 1993). Periodic renourishment of certain parts of the beach is expected to be needed.

The data from Lincoln Park verify that, within two decades, the habitat structure had changed from a relatively sparse community of interstitial detritivores to a community dominated by sessile macrofauna and seaweeds. The evolution of the beach probably proceeded from a mixed-coarse habitat, through gravel, to hardpan. At the same time, the elevation lowered and the profile of the beach flattened substantially. Lincoln Park provides the best example of what is likely to happen to the most common Puget Sound shoreline habitat type as a result of severe armoring effects. Reducing the length of shoreline armoring may have slowed the rate of shift in habitats on the beach.

It should be noted that the Lincoln Park site is an example of but one set of physical, biological, and ecological conditions, energy regimes, armoring treatments, and extent of encroachment that occurs in Puget Sound. While it is one of, if not the only site

NPW35072.T5 Ecology/Biology 4/11/94 DK

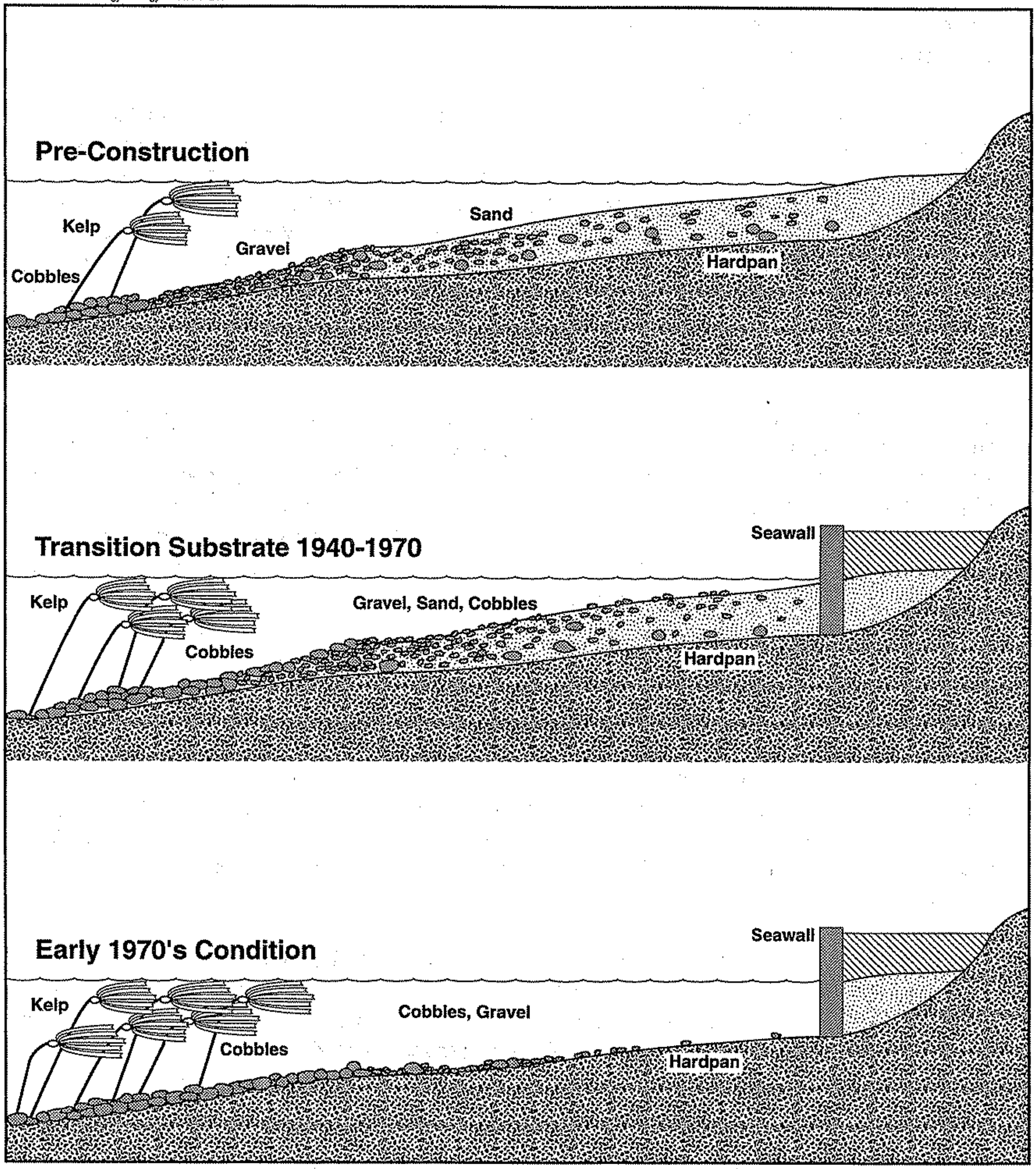


Figure 4-3
Progression of Habitats at Lincoln Beach, Seattle

available with limited physical and biological data, it is not an *ideal* study site. Areas of Puget Sound containing marine fish spawning habitat, wetland vegetation, extensive riparian canopy, and large organic debris are probably biologically more important.

4.4 Species Assemblage Shifts

Using Dethier's (1990) scheme (Table 2-1), marsh erosion in partly enclosed conditions would predictably proceed from an assemblage dominated by marsh plants, to sand dominated by infauna bivalves, worms, and amphipods, to one dominated by assemblages preferring gravel substrates. If the gravel is located at moderate to low elevations, significant numbers of bivalves could predominate in this habitat. The rate of change is unknown but is probably slower in protected situations than under more open conditions.

Open sand would erode to mixed-coarse sand, gravel, hardpan, and finally, bedrock. This would mean a shift from an assemblage dominated by small crustacea (harpacticoid copepods, amphipods) at higher elevations and eelgrass (*Zostera marina*) in the lower intertidal zone; through an *Ulva*-hardshell bivalve habitat; to one containing primarily crustaceans such as isopods and larger amphipods; to barnacles and rock-boring bivalves; and finally to barnacles and seaweed. Existing, open gravel habitats would essentially erode to hardpan and then bedrock (Figure 4-3). The rate of change from beach sand to hardpan, based upon the Lincoln Park data, would be on the order of 20 years. Periodic storm events would speed the rate of habitat alteration along some portions of the beach.

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

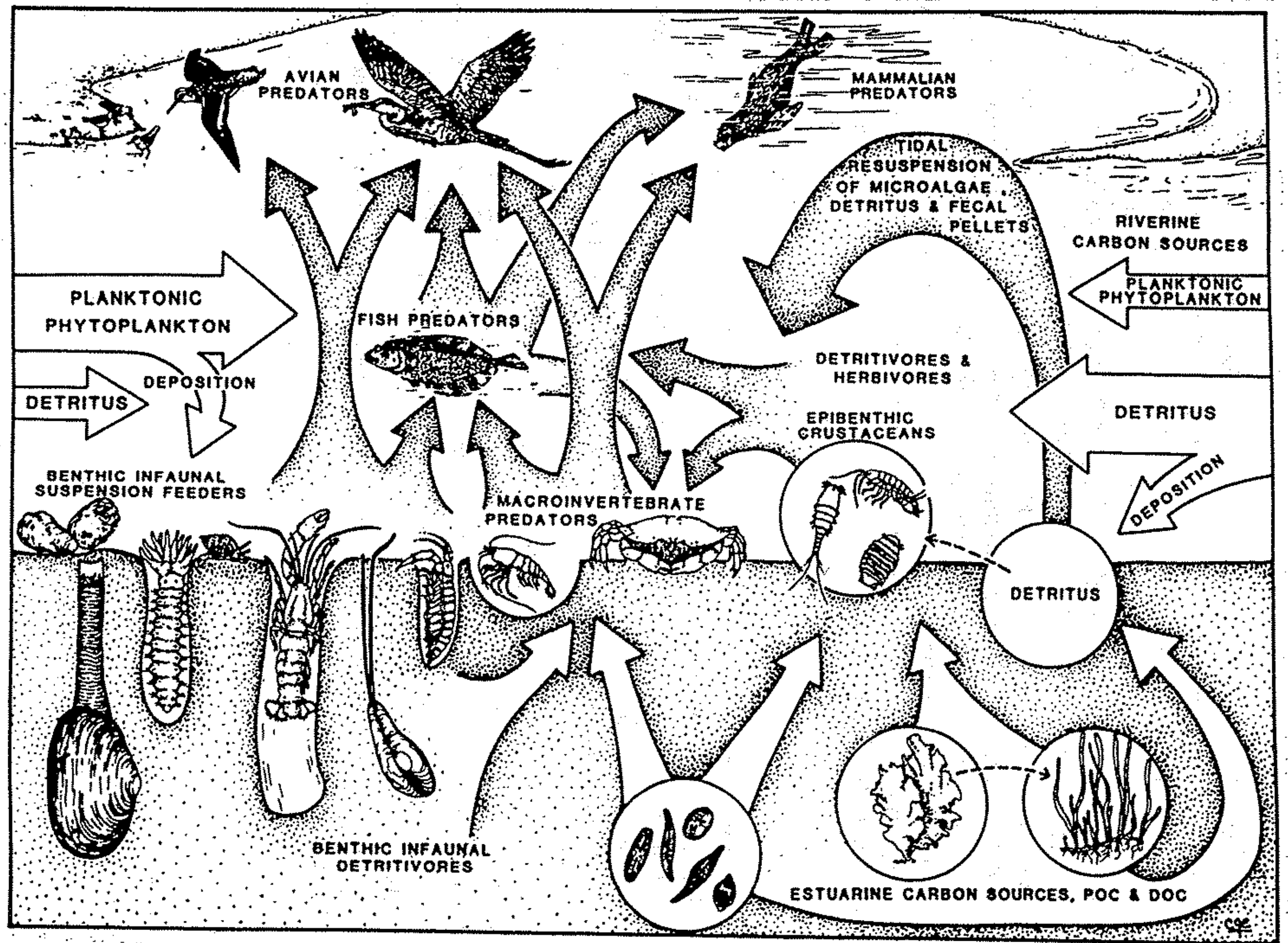
5.0 Armoring Effects on Ecological Processes

5.1 Primary Productivity and Respiration

Plant species vary in the rates at which they fix carbon (primary productivity). Hence, alterations in habitat structure that result in changes in the types and abundances of plants on the shore also result in altered primary productivity rates for that shore. Plants also differ in the seasonal dynamics of productivity. For example, phytoplankton tend to have the highest productivity rates in early spring, while maximum productivity of seaweeds, eelgrass, and marsh vegetation follows later (Thom, 1987). The availability of the organic matter produced by the plants varies also. Phytoplankton and benthic microalgae are readily eaten by small animals (zooplankton), whereas marsh plants and eelgrass may take several months to a year to break down and become available as detritus (Figure 5-1). The animals associated with particular habitats are adapted for using carbon from various sources throughout the year. In Puget Sound, there is a strong spring pulse of small fish and invertebrates that inhabit eelgrass meadows—and depend to a large degree on microalgal production during this same period (Simenstad and Wissmar, 1985; Thom et al., 1991).

Figure 2-2 shows annual primary production rates for habitat types in Puget Sound. In general, the rates range between 200 and 500 g C m^{-2} y^{-1}. These data can be used to predict shifts in productivity caused by changes in substrata type. For example, placement of rock on the upper intertidal zone will result in a loss of production by microalgae and an increase in productivity by rockweed/sea lettuce. Pomeroy and Levings (1980) found that, although placement of a rock jetty on the Fraser River delta resulted in increased surface area for algal growth, there was no appreciable enhancement of primary productivity as compared to the natural marsh/mudflat system. Data from investigations of the effects of placement of gravel on mud-sand beaches for enhancement of clam production showed that net primary productivity in graveled areas did not significantly differ from natural areas, although the composition of the plant community did change considerably (Thom et al., 1994). At one of the graveled sites (Semiahmoo Bay), the community changed from a dense eelgrass meadow to a gravel patch dominated by green algae, mussels, and barnacles. Because of the increase in trapping of organic matter as well as increased infaunal densities, benthic community respiration rates were greater in graveled plots at both sites.

These studies show that altered beach substrata—as might be expected to occur with shoreline armoring—will change the types of plants in the area, but may not alter the productivity rates per unit area. Respiration rates, which are indicative of animal density, may increase under some conditions.



DOC = dissolved organic carbon; POC = particulate organic carbon

Source: Simenstad and Armstrong in Thom (1987)

Figure 5-1
Puget Sound Nearshore
Food Web Carbon Sources

5.2 Organic Matter Flow

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

Organic matter in the form of seaweed, seagrass, marsh plants, and terrestrial plant leaves accumulates on beaches in Puget Sound. A peak in drift material generally occurs in summer, with little remaining during winter. Under extreme conditions, piles of seaweed can be 0.5 m thick and cause anoxic conditions immediately under the mat (Thom et al., 1988). A comparison of drift material dynamics was made at Seahurst Park in West Seattle (Thom and Albright, 1990). They found that a site located next to a natural bluff shoreline (high site) had drift accumulations composed primarily of seaweeds, but also containing large quantities of tree leaves. Seaward of a gabion wall that armored another portion of the beach, however, drift material was located lower on the beach and contained very little leaf material. The size of the drift material patches were on the order of 300 m^2 during peak periods (Thom et al., 1984). Although not quantified, drift material high on the beach was noted to contain insects, as well as beach hoppers (amphipods), that were probably actively using the organic matter. Amphipods were also abundant in the seaweed drift lower on the beach. The presence of the gabion wall has obviously caused erosion along the seaward portion of the beach. This has affected both the source of organic matter to the beach—by removing trees and shrubs—and changed the location and composition of detritus accumulating on the beach.

Beached drift lines of organic matter are a common feature in Puget Sound during summer and autumn. This debris, which is concentrated by the tides on upper portions of beaches, is floated off beaches during extreme high tides. A cursory examination of this drift material reveals large numbers of zooplankton and small fish, such as shiner perch, directly under the floating material. The organic matter is eventually broken down by the zooplankton and enters the food web—either by direct predation of the zooplankton by fish or by benthic organisms located where the detrital material settles. The overall importance of this drift matter to the Puget Sound ecosystem is unstudied. We can only speculate that the composition and amount of this material would be altered adjacent to beaches with armored shorelines. It is believed that this drift material, along with the very uppermost layer of the water (i.e., the microlayer), may be an important locus for concentration of organic matter and bacteria, as well as pollutants (Word et al., 1986; Gardiner, 1992).

5.3 Nutrient Dynamics

Altered substrata and habitat characteristics change the nutrient dynamics of a beach. Interruption of stream flows will remove potential sources of freshwater—but also inorganic nitrogen compounds, phosphate, and other materials. Furthermore, placement of structures that extend below the surface of the beach can affect the flow of groundwater to the beach (cf. Sapik et al., 1988).

It is clear that streams and rivers supply some of the nutrients that are utilized by Puget Sound ecosystems (Thom and Albright, 1990). A small urban stream flowing onto Lincoln Park beach contained very high concentrations of nitrate that were well above ambient Puget Sound levels (Thom et al., 1988). This loading is believed to have caused massive blooms of *Ulva* spp. on the beach, which accumulated in high enough quantities during the summer to cause odor problems. The problem was so severe in the 1980s that residents were complaining of illnesses related to the smell on the beach. It is noteworthy that the seaweed formed piles in a relatively small area of the beach following summer windy periods (usually in July). By the end of the summer the material was removed by natural currents and the odor ceased to be a problem. Whether the buildup of seaweed was directly due to shoreline armoring is in question—but this portion of the beach is backed by a seawall and residents claim that the morphology of the beach has changed dramatically over two to three decades.

Studies on the effects of beach graveling for clam production examined the effects on nutrient fluxes from the beach (Thom et al., 1994). It was found that graveling significantly increased the flux of ammonia, a breakdown product of organic matter, from the benthos to the water column. It was believed that organic matter was more easily trapped by the gravel, resulting in higher densities of detritivores and bacteria. This, in turn, resulted in enhanced remineralization rates and fluxes. As noted above, benthic respiration rates increased in the graveled areas. Hence, changing a sand/mudflat to a gravel habitat can be expected to significantly alter nutrient cycling on beaches.

Macdonald et al. (1993) noted that a concrete seawall, for example, will increase groundwater pore pressures by allowing hydraulic pressure to build up landward of the wall. Increased pore pressure can result in increased hydraulic pressure that exacerbates erosion seaward of the wall. In addition, the flow of nutrients in the groundwater to the beach could also be altered. There are few data that evaluate groundwater input to Puget Sound (e.g., Sapik et al., 1988) and none that speculate on the overall effect of such groundwater changes on beach ecology. This topic is in need of study.

5.4 Other Processes

Shoreline armoring could affect other processes, including the physical movement of animals and shading. It is obvious that obstruction of a movement corridor could significantly affect the survival of a local animal population. In the worst case, placement of a wall or culvert that obstructs a stream may result in cessation of anadromus fish runs in that stream (e.g., Heiser and Finn, 1970). The presence of a rock groin may force migratory fish to use deeper water rather than intertidal habitats, which may result in increased predation pressure on these fish.

Shading of shoreline areas by overhanging trees and shrubs reduces heating of beach substrate. According to Daniel Pentilla, WDFW, pers. comm., removal of shade could affect the survival of eggs from summer-spawning surf smelt. Survival of decomposers (i.e., amphipods, insects) associated with drift vegetation high on beaches could also be lowered if shade trees are removed.

sea100285E9.wp5

6.0 Armoring Effects on Biological Resources

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

The species included in Fish and Wildlife's list are provided in Table 6-1. In order to simplify the analysis of impacts to biological resources, we have focused on these species as *indicators* of effects from shoreline armoring. There is a body of information on most of these species that allows predictions of potential effects to be made with some certainty. However, there are only a few studies that have verified and *quantified* the effects of shoreline armoring on these resources. Hence, predictions of effects remain both qualitative and subjective.

Dethier's (1990) habitat list (Table 2-1) indicates the habitats that are used for each of six different finfish and shellfish functions, i.e., finfish spawning; juvenile finfish foraging; juvenile finfish rearing; juvenile salmon migration; hardshell clam habitat; and crab, cucumber, and urchin habitat. Certain habitats, such as mixed-coarse and open, accommodate all six functions. No habitat type accommodates fewer than two functions. The table can be used to predict how habitat loss in a given area would affect these resource functions. The table can also be used to predict how functions would change as habitats replace one another. For example, if—through erosion—a mixed-coarse beach changed to a hardpan beach, three of the six functions would be lost. It would be expected that the remaining functions would be altered to some degree also. Direct and indirect effects on finfish and shellfish resources are specifically addressed in the following sections.

6.1 Finfish Use: Direct Effects

The following section addresses concerns raised by the Washington Department of Fish and Wildlife (Neil Rickard, pers. comm., December 1993) regarding the biological effects of shoreline armoring (Table 6-2; see accompanying **Fact Sheet**). In general, the direct effects of shoreline armoring on fish communities in Puget Sound have not been well documented.

Table 6-1
Fisheries Resource Species Potentially Affected by Shoreline Armoring

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

sea10028639.wp5

Table 6-2
Shoreline Armoring Effects Linkages to Biological Processes

Direct Effects a. Temporary Construction Effects b. Permanent Effects • Habitat (Substrate) Burial or Removal • Change Vegetative Cover/Organic Inputs
Indirect Permanent Effects a. Modification of Groundwater Regime b. Changes to Shoreline Environment Due to Hydraulic Effects • Loss Spawning/Foraging/Rearing Habitat for Fish • Loss Migratory Corridor for Fish • Substrate Changes Reflected in Benthos • Effects on Shellfish
Cumulative Effects a. Incremental Increases in All Effects b. Potential Threshold Effects
Source: Macdonald et al. (1993).

sea1002863B.wp5

Fisheries Guidelines for Bulkheads and Marinas

In 1971, Washington Department of Fisheries (WDF) adopted policy guidelines regarding the construction of bulkheads, landfills, and marinas along the shores of the Strait of Juan de Fuca, Strait of Georgia, and Puget Sound basin (WDF 1971). The criteria recommended that bulkheading and filling be confined to the upper one-third of the intertidal zone.

Based on surf smelt spawning studies conducted by Fisheries from 1972-1973, it was obvious that bulkheads along Hood Canal had significantly reduced the areas of suitable surf smelt spawning habitat (Pentilla 1978). Presumed former spawning areas had been destroyed, shade trees were removed, and the littoral drift of beach material had been altered. Hence, further policy restrictions were placed on the extent to which bulkheads or riprap fills could encroach upon the intertidal zone on those beaches used by surf smelt for spawning purposes (WDF 1974). In essence, the supplementary criteria prohibited solid structures from extending very far below the mean higher water line, believed at the time to approximate the upper edge of the surf smelt spawning zone.

In 1981, Fisheries further delineated biological guidelines for the siting and design of marinas and bulkheads (Cardwell and Koons, 1981), based on studies that refined their understanding of the habitat requirements of marine organisms, the pathways of energy flow, and the ecological effects of shoreline developments.

The intent of these 1981 guidelines was to describe and justify means for reducing or precluding adverse biological impacts to economically and ecologically important fish and invertebrates by siting and designing marinas and bulkheads in biologically less sensitive areas. Guidelines are presented for protecting (1) littoral habitats used for spawning, rearing, migration corridors, and refugia from predators by a large number of fish and invertebrates; (2) the viability of juvenile salmon prey resources; (3) the physical character of the substrate; and (4) the harvestability of subtidal beds of clams.

Subsequently, these 1981 policy guidelines were adopted into Washington State law under the Hydraulic Code Rules (Chapter 220-110 WAC). The July 1, 1993, draft of the Hydraulic Code Rules contains regulations for single-family residential and residential-type property bulkheads. These regulations required that such bulkheads shall not result in permanent loss of Pacific herring, surf smelt, Pacific sand lance, and rock sole spawning beds. Spawning areas for these species are protected as "critical habitats" that serve an essential function in the developmental life history of these species. In addition, construction of bulkheads must comply with technical provisions and timing restrictions in WAC 220-110-240 through WAC 20-110-271.

6.1.1 Loss of Spawning Habitat

The quotation that follows (Neil Rickard and Daniel Pentilla, WDFW, pers. comm.) provides a general overview of spawning habitat impacts prior to discussion of direct effects on individual species.

> "Shoreline armoring and associated fill covers fish spawning/incubation beach habitat. Many examples exist throughout Puget Sound of large bulkheads intruding out into the intertidal zone, totally burying former baitfish spawning substrate, and replacing the physical space with uplands. It can be generally hypothesied that the proportion of documented spawning habitat removed by armoring structures will equal a similar reduction in the biomass of the spawning stock. Forcing spawning into continually smaller areas may accelerate stock reductions by increasing spawn predation as well as reducing the spawning site options available in the rigorous upper intertidal environment where spawn survival is already low. The degree of homing back to a specific spawning site by specific populations within the baitfish stocks is not known. It could be well-developed, considering the isolated nature of many perennially-used spawning sites. Destruction of spawning sites could result in localized extinctions of portions of the stock and loss of genetic diversity."
>
> "Shoreline armoring affects the beneficial influences of upland vegetation and the flow of groundwater. Eggs spawned in the intertidal, incubate in the surface beach material that is commonly exposed by tides twice daily for significant periods of time. It may be hypothesized that environmental factors that tend to maintain beach substrate moisture (seeps) and moderate beach surface temperature (overhanging shade trees) will tend to increase spawn survival, particularly in summer-spawning surf smelt stocks. Seeps are almost invariably controlled and culverted to increase the likelihood of short-term structure survival. Shoreline armoring construction activities almost invariably include the total removal of all significant shading trees (primarily alder, willow, and broad leaf maple) from the zone immediately above the ordinary high water line. In addition, view maintenance by beachfront homeowners along armored Puget Sound shorelines will almost invariably result in permanent shade-tree removal."
>
> "Shoreline armoring may affect shoreforms, transport of beach sediments, size distribution of beach sediments, and beach/habitat stability and profile. Existing critical fish spawning habitats/substrate deposits in Puget Sound vary widely in character within and between individual spawning beds. They also vary in character over time within specific sites depending on the vagaries of weather. Spawning substrate deposits are often of limited extent along the shoreline and of limited aerial extent and volume within any specific spawning site, due to both natural circumstances of sediment availability, wave energy regime, and existing man-caused impacts and disruptions in the natural functioning of the littoral drift system. The surface layer of silt-free motile sand and gravel suitable for spawn incubation is often just a thin veneer a few centimeters thick, overlying glacial clay, hardpan, and other unsuitable spawning material. These sandy gravel substrate deposits are vulnerable to shoreline armoring impacts even at some distance away from the physical structures themselves, down-beach and along-shore. Any activity that causes a decline in the extent of fine-grained material in the upper intertidal zone could have negative impacts on the baitfish spawning stocks not unlike those resulting from physical burial/removal of spawning habitat."

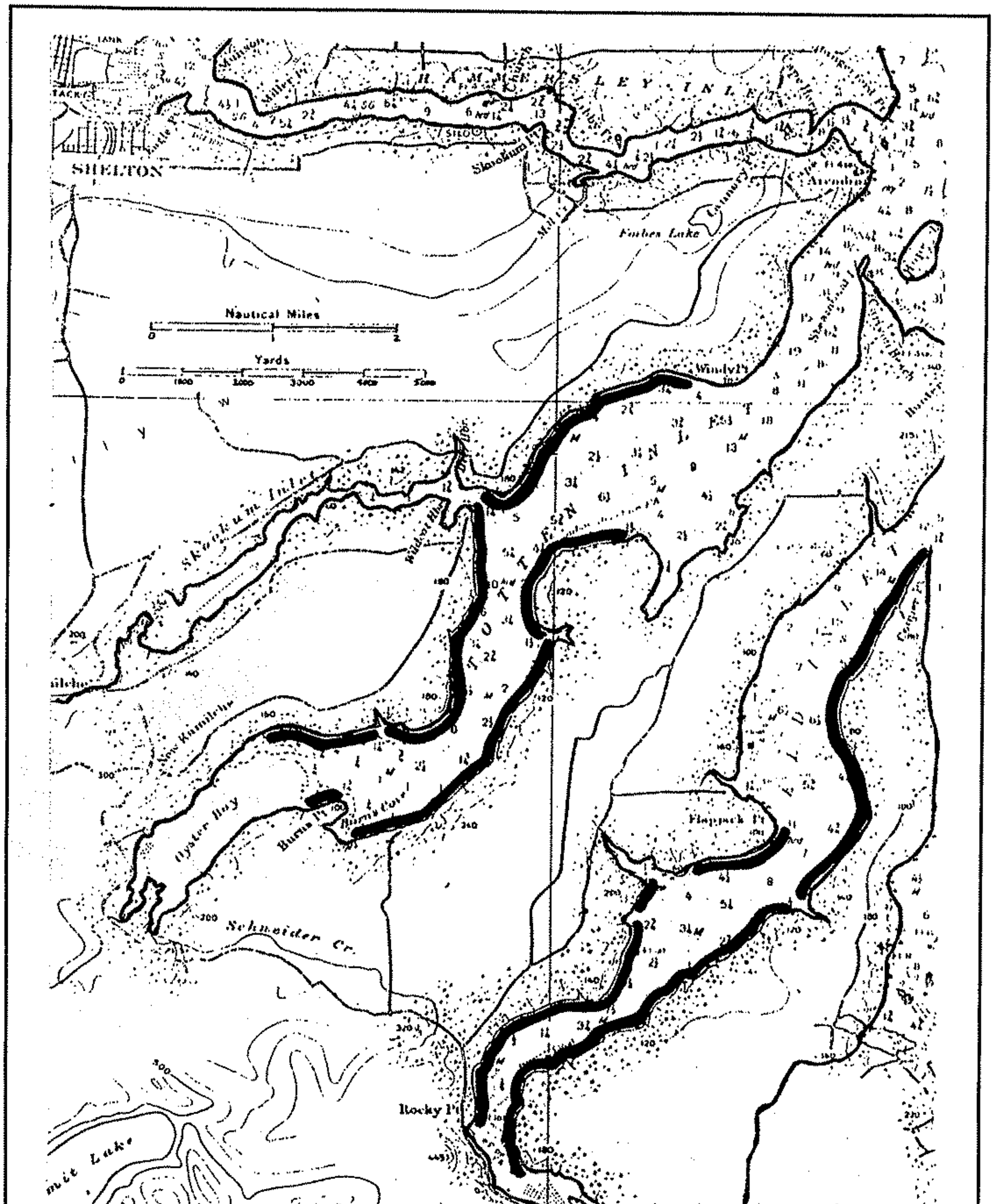
Surf smelt (*Hypomesus pretiosus pretiosus*) are widespread in Puget Sound (Garrison and Miller, 1982). Major spawning areas are found in protected inland waters of southern

Puget Sound (Figure 6-1), southern Hood Canal, northern Saratoga Passage, and the Liberty Bay area, as well as the semiprotected shores of the Strait of Juan de Fuca and on exposed beaches along the northwest shore of the Olympic Peninsula (Pentilla, 1978). Fish and Wildlife is presently in the second year of a 6-year program to fully document the extent of shoreline spawning habitat. To date, 130 miles of surf smelt spawning beaches have been documented in Puget Sound (Pentilla, pers. comm., December 1993). These beaches are typically at the heads of bays or inlets and usually somewhat shaded along the upper part by overhanging trees or by bluffs. Typical spawning substrates consist of fine gravel and coarse sand, with broken shells intermixed in some cases. Grain-size analysis of 43 substrate samples bearing smelt spawn that were collected from various Puget Sound beaches in 1972 to 1973 revealed that about 80 percent by weight of this substrate was in the size range of 1 to 7 mm in diameter (Pentilla, 1978).

Because surf smelt spawn high in the intertidal (from +7 feet MLLW up to EHHW according to Pentilla, pers. comm., December 1993), they are particularly susceptible to permanent habitat loss resulting from shoreline armoring (Figure 6-2). Surf smelt make no attempt to bury their demersal, adhesive eggs, but rely on wave action to cover the eggs with a fine layer of substrate. Because the eggs are deposited on the upper portion of the beach, they may be submerged only a short period during the 2 to 4 week incubation period (Pentilla, 1978). Pentilla hypothesized that the advantage of spawning on fine substrate, high in the intertidal could be the continuous sorting and resorting of the surface beach material by wave action, which results in larger material being deposited on the surface and smaller particles, including eggs, shifted beneath the surface. Spawning on substrate of the preferred size (1 to 7 mm) may ensure that the eggs are mixed down into a micro-environment that retains capillary moisture while allowing sufficient aeration, thus maximizing egg survival.

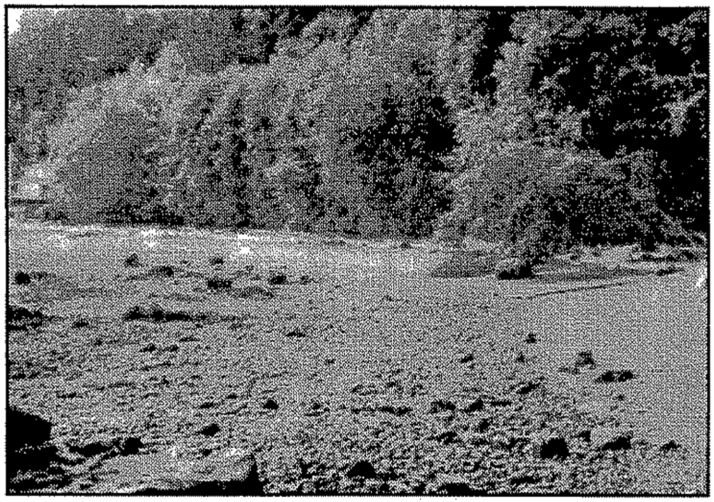
In Puget Sound, **Pacific sand lance** (*Ammodytes hexapterus*) are common and widely distributed (Garrison and Miller, 1982). According to Garrison and Miller (1982), most aspects of spawning biology of Pacific sand lance remain unstudied. Sand lance populations form localized schools that are usually associated with clean sand bottoms. Fish and Wildlife has confirmed sand lance spawning on approximately 50 miles of Puget Sound beaches to date (Pentilla, pers. comm., December 1993). Sand lance spawn at elevations from +5 feet MLLW to MHHW on substrates varying from sand to sandy gravel. Like surf smelt, sand lance are susceptible to deleterious effects of shoreline armoring because of their preference for spawning high in the intertidal.

Rock sole (*Lepidopsetta bilineata*) are widely distributed in Puget Sound and adults are typically found at depths between 10 and 40 m on a rocky or firm bottom (Garrison and Miller, 1982). They appear to spawn during a period from late winter through spring. Spawning is thought to take place on sand or soft substrates. Fish and Wildlife has documented approximately 20 miles of beaches where rock sole spawn in Puget Sound (Pentilla, pers. comm., December 1993). In some areas of Puget Sound, rock sole deposit their



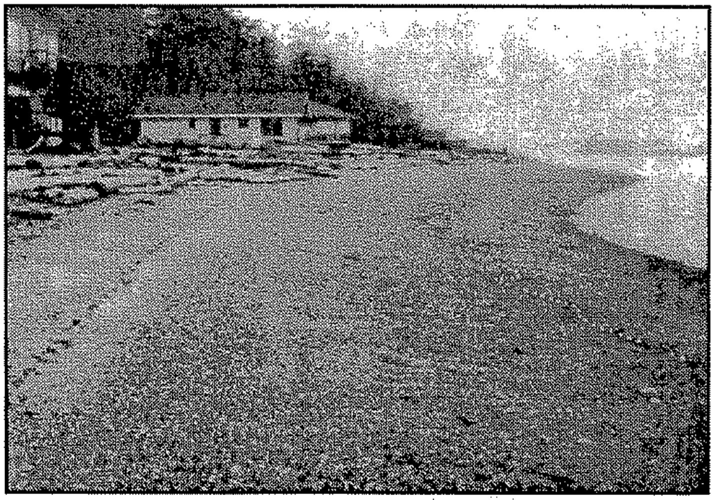
Source: Pentilla (1978)

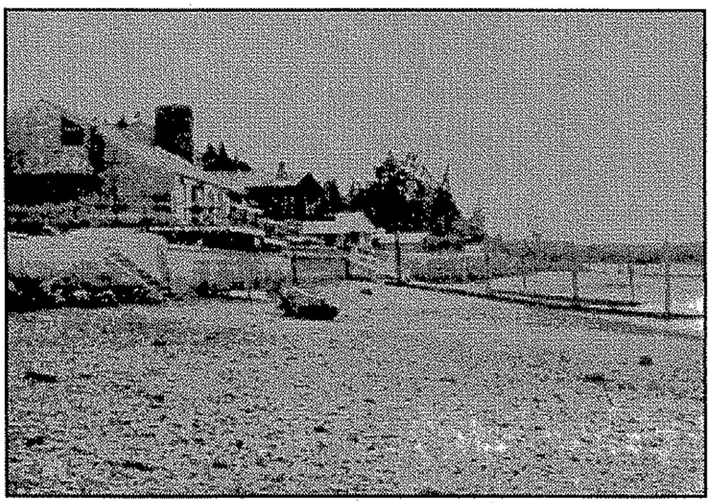
Figure 6-1
Surf Smelt Spawning Beaches,
Totten and Eld Inlets
South Puget Sound 1972-75



Cavelero's Beach, Camano Island. Spawning smelt utilize upper half of fine-grained upper-beach zone, shaded from afternoon sun by trees and bluffs.

Penn Cove, Whidbey Island. Smelt spawn found incubating from lower drift logs down to middle of the beach.





Forest Beach, S. Hood Canal. Spawning beach heavily impacted by shoreline development.

Source: Pentilla (1978)

Figure 6-2
Surf Smelt Spawning Beaches, 1972-75

eggs on the same beaches as sand lance and surf smelt, but there is some indication that rock sole are not obligate intertidal spawners like surf smelt and sand lance (Pentilla, WDFW, pers. comm., December 1993).

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

6.1.2 Loss of Shoreline Riparian Vegetative Cover

While there is a vast literature on the structural and biological importance of streamside riparian vegetation (e.g., Warner and Hendrix, 1984; Mitsch and Gosselink, 1993), much less has been written about the ecological roles of "marine shoreline riparian vegetation" along estuaries and coastal beaches. In general, riparian vegetation contributes to maintenance of both fisheries habitat and water quality and may perform many important ecological functions in estuaries and coastal beaches (Johnson and Ryba, 1992). A few of these functions include bank stabilization, shade, cover for fish and wildlife, organic input, and source of insect "fallout." Loss or reduction of shoreline riparian vegetation is likely to result in increased siltation, increased nearshore water temperatures (Beschta et al., 1987), reduced organic inputs, changes in beach substrate, and changes in beach morphology resulting from disruption of the littoral drift and habitat fragmentation. Collectively, these variables largely determine the suitability of shoreline habitat for fish and aquatic insects.

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

Shoreline riparian vegetation may have particularly high value in Puget Sound because of its contributions to marine fish species that utilize the upper intertidal zone for spawning habitat (Daniel Pentilla, WDFW, pers. comm.) and to juvenile salmonids (e.g., cover, detrital input, insect prey). Garbisch and Garbisch (1994) argue that shading from forested shorelines around Chesapeake Bay precludes establishment of bank-stabilizing emergent marsh and thus indirectly increases bank erosion. This is not a concern at most Puget Sound locations, however, perhaps because of the more localized occurrence of emergent marshes.

6.1.3 Loss of Wetland Vegetation

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

Emergent vegetation (sedges [*Carex lyngbyei*] and rushes [*Scirpus* spp., *Typha* spp.] and riparian shrubs and trees in the middle and upper intertidal zones, respectively, were identified by Levings et al. (1991) as vital components of the Fraser River estuary that provided detritus and habitat for juvenile chinook food organisms. For the purposes of managing fish habitat to achieve a goal of no net loss of habitat in the Fraser estuary, fish habitat biologists in British Columbia are assigning highest values to the sedges and rushes. To compensate for the loss of sedge marsh, for example, a 2:1 ratio (compensatory area:lost area) based on areal measurements is required, whereas 1:1 is required for riparian habitat and sand/mud flats, the other two dominant habitat types in brackish estuaries.

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

6.1.4 Loss of Large Organic Debris (Habitat Complexity)

The majority of the literature on large organic debris (typically referred to as LOD or woody debris, depending on the size of the material) pertains to stream ecosystems, and particularly to juvenile salmon in streams, whereas few studies have focused specifically on the ecological roles of LOD in estuarine or coastal habitats. Habitat complexity is a primary factor influencing the diversity of stream fish communities (Gorman and Karr, 1978; Schlosser, 1982; Angermeier and Karr, 1984) and LOD is a primary element influencing habitat diversity and complexity in streams (e.g., Bisson et al., 1987; Reeves et al., 1993).

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

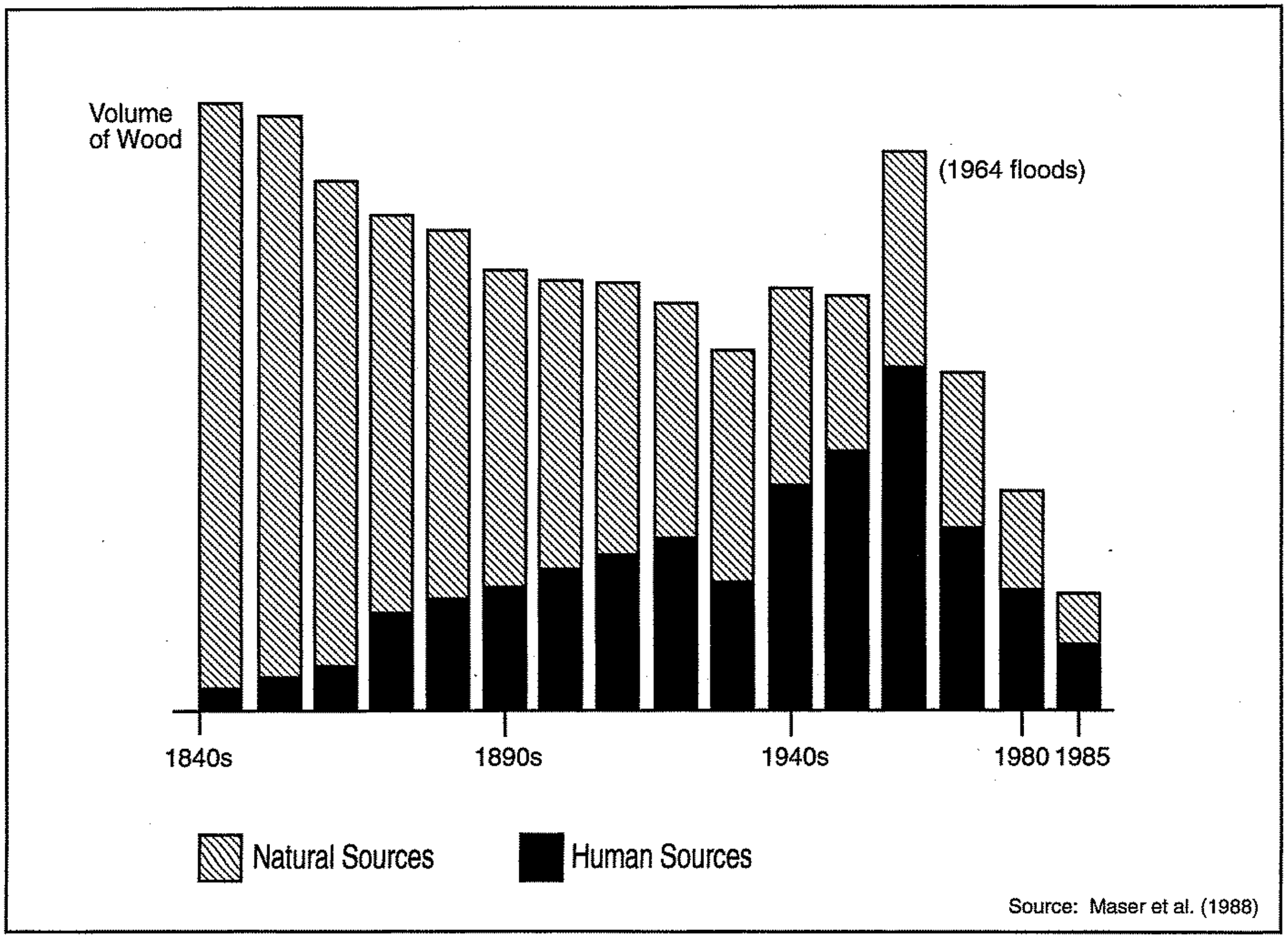


Figure 6-3
Wood Inputs to Oregon Beaches and Estuaries, 1840 - 1985

Natural sources of wood for estuaries and beaches were much more extensive prior to settlement of the northwest (Figure 6-3; Benner and Sedell, 1987; Gonor et al., 1988). While natural sources of wood became more scarce, wood inputs from land clearing, logging operations, and other human activities became more available. However, these anthropogenic inputs of wood, typically stumps and logs, lacked the length, volume, root wads, and branches of natural wood inputs. In addition, stumps and logs are less likely to remain at a site and contribute to the long-term structure of the area.

The importance of LOD to the early life stages of **juvenile salmon** in streams has been well documented (e.g., Bryant, 1983; Angermeier and Karr, 1984; Grette, 1985; Bisson et al., 1987; Andrus et al., 1988; Sedell et al., 1990; Bilby and Ward, 1991; Reeves et al., 1993). Woody debris provides habitat complexity, refuge from predation, and a source of nutrients for juvenile salmonids. Shoreline armoring often removes upland sources of LOD as well as limiting natural LOD accumulation (Macdonald et al., 1993), thereby limiting organic input and protective cover for juvenile salmonids. In addition, LOD can be very effective at buffering beaches and land from wave attack and can trap beach sediment, thereby naturally aiding beach stabilization and accretion (Terich and Milne, 1977). Thus, LOD, in the right situation, may better protect beaches from erosion than unnatural armoring structures, while also providing valuable habitat for juvenile salmonids. In our experience, state resource agencies are increasingly factoring the loss of LOD into estuarine habitat restoration scenarios, and in some cases even advocating placement of logs or large woody debris back into estuaries to provide enhanced juvenile salmonid habitat.

6.1.5 Changes in Food Resources

Natural beaches in estuaries act not only as migration corridors for juvenile salmonids, but also as transportation corridors for sediment (littoral drift), as well as inorganic and organic nutrients and detritus. Shoreline armoring disrupts this natural pattern of littoral drift and beaches can become "starved" for sediment and nutrients (Macdonald et al., 1993). One of the major biological effects that results from disrupting littoral drift is the loss or reduction of nutrients and food sources needed to sustain **juvenile salmonids.** Because juvenile salmonids are actively feeding during their outmigration, they need prey of appropriate species and sizes in appropriate quantities at the right time. Thus, growth rates of juvenile salmonids may be negatively impacted if their natural food supply is reduced or cutoff because of shoreline armoring, adversely affecting their survival. While researchers have begun to investigate the physical effects of shoreline armoring in terms of disruption of the littoral drift, no studies assessing the loss of salmonid food resources due to shoreline armoring were found. Simenstad et al. (1991) did show that placement of gravel on mudflats did enhance selected salmonid prey resources.

6.1.6 Loss of Migratory Corridors

Estuaries function as critical migratory corridors for juvenile anadromous Pacific **salmonids** as juveniles during their seaward migration, and as adults returning to spawn in freshwater (Healey, 1982; see accompanying **Fact Sheet**). Fish and Wildlife is concerned that

FACT SHEET

Juvenile Salmon Dependence on Estuaries

Because of the commercial importance of salmon to the Puget Sound region, research on estuarine habitat requirements of this group of fish has been fairly extensive. Jamison and Weitkamp (1992, unpublished) interviewed six leading experts regarding estuarine habitat requirements for juvenile chum and chinook salmon. Experts were asked to identify the most important habitats and their location in the estuary, habitat size requirements, the importance of habitat linkages, and the relative importance of water quality. Results of those interviews are summarized here because they represent useful qualitative input to the understanding of potential biological effects of shoreline armoring.

The experts pointed out that life history differences exist between chum and chinook salmon. The fundamental difference is the length of time these two species spend in fresh water following emergence. Chum salmon fry usually migrate into the estuary shortly after emergence from spawning areas and are able to adapt to elevated salinities very quickly. Chinook salmon fry, in contrast, typically exhibit prolonged rearing in fresh or brackish water (up to several months) until they reach about 80-100 mm in length. At this size, yearling (1+) chinook are generally able to withstand higher salinities. This difference in the smoltification process means that chinook fry typically tend to rear for prolonged periods in the upstream edge of the estuary, whereas chum fry use the middle or lower portions of the estuary. In some systems, however, chinook fry also rear in the lower estuary.

Both species prefer relatively fine-grained substrate and low stream gradients, but chinook fry tend to feed in tidal fresh and brackish marshes more than chum. Tidal channels and riparian vegetation are of particular importance for chinook fry feeding in these marshes. With increasing size, chinook fry move further downstream and gradually shift from feeding on floating insects to epibenthic or pelagic prey. Yearlings are likely to move directly to tidal flats and deepwater habitats in the lower estuary where they prefer epibenthic prey. Tidal flats in the range of -2 to +2 feet MLLW with slopes of 1:6 or flatter allow the greatest access and utilization, and tidal channels at minus tide levels offer important refuge habitat. Eelgrass and other estuarine vegetation is valuable to both chinook and chum salmon.

There were considerable differences in opinion among the six experts about the importance of habitat locations within the estuary. In the upper estuary, marshes were considered the most important habitat. Several experts felt that habitat throughout the estuary needed to be either a continuous band or separate parcels relatively close to each other. There was consensus that the area used for saltwater transition required substantial marsh habitat to provide prey organisms and refuge from predation. In estuarine bays, shorelines of sand-gravel-cobble are important rearing habitat.

Expert opinions also varied considerably on habitat size requirements. Several felt that parcels of 20-30 acres were required to be effective, especially in the upstream end of the estuary. Some experts believed that habitat of any size could be of some value as long as it was "large enough" to provide food and refuge.

In summary, juvenile chum and chinook salmon prefer low-gradient shallow water with fine-grained substrates and submerged or emergent vegetation. Lower intertidal habitats with adjacent channels are most important for refuge and feeding. Habitat "linkages" were cited by all experts as being extremely important. Most experts felt that critical habitats should be as close together as possible, and within one-day migration distance. This distance could be as far as 5-10 miles in some river systems. Water quality must also be high for juvenile salmon.

Historical conditions can provide a useful framework for predicting the biological effects of shoreline armoring on juvenile salmon. Many Pacific Northwest estuaries are part of a landscape that historically included a steep, heavily wooded watershed supplying ample freshwater flows. The gradient of habitats generally encountered in an estuary includes wooded upland, riparian vegetation, swamps and marshes, tidal flats, seagrass meadows, and shallow to deep channels. This basic structure resulted from geomorphic processes that would be fundamentally altered by shoreline armoring. Shoreline armoring has the potential to fragment the mix of habitat types embodied in the estuarine landscape matrix, thereby disrupting the flow of energy and materials between different habitats and the resources that depend on these habitats, such as juvenile salmon.

See also: Bax (1983), Fresh et al. (1981), Healey (1982), Levy et al. (1982, 1989), Macdonald et al. (1988), and Simenstad et al. (1982, 1984).

shoreline armoring has resulted in excessive waterward encroachment and a net loss of intertidal area and habitat functions (Neil Rickard, pers. comm., December 1993). While the permanent loss of some intertidal habitat can be predicted to result from shoreline armoring, such habitat losses have not been adequately documented throughout Puget Sound. In addition, few studies have been designed specifically to assess the biological effects of shoreline armoring on juvenile salmonids.

Through a literature review and interviews with habitat experts, Toal (1993) attempted to assess what effect, if any, bulkheads might have on juvenile salmonids migrating through Hood Canal. Estimates of the extent of shoreline bulkheading were made by aircraft, motorboat, and automobile, as well as Mason County bulkhead application records from 1984 to 1992. (Mason County had no records of bulkheads built before 1984.) However, insufficient records of bulkheading constrained the mapping effort, and insufficient funds were available to adequately document the extent of shoreline hardening.

One potential physical effect of shoreline armoring is increased slope and water depth along the shoreline (Macdonald et al., 1993). The biological ramification of this physical effect is that increased water depth is hypothesized to increase the likelihood of predation on juvenile salmonids. Chum and pink salmon, because they migrate to sea immediately upon emergence and are typically small upon entry into saltwater (<35 mm fork length), are thought to be particularly vulnerable to predation (Cardwell and Koons, 1981). Fish and Wildlife biologists have expressed concern that avoidance of bulkheads and breakwaters forces migrating salmon into deeper water where they are more susceptible to predation by coho salmon smolts and cutthroat trout (Toal, 1993). In an experiment to test the importance of estuarine residency to chinook survival, Macdonald et al. (1988) documented that marine-released fish were exposed to more bird and fish predators than river- or estuarine-released fish.

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

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

Kurt Fresh (WDFW, pers. comm.) notes that armoring such as described by Heiser and Finn (1970) usually involves significant encroachment below the ordinary high water line resulting in the permanent loss of fish habitat. Such habitat loss is not consistent RCW 75.20.100, RCW 75.20.160, WAC 220-110, and WDFW habitat policy. WDFW habitat policy (POL-410), adopted September 1990, states ". . . it is the goal of WDFW to achieve no net loss of the productive capacity of the habitat of food fish and shellfish resources of the state." This policy requires applicants of projects potentially impacting fish resources and habitat to mitigate all adverse effects. Applicants must first take all reasonable steps to avoid habitat damage, and second, take all reasonable steps to minimize any unavoidable habitat damage. Any habitat which is unavoidably damaged or lost must be replaced to its full productive capacity using proven methods.

Understanding the biological effects of shoreline hardening in better documented riverine settings may also provide insights on whether coastal shoreline armoring has similar effects. Stone revetments and spur dikes (groins) have been used extensively on the Willamette River to stabilize stream banks and channels. Li et al. (1984) compared habitats near spur dikes, continuous revetments, and natural stream banks for larval, juvenile, and adult fishes of the Willamette River. They found that natural banks, because they are diverse in structure, afforded the best habitat for resident fish. Natural habitats include secondary channels, fast and slack water banks, sloughs, and backwaters—thus physical diversity is higher and results in correspondingly greater fish diversity. Spur dikes appeared to be intermediate in quality between the natural banks and continuous revetments. Larval and juvenile fish densities and numbers of species at spur dikes were intermediate between natural banks and continuous revetments. The numbers of species of adult fishes were similar at spur dikes and continuous revetments, but less at both artificial habitats than at natural banks. Wood debris was observed to accumulate between spur dikes, offering better wintering habitat than revetted banks. The authors speculated that as wood debris accumulates and the riparian vegetation develops along the spur dikes, fish use of these habitats will increase. The relevance of this study to shoreline armoring in coastal habitats is that similar observations of diminished habitat value for fishes following shoreline hardening might be expected.

Knudsen and Dilley (1987) estimated summer and fall juvenile salmonid populations in five pairs of streams in western Washington shortly before and after construction of flood and erosion control projects. They found that the numbers of juvenile coho salmon, juvenile steelhead, and cutthroat trout were reduced by bank stabilization and streambed alterations in the three smaller, and most severely altered, stream sections. In addition, negative short-term effects of construction appeared to increase with severity of habitat alteration, to decrease with increase in stream size, and to decrease with increasing fish size. Four other studies cited in Knudsen and Dilley, 1987 (Bryant, 1983; House and Boehne, 1985; Elliott, 1986; and Brusven et al., 1986), indicate that reduction of habitat diversity, as occurs during the riprapping of a stream bank, may be detrimental to juvenile salmonids. Knudsen and Dilley suggest that future studies should attempt to determine the long-term effects of incremental additions to the total length of riprapped streambanks on salmonid productivity. Similarly, the cumulative effects of incremental shoreline armoring are largely unknown and need to be investigated for estuaries and coastal beaches.

6.2 Finfish Use: Indirect Effects

Because of their commercial importance, **Pacific herring** has been extensively studied (Garrison and Miller, 1982). Much research has been directed toward documenting areas of herring spawning activity (Figure 6-4; Stick, 1991). Spawning adults in Puget Sound appear to return each year to the same general area where they were hatched. Most spawning takes place from February to March, although spawning herring may be found somewhere in Puget Sound from January to June (Garrison and Miller, 1982). In a particular spawning location, spawning may extend over a long period (up to several months), but the spawning peak usually occurs at a similar time each year (Meyers and Adair, 1978, cited by Garrison and Miller, 1982).

The majority of spawning in Puget Sound occurs on two basic habitat types (Pentilla, 1986): (1) the most widespread is comprised of a largely subtidal soft-bottom plant community dominated by eelgrass (*Zostera marina*) and a red algae (*Gracilaria pacifica*), and (2) on exposed boulder/cobble shores of the southern Strait of Georgia, where herring commonly spawn in the intertidal on *Fucus distichus, Sargassum muticum, Laminaria saccharina, Desmarestia* sp., *Prionitis* sp., *Odonthalia* sp., and *Botryoglossum* sp. in addition to *Zostera marina*. In Puget Sound, herring spawn from the low intertidal to subtidal zones, between +1.2 m (+4 feet) to -6.1 m (-20 feet) in tidal elevation (Garrison and Miller, 1982) and the eggs are tolerant to temperatures in the range of 5°C to 14°C and salinities in the range of 3 to 33 ppt (Haegele and Schweigert, 1985). There are about 24 distinct herring spawning areas in Puget Sound that appear to be used annually (Pentilla, 1986).

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

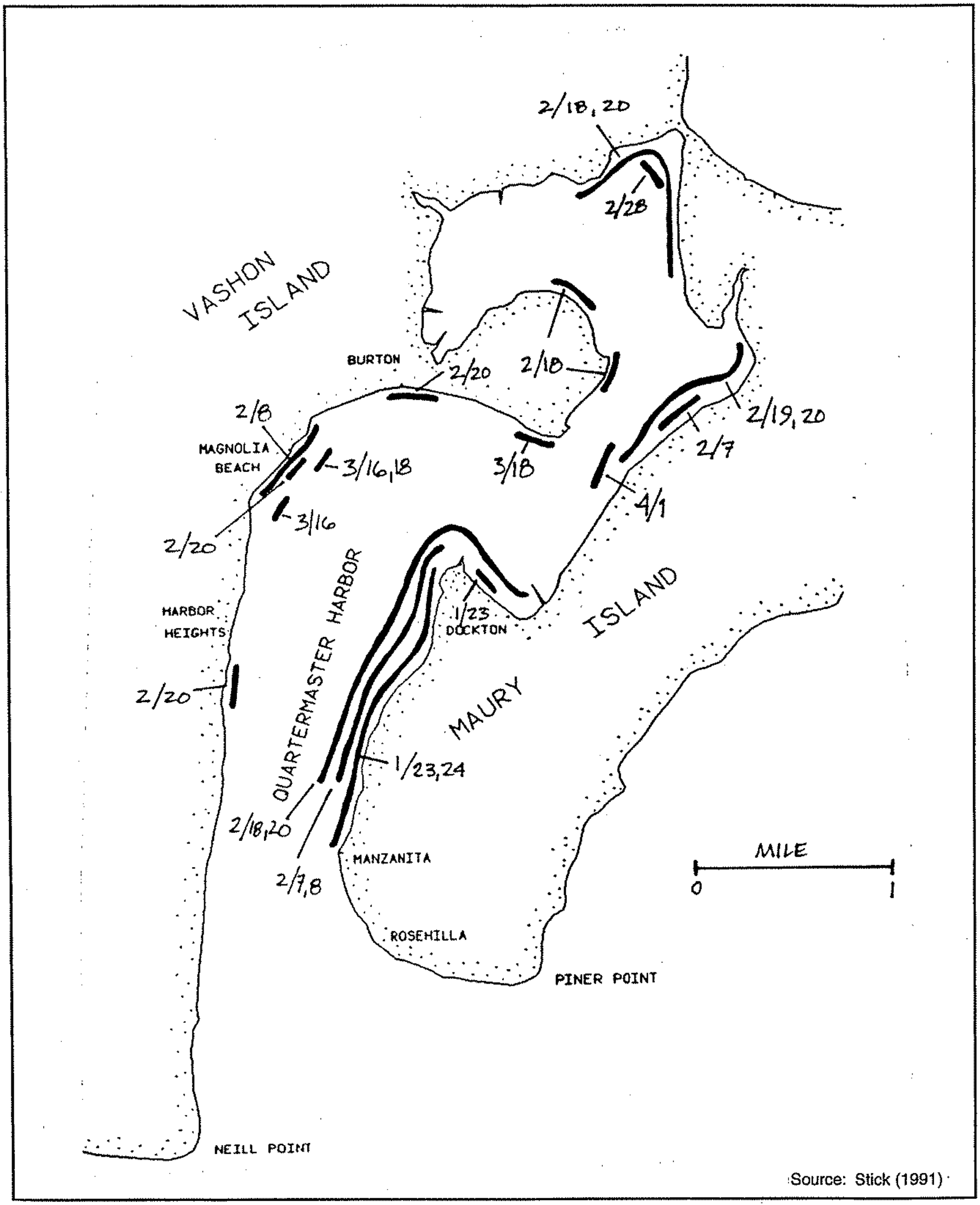


Figure 6-4
Herring Spawning Locations and Dates
Quartermaster Harbor, 1991

6.3 Shellfish Use: Direct and Indirect Effects

Reviewing potential impacts of shoreline armoring on shellfish use, Richard Bumgarner (WDFW, pers. comm.) notes that, quote:

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

6.3.1 Hardshell Clams

There are well over a dozen species of hardshell clams that are used either commercially or recreationally in Puget Sound (WDF, 1992). Table 6-1 lists those species that are most often harvested. Most species prefer a gravel/sand substrate. Mixed-coarse beaches of varying degrees of exposure are suitable for these species, which occur primarily in the intertidal zone. Manila clams occur at higher elevations as compared to other species, and can be collected in large numbers from as high as +3 feet MLLW.

Direct, short-term effects of shoreline armoring on hardshell clams would come from trampling or heavy equipment activity (i.e., bulldozers, beached barges) during construction. These areas would recover if not altered dramatically; recovery rate would depend upon location and degree of impact. There also may be short-term indirect impacts caused by turbidity related to construction activity. This may result in clams ingesting large quantities of fine sediment. With time, these species will purge these sediments from their guts. Direct, long-term impacts would be due to direct placement of armoring material (i.e, rock) on top of clam habitat. Since Manila clams occur highest on the beach, this species may be the most vulnerable to direct armoring effects.

Alterations in substrata, such as loss of fine material, could also affect the abundances of these clam species significantly. Lowering of beach elevation could not only lead to a shift in clam species but also increase the incidence of predation on existing calm species. For example, predation on Manila clams increases below the +2 MHHW because this tidal elevation is covered by water a greater amount of time making it easier for moon snails, diving ducks, etc., to prey on this clam species (Richard Bumgarner, WDFW, pers. comm.). Ellifrit et al. (1973) investigated the effect of bulkheading and attendant fill in upper intertidal levels on densities of **Manila clams** in Hood Canal. They found significantly fewer clams at stations located seaward of bulkheads, with three of the four bulkheaded stations yielding densities less than half those from adjacent natural beaches. However, they found that clams inhabiting lower intertidal levels on the beach were not affected. Alterations in current patterns caused by the bulkheads, which resulted in less favorable conditions for settlement and survival of clam larvae, were proposed to explain lower clam densities near bulkheads.

Thompson and Cook (1991) and others have documented the effect of placement of gravel on sandy and muddy Puget Sound beaches (see also Newman and Cooke, 1988; Simenstad et al., 1991a; Toba, 1992; Thom et al., 1994). Gravel placement has resulted in significant recruitment of littleneck clams onto former mudflats. Seeding of gravel patches, coupled with measures to protect small clams from predators, has resulted in enhanced clam densities. These data strongly suggest that erosion, which results in removal of some fines and exposure of gravel, may improve conditions for hardshell clams. This enhancement would only persist if erosion ceased following exposure of the gravel. No examples have been found to date where such enhancement has been documented in Puget Sound.

At Lincoln Park, where erosion removed fines from the upper portion of the beach, clams may have declined in abundance. Since beach renourishment with pit run gravel in the late 1980s, clam populations have colonized the lower elevation fill (i.e., below +4 feet MLLW; Antrim et al., 1993). Overall, clam population densities remain low on the fill, however. This suggests that clam densities may have been low in the upper elevations of the beach prior to placement of the seawall at Lincoln Park, or that not enough time has passed to allow full development of beach conditions to support hardshell clams. Clam populations were quite high in the lower elevations of the beach when studies were conducted in 1974-1976 (Armstrong et al., 1976) and 1984-1993 (summarized in Antrim et al., 1993). Erosion of fine sediments has occurred since placement of fill in the late 1980s (Macdonald et al., 1993). This suggests both that the substrate is dynamic and that organic matter may not be accumulating on the fill. Organic matter (detritus) is an important source of food for some clams while others feed on phytoplankton.

6.3.2 Geoduck

Geoducks represent an important commercial species as well as a highly prized recreational species. They generally occur in sandy and muddy sediments from the very low intertidal zone down to at least -100 feet MLLW. The vast majority of geoduck production occurs at bottom depths between -20 and -80 feet MLLW (Goodwin, 1990). Coarsening of the substrate may reduce local populations. Because this species inhabits deeper water depths, it is less likely to be impacted by shoreline armoring carried out high on the beach. Armoring structures such as vertical sheet pile, that extends to subtidal depths, could increase wave energy and result in scouring of subtidal habitats occupied by geoducks. To date, however, this impact has not been documented in Puget Sound.

6.3.3 Oysters

Oysters, in particular the **Pacific oyster**, represent another valuable commercial and recreational fishery resource. The Pacific oyster is cultured using several methods including on-ground, pole and line culture. Culture operations are generally confined to the lower intertidal zone where harvest can be carried out during extreme low tides.

In Quilcene Bay, the Quilcene River was diked by Jefferson County to prevent flooding at its delta. This has also prevented channel migration and disturbance of oyster grow out areas (Douglas Thompson, pers. comm., December 1993).

Because oysters occur naturally in the mid- to low intertidal zone, shoreline armoring effects would either be through direct disturbance during armoring construction or through indirect effects from erosion and beach lowering. Oysters can grow in a variety of substrate types ranging from mud to cobble; alteration of substrate type may not have a direct effect on oyster survival and growth. Variation in survival and growth over a variety of substrata types needs to be investigated more fully to evaluate this latter point. Oysters may benefit from benthic diatom production on mudflats (Grant et al., 1990; Simenstad and Wissmar, 1985). Based upon this information, alteration of benthic diatom productivity by a shift from a soft substrata to cobble may affect the source and amount of food available to oysters.

6.3.4 Dungeness Crab

Dungeness crabs are the most economically important crustacean shellfish resource in Washington State. Mating takes place in intertidal and subtidal areas. The larvae settle to the bottom after a period in the plankton and can be found in great numbers in intertidal and shallow subtidal habitats including eelgrass, dense seaweed (*Ulva* spp.), and shell debris (Dumbauld et al., 1993). According to Richard Bamgarner (WDFW, pers. comm., December 1993), the most critical nearshore zone occurs at elevations from -2 to +3 feet MLLW where young-of-the year crab reside.

Dumbauld's study references work on the outer coast. Several additional studies describe Dungeness crab life history within Puget Sound: Dinnel et al. (1986, 1987, 1992), Weitkamp et al. (1986), Armstrong et al. (1987), and McMillan (1991). Within the Sound, mating is known to occur in the intertidal at high tide and shallow subtidal as well as possibly in deep water. Further, ovigerous female crabs are known to overwinter in shallow subtidal eelgrass beds during the egg incubation process. This activity has been documented in Guemes Channel from Ship Harbor to Anacortes (Richard Bumgarner, WDFW, pers. comm.).

Although no studies to date have documented the effects of shoreline armoring on Dungeness crab, any action that directly or indirectly disturbs critical crab habitats could affect the survival of this species. Direct effects during armoring construction could crush both mating pairs and young crab. Recovery of the population to preconstruction levels may take several years. Long-term effects would occur with loss of habitat and, to a lesser extent, lowering of the beach profile. Increased turbidity could affect the growth of eelgrass and algae, which could, in time, reduce preferred crab habitat and critical young of the year habitat. Alterations in substrata type from soft to harder (cobble or hardpan) will result in a reduction in the use of nearshore areas by crab. Young of the year forage would be diminished and crab would be less able to bury in the substrate as they typically do to avoid predators. Crab are omnivores and will eat a wide range of organisms living in the bottom sediments as well as organic matter that settles to the bottom. Further, their diet varies considerably with age. Alterations in food resources associated with alterations in substrata, bottom depth, etc., could affect both the production and trapping of food in the habitat occupied by young of the year and adult crab (Richard Bumgarner, WDFW, pers. comm.).

6.3.5 Sea Cucumber

Of the several species of sea cucumbers in Washington State waters, only the **giant red sea cucumber** (*Parastichopus californicus*) is commercially harvested (Bradbury, 1990). This species occurs on the surface of mud and sand substrates in the subtidal zone. Overharvesting has depleted stocks of this species in Washington State. Areas with the heaviest harvest occur in central Puget Sound.

Sea cucumbers can occur in high densities in areas occupied by kelp and other seaweed species. Because of their occurrence in the subtidal zone, only indirect effects associated with shoreline armoring may affect this animal. As with geoducks, seawalls that indirectly affect subtidal habitats and reduce seaweed stocks may also affect sea cucumber abundance. These effects could include increased turbidity, increased wave energy, and increased current velocities. Because sea cucumbers feed on detritus, alterations in the settlement of organic matter could affect the supply of food to these animals.

6.3.6 Sea Urchins

Of the three species of sea urchin that are common in Washington State, only the **red urchin** (*Strongylocentrotus franciscanus*) and the **green urchin** (*S. droebachiensis*) can be commercially harvested (Bradbury, 1990). Commercial quantities of these species are concentrated in the Straits and San Juan Archipelago, with much reduced quantities in northern Puget Sound. Like sea cucumbers, urchins are taken by divers in the subtidal zone.

Urchins occur associated with rocky substrata in the subtidal zone. They graze actively on algae growing attached to rocks and can devour large quantities of kelp and other seaweeds when their populations reach high densities. Alterations in seaweed communities and abundance as a result of indirect armoring effects on turbidity, currents, or wave energies could reduce the available habitat and food resources for urchins.

6.4 Upland Habitat: Direct and Indirect Effects

In considering the potential affects of shoreline armoring on the coastal ecology and biological resources of Puget Sound, we have emphasized changes that occur *seaward* of the armoring. What happens to a beach when its sediment supply is cut off by armoring?

How does the reflected wave energy and turbulence generated by bulkheads and seawalls alter adjacent beaches; and as the beaches change, how are their associated plant and animal communities affected?

Shoreline armoring is also installed—sometimes unnecessarily—to protect and enhance development sites and property values *landward* of the armoring. The goal is to control toe erosion or help stabilize coastal banks and bluffs.

Residential development in coastal bank and bluff settings often results in land clearing, tree cutting (to enhance views), and drainage modifications (increased runoff, septic field drainage) that can seriously impact natural slope (physical) processes and habitats and may result in slope stability problems. Many of these issues are addressed in **Task 6—Management of Unstable Shoreline Slopes in Puget Sound** (Macdonald and Witek, 1994). This report section briefly addresses some of the potential effects of slope development on the ecology and resources of Puget Sound.

Initially, no systematic studies or published accounts describing the natural habitats or plant and animal communities of Puget Sound's banks, bluffs, and cliffs were identified. However, numerous narrow focus studies on the use of bluffs by avifauna have been carried out (Hirsch, 1981; Brown, 1985; Speich and Wahl, 1989; Vermeer et al., 1987, 1993). This summary is, therefore, based principally on personal communications with regional experts.[1] During the review process Neil Rickard and Robert Zeigler (WDFW, pers. comm.) pointed out that the narrative volumes associated with the *Coastal Zone Atlas of Washington* (Ecology, 1977-80; Albright et al., 1980) contain summary information on vegetation and wildlife uses of Puget Sound shoreline bluffs and cliffs—as indeed do the Atlas maps themselves.

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

Distinctions between banks, bluffs, and cliffs tend to be arbitrary, with dictionary definitions offering little help.

Bank A bench or rising ground bordering a lake, river, or sea

Bluff A high steep bank (arbitrarily greater than 10 feet high and often forested)

---

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

Cliff A very steep or overhanging face of rock (arbitrarily greater than 25 feet high and unvegetated)

Forested bluffs and cliffs provide several unique habitat features:

- Have very steep slopes, often inaccessible—resulting in protection from human disturbance.
- Experience mass wasting and failure—results in open canopy/pioneer plant communities.
- Experience fewer, less intense fires than adjacent upland habitats.
- Have unique groundwater seep habitats.
- High slopes immediately adjacent to water offer isolated trees with excellent visibility for perching/nest sites.
- Cliffs provide isolated ledges and cavities for nesting.

Bank, bluff, and cliff habitats throughout Puget Sound are expected to exhibit regional variations in plant and animal communities that reflect differences in substrate (rock, outwash sand, lake-bed clay), rainfall and relative exposure to wind (seed dispersal), storms, and sunshine.

6.4.1 Plant Communities

Prior to European development, most of the stable bluffs around Puget Sound were covered with Old Growth climax forest that extended right down to the beaches. These trees were among the earliest to be cut, for they could be readily rafted on the Sound (Maser et al., 1988; Kruckeberg, 1991). While second growth Douglas fir and red alder are now widely distributed on shoreline bluffs, there is probably much greater variation among other trees, shrubs, and groundcover species.

Kruckeberg (pers. comm.) notes that unstable bluffs might favor early pioneering successional species—alder, spiraea, ocean-spray. Crawford, noting the reduced role of fire in bluff communities, suggests fire intolerant, open canopy species such as alder, madrone, and maple are important. Lodgepole pine and blackberry are also common. Site aspect can also be expected to play a key role. A north-facing bluff, for example—moist and shaded year-round—might yield a complex community of mosses and lichens similar to that of Old Growth forest.

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

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

6.4.2 Animal Communities

Stenberg and Miller (pers. comm.) both note that high bluff and cliff habitat values for animals are mostly associated with secure nesting sites for birds. Isolated trees set high on a forested bluff or cliff provide excellent hunting perches and/or nest sites for Bald Eagles and Ospreys. Herons may use similar sites at lower elevations. Depending on substrate, unvegetated cliffs may support cavity nesters such as Pigeon Guillemot, Belted Kingfisher, or even Barn Owls. Isolated rock outcrops and ledges offer secure nest sites for colonial seabirds, as well as other species such as the Black Swift and raptors such as Peregrin Falcon (endangered) and Great Horned Owl.

Speich and Wahl (1989) prepared a *Catalog of Washington Seabird Colonies*. It lists breeding locations for pigeon guillemot, glaucous-winged gull, double-crested cormorant, Brandt's cormorant, pelagic cormorant, black oystercatcher, tufted puffin, rhinoceros auklet. It is comprehensive in its coverage of Puget Sound, islands, and coastal areas.

Washington State Department of Fish and Wildlife, Priority Habitats and Species (PHS) Program (Lea Knutson, Olympia, Washington), is presently preparing a series of habitat management guidelines designed to protect sensitive cliff habitats (see also Puget Sound Water Quality Authority, 1990). (The Priority Habitats and Species Program is identifying cliff and estuary nest, roots, and breeding areas, as well as non-breeding concentrations for: cormorants, storm petrels, common murre, pigeon guillemot, ancient murrelet, Cassins's auklet, rhinoceros auklet, tufted puffin, American white pelican, brown pelican, bald eagle, osprey, peregrine falcon, great blue heron, and band-tailed pigeon among the species that use cliffs, bluffs, and banks. While this is neither comprehensive nor systematic it does present a source of information that is accessible in GIS or map format. (PHS is also mapping other species/habitats including those in and adjacent to Puget Sound. This includes information on waterfowl and shorebird concentration areas, concentrations of loons, grebes, fulmar, shearwater, marbled murrelet, white pelican, brown pelican, brant, swans, and snowy plover.)

sea100285FB.wp5

7.0 Cumulative Ecological Effects

7.1 Definition

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

The cumulative effects of shoreline armoring are probably of most concern to resource managers. Available data indicate that increases in disturbances from contamination and physical modifications of the shoreline have resulted in measurable changes to habitats in Puget Sound (Thom and Hallum, 1990). However, we presently lack an understanding of the linkages between the degree of disturbance and changes in habitat distribution and function. Furthermore, data are lacking to quantitatively link changes in nearshore habitats (that might be affected by armoring) with resultant changes in the numbers and types of fishery resources. Nevertheless, a cumulative impact assessment framework developed for wetlands can be used to begin making these linkages. Gosselink et al. (1990) and Leibowitz et al. (1992) present comprehensive treatments of cumulative impacts on bottomland hardwood forests and wetlands, respectively, that are largely premised on landscape ecology principles.

7.2 Landscape Ecology and Puget Sound Habitats

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

Landscape ecology principles have been used to develop an approach to restoration of urban embayments in Puget Sound (Shreffler and Thom, 1993). A brief summary of the topic is presented in the accompanying **Fact Sheet**. The study shows that factors such as habitat fragmentation, migration corridors, habitat size and shape, buffer areas, and connectance among habitats are important considerations when siting and designing restoration projects. In order for the restored habitat to function optimally, it must be large and homogeneous, accessible, protected from outside disturbances, and within the migratory pathway (corridor) of animal species for which it is intended (McEuen, 1993). Alteration of any factor below some optimal level will result in reduced quality of this habitat for the resource.

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

Of the rural and suburban county shorelines bordering Puget Sound, Thurston County shoreline is among the most extensively armored. As of 1993, approximately 30 percent of the 117 miles of shoreline in the county was armored (Morrison et al., 1993). Thurston County contains primarily gravelly sand beaches fronting steep bluffs, and lowering of the beach elevations—as well as coarsening of substrata—would be predicted due to the armoring. As was discussed for Lincoln Park, coarsening of subtidal sediment may have resulted in a substantial increase in kelp. Lincoln Park shoreline, which includes a steep bluff along 40 percent of its length, is virtually 100 percent armored with a vertical seawall. The change at Lincoln Park from a gravel to a hardpan habitat, with subsequent increases in kelp distribution, could be viewed as alterations that exceed the "threshold point" for that bay. Based on comparisons of surveys made in 1911-12 and 1977, Southern Puget Sound showed the second largest increase in kelp distribution (+332 percent) among all regions of Puget Sound (Figure 7-1). It was second only to the main basin (the area between Tacoma and the southern tip of Whidbey Island) which had an increase of 483 percent in shoreline bordered by kelp beds. The linkage between armoring, sediment composition and kelp distribution requires further study but may prove to be an indicator for cumulative effects of shoreline armoring in the region. The effect on finfish and shellfish in Thurston County is unknown. We would predict a decrease in animals dependent upon intertidal soft substrata and an increase in animals associated with gravel and cobble bottom.

FACT SHEET

Landscape Ecology and Habitat Impacts

Armoring of the shoreline results in the fragmentation and reduction of natural beach landscapes into fewer and fewer smaller pieces. In general, habitat fragmentation is proceeding at an increasing rate worldwide (Weins 1985). The overall effect of fragmentation and habitat shrinkage is less exchange of materials and species among habitats. As fragmentation increases and habitat size shrinks, local populations can become extinct. The principles of landscape ecology present a framework for understanding the effects of shoreline armoring on local populations, and for designing appropriate restoration activities. Excellent written works on the subject of landscape ecology include Forman and Godron (1986), Turner (1989) and Gosselink and Lee (1989). The work of Gosselink and Lee represents perhaps the most comprehensive contribution to the understanding landscape ecology of wetland systems.

Landscape ecology is a relatively new field of science that deals with the effects of spatial extent, heterogeneity, geometry of landscape elements (e.g., animals, plants, nutrients, soils) on the flow of energy, animals, and materials through the landscape (Forman and Godron 1986). Emerging principles indicate that landscapes are heterogeneous matrices of smaller elements (e.g., habitats), and that the arrangement, size, productivity, resilience to disturbance, etc., of these elements within the matrix will affect the flow of energy, animals and materials through the landscape. Most elements within a landscape (e.g., watershed) function best in coordination with all other elements of the landscape, and removal or degradation of one or more elements may lead to dysfunction of the remaining elements. Landscape ecology provides the basis for an approach to cumulative impact assessment developed by the Wetlands Research Program of the U.S. Environmental Protection Agency (Liebowitz, et al 1992). Analysis of cumulative impacts on a landscape scale provides a basis for understanding the relationship between landscape changes, such as fragmentation, and alterations in the populations of biological resources (Gosselink and Lee 1989). This understanding can be used to assess cumulative impacts of shoreline armoring on biological resources in Puget Sound.

Of particular relevance here are the concepts of habitat patch size, shape, and accessibility. For example, certain species prefer habitat edges, whereas other species prefer interiors of habitats. Knowledge of the behavioral patterns of target species or species groups can greatly help in understanding how alteration of beach habitats will affect these species. With regard to aquatic habitat restoration, the National Research Council (1992, pp. 347-348) report concludes that "*Wherever possible . . . restoration of aquatic resources . . . should not be made on a small-scale, short-term, site-by-site basis, but should instead be made to promote the long-term sustainability of all aquatic resources in the landscape.*"

Some of the more relevant principles of landscape ecology that apply to shoreline armoring are as follows:

Scale: Landscapes vary widely in scale from a few to hundreds of km^2. It is important to note that the scale at which humans perceive boundaries and patches in the landscape may have little relevance to the real flows of energy and materials. Hence, investigations of these aspects may be required to determine the appropriate scale at which to assess effects. A well established relationship based upon island biogeography (MacArthur and Wilson 1967), S = cAz, between number of species (S) and habitat area (A) has been used to predict the effect of habitat fragmentation on species in reserves. It has been shown that, in general, a loss of 90 percent of the habitat area will result in a 50 percent reduction in number of species. Hence, larger reserves are better than small ones in maintaining high numbers of species.

Structure: Landscapes can basically be divided into matrices of patches and corridors. A matrix is the surrounding area within which a patch occurs, and represents the most extensive and most connected landscape element. The matrix, therefore, plays a dominant role in the functioning of the landscape. It is well established that the number of species within a patch is a function of a number of factors including patch area, within-patch heterogeneity, disturbance patterns, degree of isolation from sources of species, patch age, and the matrix heterogeneity. Is there an optimal structure for selected target species groups?

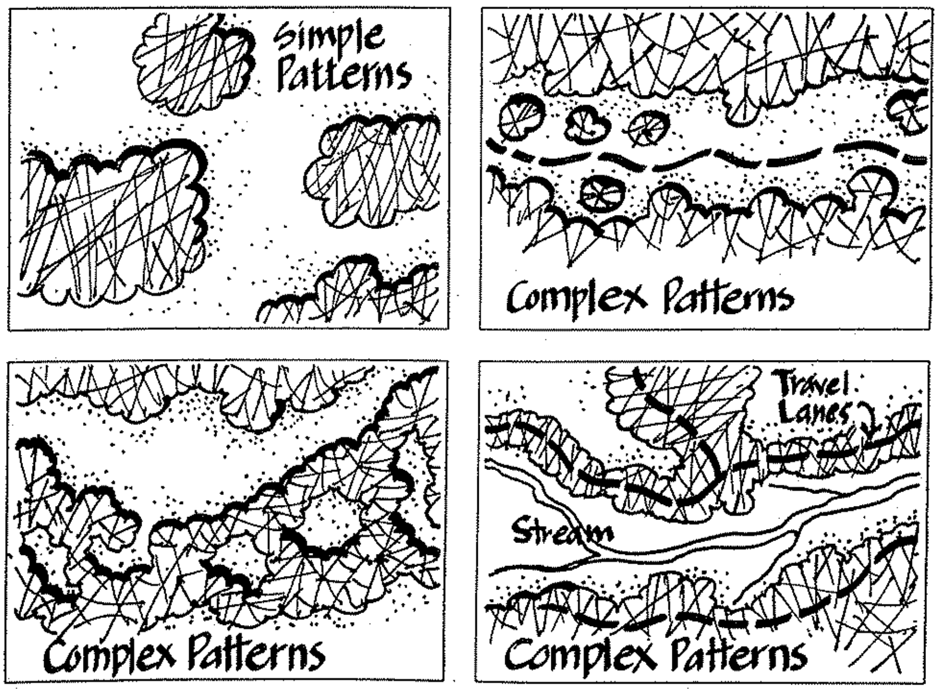
Shape: The shape of a patch or contiguous habitat affects the types and number of species in the patch. Species show preferences for edges or interiors of patches. Round patches have a large interior to edge ratio as compared to very narrow linear patches. Small patches may act as edges depending upon the size of the animal potentially occupying the patch. The number of "edge" species or "interior" species in a patch will be dependent to a certain extent on this ratio. Processes such as benthic productivity and nutrient flux will be dependent upon patch shape

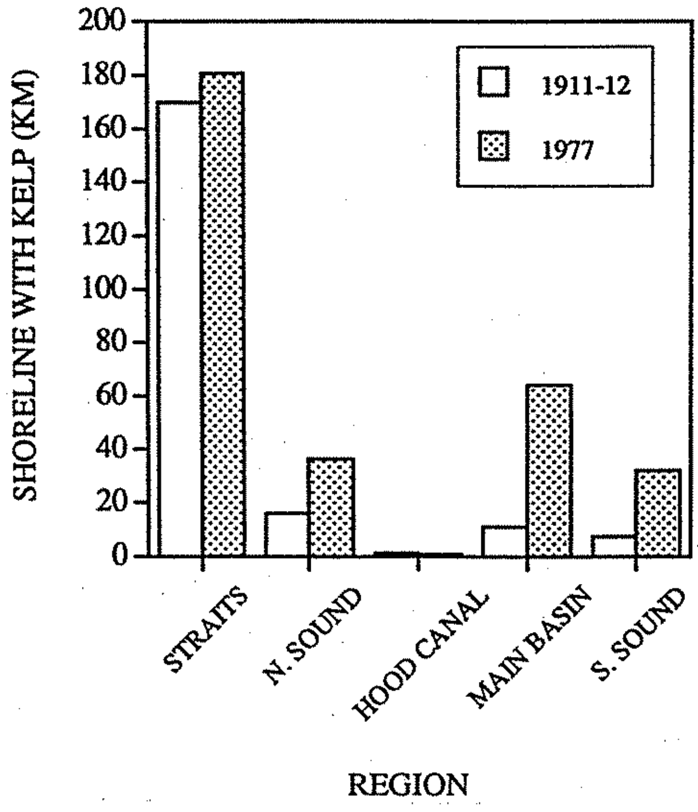
Number of Patches and Configuration: In general, single large patches contain more species than several smaller patches within a matrix. However, more species are found in several patches if the patches are widely separated, due to adaptation by species to somewhat unique environments associated with each individual patch. The density of patches within a matrix is termed the matrix porosity. The arrangement of patches is called the network. Flow of material and animals among patches is dependent upon the density of patches, arrangement of patches and other factors that pose an impediment to movement.

Corridors: A corridor is a strip of habitat that differs from the habitats on either side. Corridors form very important routes of migration for many species. Corridors represent a more or less protected route of ingress and egress to habitats. Relative to shoreline armoring impacts, corridors between sources of species and the habitats they utilize are critical. Corridors may also function as habitat for some species; they can also function as barriers or filters (e.g., riparian buffer zones).

Disturbance and Stability: Landscapes change naturally with time. The long-term viability of a habitat is dependent upon a variety of factors inherent to the habitat including stability, persistence, resistance, and resilience. The term stability refers to systems that essentially show no long-term variability (i.e., tendency to move to another type of system). Persistence refers to the time period during which a certain characteristic of the landscape continues to be present. Resistance and resilience mean, respectively, the ability of the system to withstand and recover from disturbances. In general, an important habitat within a system is one that is relatively stable, persistent, resistant and resilient.

(Shreffler and Thom, 1993)





Source: Thom and Hallum (1990)

Figure 7-1
Regional Changes in Kelp Habitat 1911-1977

of armored shoreline by 1977 versus change in kelp distribution provides a simple example of how such a calculation might be made. Assuming that armoring is solely responsible for increasing kelp distribution, the rate of conversion would be 24.6 km increase in kelp in southern Puget Sound (Thom and Hallum, 1990) during a period when 25.0 km of shoreline was armored (Morrison et al., 1993). The ratio is about 1:1 for kelp to armored shore. At Lincoln Park, armoring of 792 m of beach immediately seaward of the bluff was associated with an increase in kelp of approximately 420 m, for a ratio of approximately 0.5:1.0 (kelp:armoring). Clearly, several assumptions must be verified, and the calculation must be carried out for other resources and habitats, to further evaluate this approach for quantifying cumulative impacts.

The Habitat Assessment Protocol (HAP, see accompanying **Fact Sheet** and Table 7-1) was used by Shreffler and Thom (1993) to define the incremental effect of adding new habitats to an estuarine system, on the total number of species that provide key supporting functions in that system. The results of the analysis are shown in Figure 7-2. This figure illustrates that the number of species identified as providing key supporting functions in the total system increases when increasing numbers of habitat types are added. Because the habitats are used for a variety of reasons depending upon the species (e.g., spawning, feeding, rearing, resting), a species may occur in a system that does not contain *all* of the habitats it is associated with. However, such a system is less than optimal for this species. For example, herring may be found feeding in an embayment that contains no macroscopic vegetation. However, in order for the embayment to serve as herring spawning habitat, some macroscopic vegetation (e.g., eelgrass) is required. The HAP contains perhaps the strongest set of data linking Puget Sound's 105 most common estuarine species to specific habitats (Table 7-1). Thus, it provides a robust method for assessing the potential effects of habitat losses on the ability of a particular system to support these species.

Based upon Figure 7-2, a loss of emergent marsh, eelgrass, and subtidal soft bottom—directly or indirectly related to cumulative shoreline armoring—would result in the loss of a large number of species from the system. Shreffler and Thom (1993), however, noted that near-optimal conditions must exist in the system in order for the entire compliment of species to be present and fully benefit from the system. These conditions include an adequate source of species, corridors, water and sediment quality, buffer areas, habitat size, habitat maturity, and appropriate hydrogeomorphology. Habitat degradation or suboptimal conditions would limit the quality of the system for each of the species. Use of the HAP for this purpose remains semiquantitative. Modeling of cumulative impacts requires *quantification of links* between habitat "quality" and biological resource use.

Cumulative effects of shoreline armoring on habitat functions *other than* resource support are not quantified. Changing longshore drift velocities and lowering of the beach profile would alter organic deposition on beaches. The process of nutrient flux from sediments would also be altered. However, the overall cumulative effects of armoring on the system as a whole are not predictable at present.

FACT SHEET

Estuarine Habitat Assessment Protocol

Puget Sound Estuary Program

The Estuarine Habitat Assessment Protocol (Protocol; Simenstad et al. 1991) was developed to provide sampling methods for assessing the ecological performance of estuarine habitat mitigation and restoration projects. Protocol development was driven by the need to develop systematic data bases on constructed or restored systems that could be used to help predict the outcome of future projects. The Protocol describes target assemblages and identifies habitats where these assemblages occur. It also outlines methods for sampling selected parameters. The most pertinent aspect of the Protocol for the present work is the fact that assemblages and habitat requirements were identified through a rigorous and extensive process involving published literature, empirical data, and opinions from approximately 180 specialists in the Puget Sound region. The Protocol represents the most comprehensive compendium of habitat vs. species information available for estuaries in the Puget Sound basin, and it may be useful for trying to predict the biological effects of shoreline armoring.

The Protocol assesses attributes of estuarine habitats that promote fish and wildlife utilization and ". . . the potential to provide a specific function which . . . provides design criteria for habitat restoration" (Simenstad et al. 1991, page vii). The Protocol species list includes representative species for each estuarine habitat type. These 105 total species were selected primarily because they are believed to comprise important functional groups (assemblages) within the habitats, and secondarily because a relatively large amount of information was available on these species. The protocol species list is presented in Table 7-1.

The Protocol species list can be used in predicting the impacts of shoreline armoring in the following way. First, the arrangement of habitat types, which approximates a gradient from upland freshwater through the estuary to open water, can be used to indicate the effect of altering or eliminating habitats because of shoreline armoring. For example, gravel-cobble substrate provides for the greatest number of species, and subtidal hard substrate the least.

Emergent marsh habitats contain the largest number of unique species (i.e., those not found in the list for the other habitats), and mudflats the least. Unique species may occur in the other habitats but may not be prominent or contribute to the functionality of the habitat. The types of habitats eliminated by shoreline armoring will determine the number of species eliminated depending on the number of species unique to each habitat.

Table 7-1 indicates the overlap in species groups among habitats, and can be useful in predicting the types of organisms that would be favored by various mixtures of habitats. For example, emergent marsh alone supports 38 species. Adding an adjacent mudflat should predictably add six more species, and integrating a gravel patch is predicted to add another 21 species. The Protocol assumes that, if habitats are built, species will occupy or otherwise utilize and benefit from the habitats. This assumption can only be met if:

- adequate sources of species (i.e., local species pool) exist,
- corridors of access are suitable,
- water and sediment quality does not impair use,
- adequate buffer areas are incorporated,
- habitats are large enough,
- habitats are "mature" enough to provide benefit to the species that do occupy the habitats (mature means that there is adequate plant density and size, and the habitat is stable over time), and
- habitat mixtures are appropriate to the hydrogeomorphology at the site.

In contrast, if habitats are altered or lost because of human impacts such as shoreline armoring, the Protocol could theoretically be used to determine the number and types of species that will be affected. Use of the Protocol as a tool for predicting the effects of shoreline armoring on estuarine biota has not been tested to date.

Simenstad et al. (1991) summarized in Shreffler and Thom (1993)

Table 7-1
Protocol-Based Species versus Habitat Matrix

(Shaded cells indicate most common occurence/use [1])

NO.	GROUP	SPECIES	EMER. MARSH	MUDFLAT	SANDFLAT	GRAV.-COB.	EELGR.	SUBT. SOFT	SUBT. HARD	WAT. COL.
1	Birds	American coot	X							
2	Birds	American goldfinch	X							
3	Birds	American wigeon	X							
4	Birds	black brant	X			X	X			
5	Birds	black turnstone				X				
6	Birds	bufflehead	X	X		X	X			X
7	Birds	Canada goose	X	X			X			
8	Birds	cassins auklet								X
9	Birds	common goldeneye	X	X	X	X				X
10	Birds	common merganser								X
11	Birds	common murre						X		
12	Birds	common snipe	X	X	X		X			
13	Birds	dark-eyed junco	X							
14	Birds	double-crested cormorant				X				X
15	Birds	dunlin		X	X					
16	Birds	gadwall	X							X
17	Birds	glaucous-winged gull					X			
18	Birds	great blue heron	X	X	X		X			
19	Birds	greater yellowlegs	X	X	X		X			
20	Birds	green-winged teal	X							
21	Birds	horned grebe			X	X				
22	Birds	killdeer	X							
23	Birds	least sandpiper	X	X	X	X	X			
24	Birds	mallard	X							
25	Birds	merlin	X							
26	Birds	mew gull				X				X
27	Birds	northern oriole	X							
28	Birds	osprey	X				X			X
29	Birds	red-breasted merganser								X
30	Birds	red-tailed hawk	X							
31	Birds	redwing blackbird	X							
32	Birds	savannah sparrow	X							
33	Birds	short-billed dowitcher	X	X						
34	Birds	short-eared owl	X							
35	Birds	song sparrow	X							
36	Birds	spotted sandpiper	X	X	X	X	X			
37	Birds	Virginia rail	X							
38	Birds	western grebe				X				X
39	Birds	western sandpiper	X	X						
40	Fish	bay goby		X	X					
41	Fish	bay pipefish					X			
42	Fish	black rockfish							X	
43	Fish	brown rockfish							X	
44	Fish	buffalo sculpin				X				
45	Fish	cabezon							X	

Table 7-1 (continued)

Protocol-Based Species versus Habitat Matrix

(Shaded cells indicate most common occurence/use [1])

NO.	GROUP	SPECIES	EMER. MARSH	MUDFLAT	SANDFLAT	GRAV.-COB.	EELGR.	SUBT. SOFT	SUBT. HARD	WAT. COL.
46	Fish	chinook salmon								
47	Fish	chum salmon								
48	Fish	coho salmon								
49	Fish	copper rockfish								
50	Fish	c-o sole								
51	Fish	crescent gunnel								
52	Fish	cutthroat trout								
53	Fish	dolly varden								
54	Fish	Dover sole								
55	Fish	English sole								
56	Fish	great sculpin								
57	Fish	green sturgeon								
58	Fish	hybrid sole								
59	Fish	kelp greenling								
60	Fish	kelp perch								
61	Fish	largescale sucker								
62	Fish	lingcod								
63	Fish	mountain whitefish								
64	Fish	northern anchovy								
65	Fish	northern squawfish								
66	Fish	Pacific cod								
67	Fish	Pacific hake								
68	Fish	Pacific herring								
69	Fish	Pacific sandlance								
70	Fish	Pacific sanddab								
71	Fish	Pacific staghorn sculpin								
72	Fish	Pacific tomcod								
73	Fish	padded sculpin								
74	Fish	penpoint gunnel								
75	Fish	pile perch								
76	Fish	pink samon								
77	Fish	quillback rockfish								
78	Fish	ratfish								
79	Fish	river lamprey								
80	Fish	rock sole								
81	Fish	rough sculpin								
82	Fish	sand sole								
83	Fish	shiner perch								
84	Fish	snake prickleback								
85	Fish	soft sculpin								
86	Fish	speckled sanddab								
87	Fish	starry flounder								
88	Fish	steelhead								
89	Fish	striped seaperch								
90	Fish	sturgeon poacher								

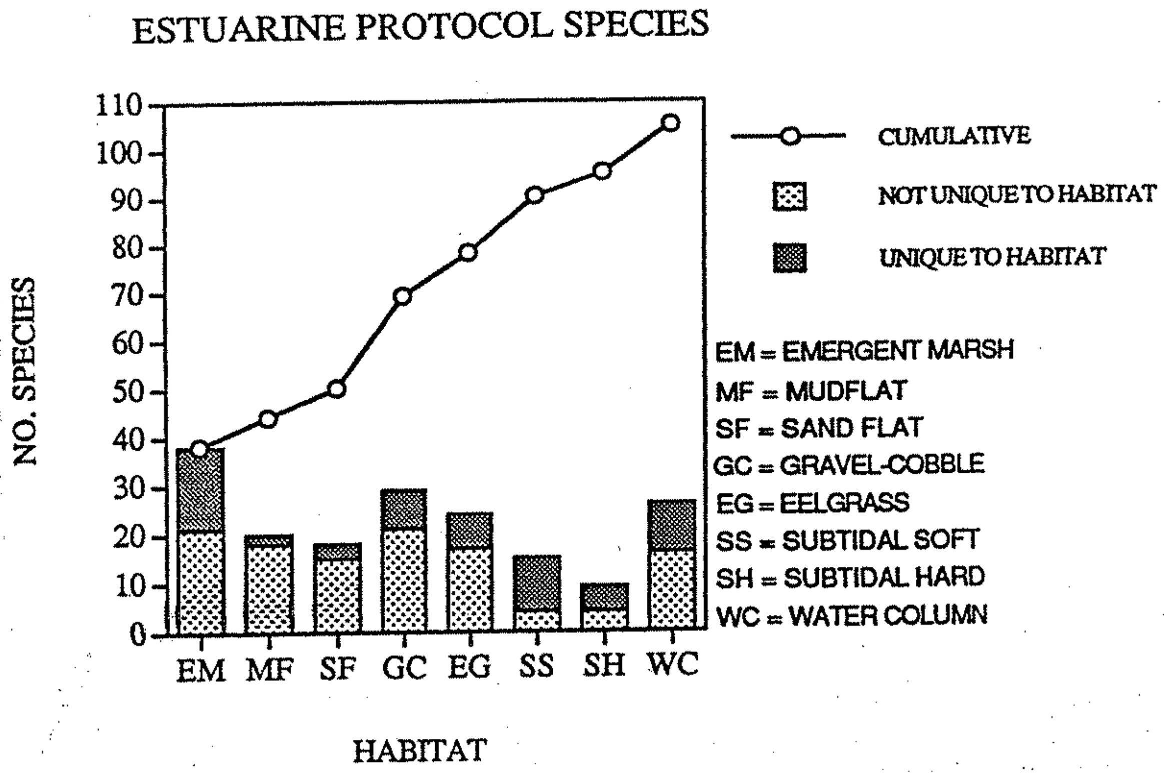
Table 7-1 (continued)

Protocol-Based Species versus Habitat Matrix

(Shaded cells indicate most common occurence/use [1])

NO.	GROUP	SPECIES	EMER. MARSH	MUDFLAT	SANDFLAT	GRAV.-COB.	EELGR.	SUBT. SOFT	SUBT. HARD	WAT. COL.
91	Fish	surf smelt								
92	Fish	threespine stickleback								
93	Fish	tubesnout								
94	Fish	walleye pollock								
95	Fish	western brook lamprey								
96	Fish	whitespotted greenling								
97	Invertebrate	Dungeness crab								
98	Invertebrate	red rock crab								
99	Mammal	gray whale								
100	Mammal	muskrat								
101	Mammal	northern sea lion								
102	Mammal	Pacific harbor seal								
103	Mammal	raccoon								
104	Mammal	river otter								
105	Mammal	Townsend vole								

[1] Simenstad et al (1991), Shreffler and Thom (1993)



Source: Simenstad et al. (1991)

Figure 7-2
Cumulative Species Gained as Estuarine Habitats Added

8.0 Conclusions and Research Needs

8.1 Summary of Conclusions

There is ample evidence illustrating various effects of shoreline armoring on the physical structure of Puget Sound's beaches. Changes in physical structure include loss of shade, reduction in leaf fall, lowering of beach profiles, coarsening of beach sediment, narrowing of the beach, and alteration of groundwater flows. Ecological effects associated with these physical changes are presently poorly understood in Puget Sound and are not well documented anywhere in the United States. Based upon the critical links between physical conditions and habitats, and links between habitats and biological resources, conclusions can be drawn about potential effects of armoring on the ecology of beaches and resource species (Table 8-1). These conclusions are verified by numerous general anecdotal observations and by field data collected from a small number of specific beaches.

The conclusions are as follows:

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

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

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

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

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

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

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

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

Table 8-1
Resource Species Armoring Effects Summary

RESOURCE SPECIES	ARMORING EFFECTS: Armoring-related Habitat Shift [1]	Loss of Spawning Habitat	Loss of Shoreline Riparian Vegetation	Loss of Wetland Vegetation	Loss of Large Organic Debris	Changes in Food Resources	Loss of Migratory Corridors
Surf Smelt	●	●	●		◍		
Pacific Sand Lance	●	●	●		◍		
Rock Sole	●	●	●		◍		
Juvenile Salmonids [2]	●		●	●	●	●	●
Pacific Herring	◍	◍					
Hardshell Clams [2]	●	◍ [3]				●	
Geoduck	○						
Oysters	○	○				○	
Dungeness Crab	◍	◍ [3]				◍	
Sea Cucumber	○					○	
Sea Urchins	○					○	

Key

● Well documented evidence of negative effects.

◍ High potential for negative effects but not documented.

○ Some potential for longterm effects but not documented.

Footnotes

[1] Includes coarsening of substrate, changes in benthic vegetation, changes in primary production and nutrient flow, potential net loss of organic matter and shading.

[2] Multiple species.

[3] Loss of habitat for settlement.

9. It is not presently possible to *quantitatively* predict the effects of shoreline armoring on the ecology of beaches or the biological resources they support. However, simple calculations based upon very limited data indicate an approximately 1:1 alteration of habitat distribution associated with the length of armored shoreline—i.e., bulkheading 10 percent of the shoreline will result in alteration of 10 percent of the beach and shallow offshore habitat.

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

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

8.2 Research Needs

Reviewing this report Neil Rickard (WDFW, pers. comm.) expressed concern about data gaps that must be still filled to gain an understanding of the individual and cumulative biological and ecological effects of shoreline armoring. A partial list of additional research/informational needs includes: 1) the historic and current areas of specific habitats available (e.g., surf smelt spawning habitat, intertidal wetland vegetation), 2) the areas of these habitats adversely affected by various armoring techniques, 3) the biological and ecological effects of armoring: a) from various armoring techniques, b) depending on the extent of encroachment on the beach, and c) relative to the location of the armoring structure within a drift sector.

We believe there are three additional fundamental areas that require research to better understand and predict the effects of shoreline armoring on the ecology of Puget Sound beaches. These include: (1) systematic studies of existing sites, (2) experimental studies to evaluate new or unique technologies, and (3) cumulative impact model development.

8.2.1 Systematic Studies of Existing Sites

There is a paucity of data that document the before and after effects of shoreline armoring on the ecology of Puget Sound's beaches. Virtually all of the information available is from qualitative observations by biologists familiar with beaches, and who have made observations over a wide area for a long period of time. The data on physical changes are somewhat better known and quantified, and there is at least a qualitative link between physical conditions on a beach and the habitats, resources and processes that the beach supports. A systematic study that evaluates factors—including physical conditions of the beach, habitat quantity and quality, resource use and several other factors—in areas that are armored, and adjacent areas not affected by armoring would advance understanding dramatically. Ecology did begin such monitoring studies in 1990 in conjunction with Western Washington University. Funding cuts, however, prevented the programs from being carried forward. Availability of such data would also link physical conditions in Puget Sound directly with beach habitat structure and function, which is required to directly assess effects of shoreline alterations on the beach.

8.2.2 Experimental Studies to Evaluate New or Unique Technologies

Although not the subject of this report, an earlier report (Cox et al., 1993) evaluated a variety of potential armoring technologies for their effectiveness and suitability in the range of beach types found in Puget Sound. Some of these methods, such as *headland and pocket beach systems, shoreline vegetation enhancement,* and even *breakwaters* may impact the beach ecosystem less than the present widely used armoring methods. These technologies should be subjected to further analysis relative to their effectiveness in Puget Sound, along with their ability to minimize ecological impacts.

8.2.3 Cumulative Impact Model Development

Agency personnel and others were adamant regarding the need for a tool that predicts the cumulative impact of potential armoring on beach ecosystems. To this end, there are useful concepts borrowed from Island Biogeography (MacArthur and Wilson, 1967) and landscape ecology (Forman and Godron, 1986) that may be applicable to assessing cumulative ecological impacts to Puget Sound beaches from armoring. The recent approach developed by the EPA's Corvallis Environmental Research Laboratory (Leibowitz et al., 1992), which uses a synoptic approach to cumulative wetland impact assessments, is worthy of evaluation in this regard.

The Habitat Assessment Protocol (HAP) developed for Puget Sound habitats may offer the most accurate and relevant model presently available (Simenstad et al., 1991; Shreffler and Thom, 1993). It is generally established that the number of species occupying an area is a function of +habitat diversity, -disturbance, +area, -isolation, and +age (Forman and Godron, 1986). The signs preceding the factors relate to the positive or negative influence of the factor on number of species. Habitat diversity, area, isolation and age can be quantified relatively easily for most systems. Degree of disturbance can involve a large variety of disturbance types and is less well represented by a single value. However, a "relative index of disturbance" can be established and used for the purposes of the model. Using the HAP, if all of the habitats are contained in a particular embayment—and all of the assumptions are satisfied for optimal habitat quality (e.g., area, low disturbance, low isolation, mature age)—then all of the 105 Protocol species will predictably occur in the embayment system. Rarely is this the case, however. Typically, a beach functions best for a subset of species. As the values for optimal habitat quality factors change with increasing shoreline armoring along a beach, the number of species would change also. The *rate of change* would depend upon the individual habitat requirements of the species within the system.

The rate of change would not be expected to be linear, rather there would be a point at which the rate change would indicate a "threshold."

The HAP was developed based upon data on habitat requirements for all of the species, and could be a comprehensive source of information for quantifying these requirements. A more practical approach might be to focus assessments of cumulative impacts using a small subset of "indicator species." These species could include commercially valuable fish species as well as noncommercial, but ecologically important, waterfowl species. The approach would then be to establish how the abundance of (or degree of use by) each of these selected indicator species varies according to habitat diversity, disturbance, area, isolation, and habitat age. Using this model, physical beach alterations caused by armoring could first be used to predict habitat changes; then the habitat changes could be used to predict changes in the abundance of the selected species.

A note of caution must be added in closing however. Studies available to date indicate there is no simple cumulative impact formula or "cook-book" approach that can be easily applied to assess shoreline armoring impacts. The issue is a complex one and in many cases the necessary background and supporting data are simply not available.

sea10028625.wp5

9.0 References Cited

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

Andrus, C.W., B.A. Long, and H.A. Froehlich. 1988. "Woody Debris and its Contribution to Pool Formation in a Coastal Stream 50 Years after Logging." *Can. J. Fish. Aquat. Sci.* 45: 2080-2086.

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

Antrim, L.D., R.M. Thom, and W.W. Gardiner. 1993. Lincoln Park Shoreline Erosion Control Project: Monitoring for Surface Substrate, Infaunal Bivalves and Eelgrass, 1993. Final Report Prepared for U.S. Army Corps of Engineers, Seattle District. Battelle Pacific Northwest Laboratory, Richland, Washington.

Armstrong, D.A., J.L. Armstrong, and P.A. Dinnel. 1987. Ecology and Population Dynamics of Dungeness Crab, *Cancer magister* in Ship Harbor, Anacortes, Washington. Final report for Leeward Development Co. and Washington Department of Fisheries by School of Fisheries, University of Washington, Seattle, Washington. FRI-UW-8701: 79 pp.

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

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

Atwater, B.F., and A.L Moore. 1992. A Tsunami About 1000 Years Ago in Puget Sound, Washington. Science 258:1614-1617.

Baldwin, J.R., and J.R. Lovvorn. 1992. "Populations, Diet, Food Availability and Food Requirements of Dabbling Ducks in Boundary Bay." In R.W. Butler (ed). Abundance, Distribution, and Conservation of Birds in the Vicinity of Boundary Bay, British Columbia. pp. 42-69. *Can. Wildl. Serv. Tech. Rep. Ser.* 155.

Bax, N.J. 1983. The early marine migration of juvenile chum salmon (*Oncorhynchus keta*) through Hood Canal—Its variability and consequences. Ph.D. dissertation, University of Washington, Seattle, Washington.

Bayer, R.D. 1980. Birds Feeding on Herring Eggs at the Yaquina Estuary, Oregon. *Condor* 82:193-198.

Beale, H. 1990. Relative Rise in Sea-Level During the Past 5000 Years at Six Salt Marshes in Northern Puget Sound, Washington. Final Report Prepared for Washington State Department of Ecology, Olympia, Washington.

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

Beschta, R.L. 1991. "Stream Habitat Management for Fish in the Northwestern United States: The Role of Riparian Vegetation." Amer. Fish. Soc. Symp., 10:53-58.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. "Stream temperature and aquatic habitat: fisheries and forestry interaction." pp. 191-232 in Salo and T.W. Cundy (eds). Streamside Management: Forestry and Fishery Interactions. University of Washington, Institute of Forest Resources Contribution 57, Seattle, Washington.

Bilby, R.E., and J.W. Ward. 1991. "Large Woody Debris Characteristics in Streams Draining Old-Growth, Clear-Cut, and Second-Growth Forests in Southwestern Washington." *Can. J. Fish. Aquat. Sci.* 48: 2499-2508.

Bisson, P.A., and J.R. Sedell. 1984. "Salmonid Populations in Streams in Clearcut vs. Old-Growth Forests of Western Washington." pp. 121-129 in W.R. Meehan, T.R. Merrell, Jr, and T.A. Henley (eds). Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a Symposium. American Institute of Fishery Biologists, Moorehead City, North Carolina.

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

Blomberg, G., C. Simenstad, and P. Hickey. 1988. "Changes in Duwamish Estuary Habitat Over the Past 125 years." pp. 437-454 in Proceedings First Annual Meeting on Puget Sound Research, Vol. 2. Puget Sound Water Quality Authority, Seattle, Washington.

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

Boulé, M.E., N. Olmsted, and T. Miller. 1983. "Inventory of Wetland Resources and Evaluation of Wetland Management in Western Washington." Final Report to Washington State Department of Ecology, Olympia, Washington. 102 p.

Bradbury, A. 1990. Management of the Commercial Dive Fisheries for Sea Urchins and Sea Cucumbers. pp. 56-65 in, Armstrong, J.W. and A.E. Copping (eds). Status and Management of Puget Sound's Biological Resources. U.S. Environmental Protection Agency, Seattle, Washington. EPA 910/9-90-001.

Brennan, L.A., J.B. Buchanan, S.G. Herman, and T.M. Johnson. 1985. "Interhabitat Movements of Wintering Dunlins in Western Washington." *Murrelet* 66:11-16.

Britsch, L.D., and E.B. Kemp III. 1990. Land loss rates: Mississippi River Deltaic Plain. U.S. Army Engineer District, New Orleans, Louisiana, Technical Report GL-90-2.

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

Bryant, M.D. 1983. "The Role and Management of Woody Debris in West Coast Salmonid Nursery Streams." *North Am. J. Fish. Mgmt.* 3:322-330.

Bucknam, R.C., E. Hemphill-Haley, and E. Leopold. 1992. Abrupt Uplift Within the Past 1700 Years at Southern Puget Sound, Washington. *Science* 258:1611-1614.

Burton, B.A. 1977. Some Aspects of the Ecology of the Lesser Snow Geese Wintering on the Fraser River Estuary. M.S. Thesis, Univ. British Columbia, Vancouver, British Columbia.

Butler, R.W., N.K. Dawe, and D.E.C. Tretheway. 1989. "The Birds of Estuaries and Beaches in the Strait of Georgia." In K. Vermeer and R. W. Butler (ed). The Ecology and Status of Marine and Nearshore Birds in the Strait of Georgia, British Columbia. Pp. 142-147. *Spec. Publ. Can. Widl. Serv.*, Ottawa.

Butler, R.W. 1991. Habitat Selection and Time of Breeding in the Great Blue Heron (Ardea herodias). Ph.D. Thesis, University of British Columbia, Vancouver, British Columbia.

Canning, D.J., and H. Shipman. 1993. Washington State Coastal Erosion Management Strategy. Coastal Zone 93, New Orleans, Louisiana.

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

Couch, A.B. 1966. Feeding Ecology of Four Species of Sandpipers in Western Washington. M.S. Thesis, University of Washington, Seattle, Washington.

Cox, J., K.B. Macdonald, and T. Rigert. 1993. Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound. Preliminary Report Prepared by CH2M HILL for Washington State Department of Ecology, Olympia, Washington.

Culliton, T.J., J.J. McDonough III, D.G. Remer, and D.M. Lott. 1992. Building Along America's Coasts. National Oceanographic and Atmospheric Administration, Rockville, Maryland.

Dethier, M.D. 1990. A Marine and Estuarine Habitat Classification System for Washington State. Washington Natural Heritage Program, Department of Natural Resources, Olympia, Washington.

Dinnel, P.A., J.L. Armstrong, and R.O., McMillan. 1982. Evidence for Multiple Recruitment-Cohorts of Puget Sound Dungenes Crab. *Cancer Magister. Mar. Biol.* 115: 53-63.

Dinnel, P.A., D.A. Armstrong, and R.O. McMillan. 1986. Dungeness Crab, *Cancer Magister*, Distribution, Recruitment, Growth, and Habitat Use in Lummi Bay, Washington. Final report to Lummi Indian Tribe by Fish. Res. Institute, University of Washington, Seattle, Washington. FRI-UW-8612: 61 pp.

Dinnel, P.A., et al. 1987. Padilla Bay Dungeness Crab, *Cancer Magister*, Habitat Study. Final Report for NOAA/Division of Marine and Estuarine Management and U.S. Environmental Protection Agency of Fish. Res. Institute, University of Washington, Seattle, Washington. FRI-UW-8704: 78 pp.

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

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

Dumbauld, B.R., D.A. Armstrong, and T.L. McDonald. 1993. Use of Oyster Shell to Enhance Intertidal Habitat and Mitigate Loss of Dungeness Crab (*Cancer magister*) Caused by Dredging. Can. J. Fisheries Aquat. Sci. 50:381-390.

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

Eilers, H.P. 1975. Plants, Plant Communities, Net Production and Tide Levels: The Ecological Biogeography of the Nehalem Salt Marshes, Tillamook County, Oregon. Ph.D. Thesis, Oregon State Univ., Corvallis, OR.

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

Fresh, K.L., R.D. Cardwell, and R. Koons. 1981. Food habits of Pacific salmon, baitfish, and their potential competitors and predators in the marine waters of Washington, August 1978 to September 1979. Washington Department of Fisheries. Progress Report No. 145. 58 pp.

Garbisch, E., and J. Garbisch. 1994. "The Effects of Forests Along Eroding Shoreline Banks of the Chesapeake Bay." Environmental Concern, Inc., *Wetland Journal*. 6(1):18-19 (Winter 1994). St. Michaels, Maryland.

Gardiner, W.W. 1992. Sea Surface Films: Deposition and Contamination in Intertidal Habitats. Master's Thesis, Western Washington Univ., Bellingham, Washington.

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

Giblin, A.E. and A.G. Gaines. 1990. Nitrogen imputs to a marine embayment: the importance of groundwater. *Biogeochemistry*. 10: 309-328.

Gonor, J.J., J.R. Sedell, and P.A. Benner. 1988. What We Know About Large Trees in Estuaries, in the Sea, and on Coastal Beaches. Chapter 4, pp. 83-150 in, C. Maser, R.F. Tarrant, J.M. Trappe, and J.F. Franklin (eds). From the Forest to the Sea: A Story of Fallen Trees. U.S. Department of Agriculture, Forest Service, Portland, Oregon. General Tech. Rep. PNW-GTR-229.

Goodwin, L. 1990. Commercial Geoduck Dive Fishery. pp. 24-31 in, Armstrong, J.W. and A.E. Copping (eds). Status and Management of Puget Sound's Biological Resources. U.S. Environmental Protection Agency, Seattle, Washington. EPA 910/9-90-001.

Gosselink, J.G., and L.C. Lee. 1989. Cumulative Impact Assessment in Bottomland Hardwood Forests. *Wetlands*. 9:89-174.

Goselink, J.G., L.C. Lee, and T.A. Muir (eds). 1990. Ecological Processes and Cumulative Impacts. Lewis Publishers, Chelsea, Michigan.

Grant, J., C.T. Enright, and A. Griswold. 1990. Resuspension and Growth of *Ostrea edulis*: a Field Experiment. *Marine Biol.* 104:51-59.

Grette, G.B. 1985. "The Role of Large Organic Debris in Juvenile Salmonid Rearing Habitat in Small Streams." M.S. Thesis, School of Fisheries, University of Washington, Seattle, Washington.

Haegele, C.W., and J.F. Schweigert. 1985. "Distribution and Characteristics of Herring Spawning Grounds and Description of Spawning Behavior. " *Can. J. Fish. Aquat. Sci.* 42(Suppl. 1): 39-55.

Healey, M.C. 1979. "Detritus and Juvenile Salmon Production in the Nanaimo Estuary: I. Production and Feeding Rates of Juvenile Chum Salmon (*Oncorhynchus keta*)." *J. Fish Res. Board Can.* 36: 488-496.

Healey, M.C. 1982. "Juvenile Pacific Salmon in Estuaries: the Life Support System." p. 315-341 in V.S. Kennedy (ed). Estuarine Comparisons. Academic Press, New York, New York.

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

Hicks, B.J. 1990. The Influence of Geology and Timber Harvest on Channel Geomorphology and Salmonid Populations in Oregon Coast Range streams. Ph.D. Dissertation. Oregon State University, Corvallis, Oregon.

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

Hiss, J.M., S.R. Hager, J.L. Schroeder, and E.E. Knudsen. 1990. Impact of Beach Gravel Enhancement on Epibenthic Zooplankton at Lincoln Park, Seattle, Washington. U.S. Fish and Wildlife Service, Fisheries Assistance Office, Olympia, Washington.

Hourston, A.S. 1982. "Homing by Canada's West Coast Herring to Management Units and Divisions as Indicated by Tag Recoveries." *Can. J. Fish. Aquat. Sci.* 39: 1414-1422.

Jamison, D.W., and D. Weitkamp. 1992. Unpublished Manuscript. Avail. from D.W. Jamison, Washington State Department of Natural Resources, Olympia, Washington.

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

Kahl, R. 1991. "Boating Disturbance of Canvasbacks During Migration at Lake Poygan, Wisconsin." *Wildl Soc. Bull.* 19: 242-248.

Klarin, P.N., K.M. Branch, M.J. Hershman, and T.F. Grant. 1990. An Analytical Review of State and Federal Coastal Management Systems and Policy Responses to Sea Level Rise. Report to Washington State Department of Ecology, Olympia, Washington.

Knudsen, E.E., and S.J. Dilley. 1987. "Effects of Riprap Bank Reinforcement on Juvenile Salmonids in Four Western Washington Streams." *North American Journal of Fisheries Management* 7:351-356.

Kruckeberg, A.R. 1991. The Natural History of Puget Sound Country. University of Washington Press, Seattle. 468 pp.

Leibowitz, S.G., B. Abbruzzese, P.R. Adamus, L.E. Hughes, and J.Y. Irish. 1992. A Synoptic Approach to Cumulative Impact Assessment. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR. EPA/600/R-92/167.

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

Levy, D.A. and T.G. Northcote. 1982. Juvenile salmon residency in a marsh area of the Fraser River estuary. *Can. J. Fish. Aquat. Sci.* 39: 270-276.

Levy, D.A., T.G. Northcote, K.J. Hall, and I. Yesaki. 1989. Juvenile salmon responses to log storage in littoral habitats of the Fraser River estuary and Babine Lake pp. 82-91 in C.D. Levings, L.B. Holtby, and M.A. Henderson (eds.,) Proc. Natl. Workshop, Effects of Habitat Alteration on Salmonid Stocks. *Can. Spec. Publ. Fish. Aquat. Sci.* 105. 199 pp.

Li, H.W., C.B. Schreck, and R.A. Tubb. 1984. "Comparison of Habitats Near Spur Dikes, Continuous Revetments, and Natural Banks for Larval, Juvenile, and Adult Fishes of the Willamette River." Water Resources Research Institute WRRI-95, Oregon State University, Corvallis, Oregon.

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

Macdonald, K.B., D. Simpson, B. Paulson, J. Cox, and J. Gendron. 1993. Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound. Preliminary Report Prepared by CH2M HILL for Washington State Department of Ecology, Olympia, Washington.

Macdonald, K.B., and B. Witek. 1994. Management of Unstable Shoreline Slopes in Puget Sound. Prepared by CH2M HILL for Washington State Department of Ecology, Olympia, Washington.

Mac Arthur, R.H., and E.O. Wilson. 1967. The Theory of Island Biogeography. Princeton Univ. Press.

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.

McEuen, A. 1993. "The Wildlife Corridor Controversy: A Review." Endangered Species Update. Vol. 10, No. 11 and 12:1-12.

McMillan, R.O. 1991. Abundance, Growth, and Habitat Use by Juvenile Dungeness Crab, *Cancer Magister*, In Inland Waters of Northern Puget Sound, Washington. MS Thesis, School of Fisheries, University of Washington, Seattle, Washington. 53 pp.

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

Morrison, S.W., J. Keltman, and D. Haug. 1993. Inventory and Characterization of Shoreline Armoring, Thurston County, Washington. 1977-1993. Prepared by Thurston Regional Planning Council for Washington Department of Ecology, Olympia, Washington.

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

Naiman, R.J., and J.R. Sibert. 1979. "Detritus and Juvenile Salmon Production in the Nanaimo Estuary: III. Importance of Detrital Carbon to the Estuarine Ecosystem." *Journal of the Fisheries Research Board of Canada* 36: 504-520.

National Research Council (NRC). 1992. Restoration of Aquatic Ecosystems. National Academy Press. Washington, D.C.

Nesbit, D.M. 1885. Tide Marshes of the United States. Department of Agriculture Miscellaneous Special Report No. 7. Washington, D.C. 259 p.

Newman, J.R., and W.A. Cooke. 1988. Final EIS for the Enhancement of Hardshell Clam Production by Beach Graveling. State of Washington, Department of Fisheries. Olympia, Washington. 85 pp.

Nordstrom, K.F. 1992. *Estuarine Beaches.* Elsevier Science Publishing Co., Inc., New York.

Paulson, D.R. 1992. Northwest Bird Diversity: From Extravagant Past and Changing Present to Precarious Future. *Northwest Environmental Journal.* 8: 71-118.

PENTEC. 1993. Lincoln Park Shoreline Erosion Control Project: Post-Construction Monitoring of Epibenthic Zooplankton, 1993. Final Report to Seattle District, U.S. Army Corps of Engineers.

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

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

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

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

Pryne, E. 1994. Many Fish Species on Decline in Northwest. Seattle Times, 3/18/94.

Puget Sound Water Quality Authority. 1990. Issue Paper: Protecting Fish and Wildlife Habitat in Puget Sound. PSWQA, Seattle, Washington (March 1990).

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

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

Rigg, G.B. 1917. Seasonal Development of Bladder Kelp. *Publ. Puget Sound Biological Station* 1:309-318.

Ruotsala, A.A. 1973. A beach processes field guide for the Pacific Northwest. Privately produced with assistance from the University of Washington Sea Grant Program. 322 pp.

Sapik, D.B., G.D. Bortleson, B.W. Drost, M.A. Jones, and E.A. Prych. 1988. Groundwater Resources and Simulation of Flow in Aquifers Containing Freshwater and Seawater, Island County, Washington. U.S. Geological Survey, Water-Resources Investigations, Report 87-4182. Tacoma, Washington.

Schwartz, M.L. and R.G. Wallace. 1986. Quantification of net shore-drift rates in Puget Sound and the Strait of Juan de Fuca. Washington Department of Ecology, Olympia. WDOE 87-10. 41 pp.

Sedell, J.R., G.H. Reeves, F.R. Hauer, J.A. Stanford, and C.P. Hawkins. 1990. "Role of Refugia in Recovery from Disturbances: Modern Fragmented and Disconnected Landscapes." *Environmental Management* 14: 711-724.

Sedell, J.R., and R.L. Beschta. 1991. "Bringing Back the "Bio" in Bioengineering." Amer. Fish. Soc. Symp., 10:160-175.

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

Shreffler, D.K., C.A. Simenstad, and R.M. Thom. 1990. "Temporary Residence by Juvenile Salmon in a Restored Estuarine Wetland." *Can. J. Fish. Aquat. Sci.* 47: 2079-2084.

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

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

Sibert, J. 1979. "Detritus and Juvenile Salmon Production in the Nanaimo Estuary: II. Meiofauna Available as Food to Juvenile Chum Salmon (*Oncorhychus keta*)." *Journal of the Fisheries Research Board of Canada* 36: 497-503.

Sibert, J.T., T.J. Brown, M.C. Healey, B.A. Kask, and R.J. Naiman. 1977. "Detritus-based food webs: Exploitation by Juvenile Chum Salmon (*Oncorhynchus keta*)." *Science* 196: 649-650.

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

Simenstad, C.A., J.R. Cordell, and L.A. Weitkamp. 1991a. Effects of Substrate Modification on Littoral Flat Microfauna: Assemblage Structure Changes Associated with Adding Gravel. University of Washington Fisheries Research Institute, FRI-UW-9124, Seattle, Washington. 91 pp.

Simenstad, C.A., J.R. Cordell, R.C. Wissmar, K.L. Fresh, S. Schroder, M. Carr, and M. Berg. 1988. Assemblages Structure, Microhabitat Distribution, and Food Web Linkages of Epibenthic Crustaceans in Padilla Bay National Estuarine Research Reserve, Washington. Univ. Washington Fisheries Research Institute, FRI-UW-8813, Seattle, Washington.

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

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

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

Simenstad, C.A. and R.C. Wissmar. 1984. Variability of estuarine food webs and productivity may limit our ability to enhance Pacific salmon (*Oncorhynchus spp.*), pp. 272-286. In W.G. Pearcy (ed.) The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific, Oregon State University Press. ORESU-W-83.001.

Simenstad, C.A. and R.C. Wissmar. 1985. "$\delta^{13}C$ Evidence of the Origins and Fates of Organic Carbon in Estuarine and Nearshore Food Webs." *Mar. Ecol. Prog. Ser.* 22: 141-152.

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

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

Stick, K. 1991. Summary of 1991 Pacific Herring Spawning Ground Surveys in Washington State Waters. WDF, Olympia, Washington. Progress Report No. 292 (October 1991).

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

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

Thom, R.M. 1987. The Biological Importance of Pacific Northwest Estuaries. *Northwest Environmental* J. 3:21-42.

Thom, R.M. 1988. Lincoln Park Beach Eelgrass Baseline Study. Final Report to U.S. Army Corps of Engineers, Seattle District. Evans-Hamilton, Inc., Seattle, Washington.

Thom, R.M. 1989. Plant Standing Stock and Productivity on Tidal Flats in Padilla Bay National Estuarine Research Reserve, Washington. Univ. Washington, Fisheries Research Institute, FRI-UW-8909, Seattle, Washington.

Thom, R.M. 1992. Accretion Rates of Low Intertidal Salt Marshes in the Pacific Northwest. *Wetlands* 12:147-156.

Thom, R.M., and R.G. Albright. 1990. Dynamics of Benthic Vegetation Standing Stock, Irradiance, and Water Properties in Central Puget Sound. *Marine Biology* 104:129-141.

Thom, R., R. Albright, C. Simenstad, J. Hampel, J. Cordell, and K. Chew. 1984. Intertidal and Shallow Subtidal Benthic Ecology. In, Q.J. Stober and K.K. Chew (eds). Renton Sewage Treatment Plant Project: Seahurst Baseline Study. Univ. Washington, School of Fisheries, Fisheries Research Institute FRI-UW-8413, Seattle, Washington.

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

Thom, R.M., A.E. Copping, and R.G. Albright. 1988. Nearshore Primary Productivity in Central Puget Sound: A Case Study for Nutrient Limitation in the Nearshore Systems in Puget Sound. pp. 378-391 in, Proceedings Puget Sound Research '91. Puget Sound Water Quality Authority, Olympia, Washington.

Thom, R.M., and L. Hallum. 1989. Beach Nourishment, Post-Project Ecological Monitoring at Lincoln Park Beach: Initial Observations, Summer 1989. Final Report to Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

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

Thom, R.M., and L. Hamilton. 1991. Lincoln Park Shoreline Erosion Control Project: Post-construction Monitoring of Eelgrass, Infaunal Bivalves,and Macroalgae, 1990. Univ. Washington, Fisheries Research Institute, FRI-UW-9109, Seattle, Washington.

Thom, R.M., and J.J. Hampel. 1985. Lincoln Park Benthic Resource Assessment/ Enhancement Study. Final Report to U.S. Army Corps of Engineers, Seattle District. Evans-Hamilton, Inc., Seattle, Washington.

Thom, R.M., B. Miller, and M. Kennedy. 1991. Temporal Patterns of Grazers and Vegetation in a Temperate Seagrass System. NOAA Technical report Series OCRM/ MEMD. Final Report to U.S. Department of Commerce, National Oceanographic and Atmospheric Administration. Univ. Washington, Fisheries Research Institute, FRI-UW-9122, Seattle, Washington.

Thom, R.M., T.L Parkwell, D.K. Niyogi, and D.K. Shreffler. 1994. Effects of Gravel Placement on Estuarine Tidal Flat Primary Productivity, Respiration, and Nutrient Flux. *Marine Biology* 118:329-341.

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

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

Toba, D.R. 1992. The Effects of Substrate Modification on Hardshell Clams. Master's Thesis, Department of Fisheries, University of Washington, Seattle, Washington. June 1992.

Turner, M.G. 1989. Landscape Ecology: The Effect of Pattern on Process. *Ann. Rev. Ecol. Syst.* 20:171-197.

Valiela, I., J.M. Teal, S. Volkmann, D. Shafer, and E.C. Carpenter. 1978. Nutrient and Particulate Fluxes in a Salt Marsh Ecosystem: Tidal Exchanges and Inputs by Precipitation and Groundwater. *Limnol. Oceanogr.* 23:798-812.

Vermeer K., K.T. Briggs, K.H. Morgan, and D. Siegel-Causey (eds.). *The Status, Ecology and Conservation of Marine Birds of the North Pacific.* 1993. Canadian Wildlife Service Special Publication.

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

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

Wallace, R.S. 1988. Quantification of net shore-drift rates in Puget Sound and the Strait of Juan de Fuca, Washington. *J. Coastal Research.* 4(3): 395-403.

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

Washington Department of Fisheries. 1971. "Criteria Governing the Design of Bulkheads, Land Fills, and Marinas in Puget Sound, Hood Canal, and Strait of Juan de Fuca for Protection of Fish and Shellfish Resources." State of Washington, Department of Fisheries, Olympia, Washington.

Washington Department of Fisheries. 1974. "Bulkhead Criteria for Surf Smelt (*Hypomesus pretiosus*) Spawning Beaches in Puget Sound, Hood Canal, Strait of Juan de Fuca, San Juan Islands, and the Strait of Georgia." State of Washington, Department of Fisheries, Olympia, Washington.

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

Weins, J.A. 1985. Vertebrate Responses to Environmental Patchiness in Arid and Semi-arid Ecosystems. In, S.T.A. Pickett and P.S. White (eds). The Ecology of Natural Disturbances and Patch Dynamics. Academic Press, Inc., New York.

Weikamp, D.E., D. McEntee, and R. Whitman. 1986. Dungeness Crab Survey of Everett Harbor and Vicinity, 1984-1985. Final report to U.S. Navy by Parametrix, Inc., Bellevue, Washington. 29 pp.

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

Wissmar, R.C., and C.A. Simenstad. 1988. "Energetic Constraints of Juvenile Chum Salmon (Oncorhynchus keta) migrating in estuaries." *Can. J. Fish. Aquat. Sci.* 45: 1555-1560.

Word, J.Q., L.S. Word, J.N. McElroy, and R.M. Thom. 1986. *The Surface Microlayer: Review of Literature and Evaluation of Potential Effects of Dredge Activities in Puget Sound.* Prepared for the U.S. Army Corps of Engineers, Seattle District, by Evans Hamilton, Inc., Seattle, Washington.

sea1002862B.wp5